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A model of how working memory capacity influences insight problem solving in situations with multiple visual representations: An eye tracking analysis

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ABSTRACT

Insight problem solving, which involves the restructuring of problems and insights, should be closely related to attention and working memory (WM). This study aimed to employ eye-tracking techniques to understand the process by which attention and WM capacity may influence insight problem solving when situations with multiple visual representations are employed. Fourteen graduate students participated in a 70-minute experimental session in this study. The adapted situation-based creativity task (SCT) and the adapted situation-based WM task (SWMT) were employed to measure WM capacity and insight problem solving. Using situation-based visual WM tasks and insight problem solving the findings of this study suggest the following. First, fixation, gaze duration, and saccades to targets are effective eye movement indicators that can aid in the understanding of the cognitive processes of WM and insight problem solving. Second, attention, eye movements, and WM capacity interactively influence insight problem solving, and that influence varies with WM capacity and the insight stage. Accordingly, we propose three stages of insight processes based on eye movements.

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1. Introduction

Insight is the process by which a problem solver reconstructs a problem and suddenly comes up with a solution after systematic searches for solutions have failed. Moreover, insight is usually sporadic and unpredictable (De Dreu, Baas, & Nijstad, 2008). In cognitive psychology, many researchers focus on the process of insight by studying insight problem solving because this approach enables researchers to experimentally examine the process of insight within a relatively short time period (Abraham & Windmann, 2007). Insight problems typically involve an open problem and closed solution, and they also involve restructuring the problem before the problem can be solved (Abraham & Windmann, 2007).

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Working memory (WM) is considered an online cognitive process through which the learner acquires and processes new information to solve the encountered problem (Baddeley & Logie, 1999; Cowan, 1999). WM capacity is also considered as a prerequisite for cognitive flexibility, strategic planning, and the speed with which information is transferred to long-term memory (Baddeley, 2000; Cowan, 2010; Dietrich, 2004). WM also allows one to hold in mind knowledge that is relevant to solving a particular problem (Dietrich, 2004). Study findings have suggested that WM span is related to the ability to solve difficult problems (Song, He, & Kong, 2011) and that WM capacity benefits creative insight because it enables the individual to maintain focused attention on the task and prevents undesirable mind wandering (De Dreu, Nijstad, Baas, Wolsink, & Roskes, 2012). Thus, WM capacity should have a strong influence on insight problem solving. Previous related studies, however, have seldom measured WM and insight problem solving using tasks that share similar but complex contexts in which multiple visual objects are presented (i.e., few studies have measured WM that required some combination of instruments and then measured how participants employed these instrument combinations to solve subsequent insight problems in which more than 10 objects were presented). Will the relationship between WM and insight problem solving be different in such a complex situation? This study seeks to answer that question.

Moreover, although a few studies have investigated the relationship between WM and insight problem solving, few researchers have examined the process by which WM influences insight problem solving using eye movements. Numerous researchers since the 1970s have developed methods of recording eye movements to further the understanding of cognitive processes during learning. Specifically, eye tracking has been useful in revealing the on-line process of diagram-based problem solving (Grant & Spivey, 2003). Recently, eye tracking has also been applied to further understanding how learners interact with multiple representations and how their attention to different representations influences learning (van Gog & Scheiter, 2010).

Based on the merits of the eye tracking technology, this study sought to use eye movement data to understand the process by which WM capacity influences insight problem solving that involves the employment of multiple visual representations. We simultaneously investigated whether individuals with different WM capacities and insight problem solving abilities would show different eye movement patterns, by which a model that depicts the relationship between WM capacity, eye movements, and insight problem solving would be proposed.

2. Definitions and theories of WM and insight problem solving

2.1. WM

According to Baddeley's (2003) multicomponent model of WM, WM is composed of the following four subcomponents: (1) the central executive, which is an attention-controlling system that is responsible for directing attention to relevant information, suppressing irrelevant information, and coordinating two slave systems, i.e., the phonological loop and the visuospatial sketch pad; (2) the phonological loop, which consists of a phonological store that can hold memory traces for a few seconds and an articulatory rehearsal process that is analogous to subvocal speech; (3) the visuospatial sketch pad, which handles visual images and spatial information; and (4) the episodic buffer, which is a limited-capacity store that binds information together to form integrated episodes that is assumed to be under the attentional control of the executive.

The other commonly cited WM theory is Cowan's (1999) embedded-process model. This model assumes that WM is a part of long-term memory and that the memory system is operated via the interactions between attentional and memory mechanisms. In addition, WM is organized into two embedded levels (Cowan, 1999). The first level consists of activated long-term memory representations. Information in the memory system can be held in activated or non-activated states; when in non-activated states, these elements represent long-term memory (LTM). The second level is the focus of attention. Attentional resources are used to retrieve information from LTM in to meet current needs. Moreover, activated units can arise from multi-modal sensory input and semantic and episodic information from LTM. Though these representations may or may not be in conscious awareness, they are readily accessible for use when necessary. A portion of these items can further become the focus of attention (Cowan, 2010). Cowan also suggested that deliberate actions are based on the contents of the focus of attention. Accordingly, WM is used to indicate a functional level at which activated memory, the focus of attention, and central executive processes work together to keep items in mind and thus address various cognitive tasks.

2.2. Insight problem solving

Wakefield (1989) defined four types of problems: (1) closed problems with open solutions; (2) open problems with closed solutions; (3) open problems with open solutions; and (4) closed problem with closed solutions. In an open problem, the valid solution path is not clearly defined; the solver needs to discover it. Conversely, in a closed problem, the information presented is quite clear and logically entails the solution. Of these types of problems, "open problems with closed solutions" are the classic insight problems. Insight tasks typically require a mental restructuring of problem information that leads to a sudden understanding of the solution to the problem (Bowden, Jung-Beeman, Fleck, & Kounios, 2005; De Dreu et al., 2008). Pretz, Naples, and Sternberg (2003) also proposed that problems can be divided into two categories: well- and ill-defined. In a well-defined problem, the problem is presented with the expectation that the current state, goal state, and operators will be sufficient to allow steady progress toward the goal. In an ill-defined problem, uncertainty exists not only in whether the goal will be reached but also in how to conceive the current state, goal state, and operators. Moreover, an ill-defined

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problem requires an individual to restructure his or her formulation before solution is possible. "Insight" typically indicates the moment when a new and more effective formulation appears in mind. Accordingly, insight problems are often ill-defined problems (DeYoung, Flanders, & Peterson, 2008).

In insight problems, there is always one right answer, but the path to reach that answer is seldom clear. The problem solver must first restructure the information given in the problem before he or she can make sense of the problem. Some researchers (e.g. Abraham & Windmann, 2007) have suggested that the progression through the insight problem solving process is not incremental but involves a sudden discovery of a solution – a phenomenon that is commonly referred to as the "aha" experience. However, recent studies (Cushen & Wiley, 2012; Lin, Hsu, Chen, & Wang, 2011) have found that that both insight-like patterns and incremental patterns may occur during the solution progress. Furthermore, the process of insight problem solving requires convergent and divergent thinking (DeYoung et al., 2008). Divergent thinking refers to unbound searching or open-ended thinking that is typically evoked in creativity tasks where solutions do not have any right or wrong answers. Convergent thinking, on the other hand, is required for problems that are designed to have a single and correct solution for it helps converging the activated cognitive processes (Abraham & Windmann, 2007). An insight problem therefore is convergent in that it seeks to arrive at the single correct solution. However, as the problem needs to be restructured by means of flexible thought, it also requires divergent thinking (Abraham & Windmann, 2007). Therefore, insight problems may involve both insight-like and incremental patterns of problem solving as well as divergent and convergent thinking.

3. The relationship among eye movement, WM, and insight problem solving

3.1. WM, and insight problem solving

Research findings have suggested a relationship between WM capacity and the ability to solve insight problems (Zhou, Hoogenraad, Joels, & Krugers, 2012). For example, Song et al. (2011) found a main effect of verbal WM span on high-level difficulty word problem solving ability, which suggests that WM span is related to the ability to solve difficult problems. Fleck (2008) found that differences exist in the cognitive processes underlying insight vs. analytic problem solving; he suggested that restructuring in insight is the end result of active memory search or spontaneous processes.

The close relationship between WM and insight problem solving is also supported by findings from studies of creative insight. For example, De Dreu et al. (2012) claimed that executive control plays an important role in achieving creative insights, and they found that under cognitive load, participants performed worse on a creative insight task. Moreover, these authors concluded that WM capacity benefits creativity because it enables the individual to maintain focused attention on the task and prevents undesirable mind wandering. Hirt, Devers, and McCrea (2008) also found that providing a retrieval cue for positive material in memory leads to multiple interpretations and organizations of material in memory, which contributes to the creativity of associations.

3.2. Eye movement indicators and their relationship to attention

Many researchers have employed eye movements to develop and test cognitive models in various domains. Typically, eye movements are analyzed in terms of aggregate measures (e.g., the number of fixations on an item or the total time spent fixating an item), and many cognitive models are tested with respect to these measures (Grant & Spivey, 2003). The most frequently reported information from eye-tracking data is actually not related to movements but instead to the periods of time in which the eyes remain still. These time periods are called fixations, and they last from tens of milliseconds to several seconds. It is generally assumed that the location of fixation is the focus of attention and that fixation duration indicates processing efforts directed at that location, although exceptions exist that separate attention and eye movements (Holmqvist et al., 2011). Many studies have demonstrated different effects of cognitive processing on fixation-related measures, including the following examples: more overall fixations indicate less efficient search (Goldberg & Kotval, 1999); more fixations on a particular area indicate that the area is more noticeable or important to the viewer than other areas (Poole & Ball, 2005); and longer fixation durations indicate difficulty in extracting information or that the object is engaging in some way (Rayner, 1998). Fixations concentrated in a small area indicate focused and efficient searching, and evenly spread fixations reflect widespread and inefficient search (Cowen et al., 2002). In eye-tracking studies, gaze and saccades are also frequently measured. Gaze, the sum of all fixation durations within a prescribed area before moving out of the area, is best used to compare how attention is distributed between targets (Mello-Thoms, Nodine, & Kundel, 2002). The number of fixation transitions is defined as gaze alternations across the borders of different areas of interest (Nitschke, Ruh, Kappler, Stahl, & Kaller, 2012); a lower ratio of the number of on-target fixations divided to the total number of fixations indicates lower search efficiency (Goldberg & Kotval, 1999).

The relationship between attention and eye movements has been extensively investigated. There is evidence suggesting that attention precedes saccades to a given location in space and that attentional movements and saccades are obligatorily coupled. Although we can decouple the locus of attention and eye location in simple discrimination tasks, it is hard to decouple the two in complex information processing tasks (Rayner, 1998). Most researchers, however, support the notion that attention and eye movements are dynamically interactive. For example, Szinte, Jonikaitis, Rolfs, and Cavanagh (2012) found that dynamic attention allocation exists before and after saccadic eye movements. Zhao et al. (2012) suggested that

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saccadic eye movements and perceptual attention work coordinately to allow selection of the objects or features with the greatest current need for limited visual processing resources. Theeuwes and Van der Stigchel (2009) also claimed that the process of memorizing a location is the same as the process of programming eye movements to that location. Accordingly, attention and eye movement may work interactively work during the completion of WM and of insight problem solving tasks. This study therefore assumes that attention and eye movements are interactive and that the relationships among eye movements, WM and insight problems can be explained from the viewpoint of attention.

3.3. Attention, eye movements, and WM

Many theoretical arguments and empirical findings support the strong relationship between attention and WM. Cowan (1988) declared that WM is best understood as a subset of activated representations of the long-term memory that is currently within the focus of attention. He claimed that "there is no single separate theoretical entity that I would call working memory. . .What are potentially more meaningful in a theoretical sense are the basic mechanisms proposed to underlie this complex system, including activation of memory contents of an attentional process, and the contextual organization of memory" (Cowan, 1999, p. 88). In the multicomponent model of WM, Baddeley (2003) also emphasized that the central executive is an attentional-controlling system that is responsible for directing attention to relevant information and that the episodic buffer is assumed to be under the attentional control of the executive. On the other hand, Theeuwes, Belopolsky, and Olivers (2009) claimed that attention is used to maintain information in memory and to store and retrieve information from WM. WM capacity is thought to reflect the domain-general processing abilities of the central executive WM capacity, and more generally the central executive, predicts performance in tasks involving selective attention.

In addition, Theeuwes et al. (2009) declared that eye movement, attention and WM are related. These authors suggested that attention precedes an eye movements and that attention is the mechanism by which information is stored in WM. They also found that keeping a location in memory systematically influences saccade trajectories. Godijn and Theeuwes (2012) suggested that rehearsal during memory retention can operate equally well overtly via sequences of eye movements and covertly via attention shifts during fixations. The aforementioned findings lead to our argument that attention, eye movements, and WM are interactive and individuals with different WM capacity may show different patterns of eye movements while completing WM tasks.

3.4. Attention, eye movement, and insight problem solving

Research findings have suggested that eye movement recordings provide an important new window into processes of insight problem solving. For instance, Knoblich, Ohlsson, and Raney (2001) used matchstick arithmetic problems and eye movement recordings to verify the representational change theory of insight, which hypothesizes that insight problems cause impasses because they mislead problem solvers into constructing inappropriate initial representations and that insight is attained when the initial representation is changed. Litchfield and Ball (2011) investigated whether following the specific saccades of another person could induce similar attentional shifts and increase solution rates for insight problems; they found that another person's eye movements can promote attentional shifts that trigger insight problem solving. In the same vein, Thomas and Lleras (2009) used Duncker's radiation problem tasks and found that aiding participants in shifting their attention in a pattern compatible with the solution can facilitate insight. Moreover, Hafed and Clark (2002) declared that small saccades reflect attention shifts. Notably, it is often the situation that attention and eye movements are coupled together. Therefore, the measurable eye movements can be used to reflect the attention allocation in cognitive tasks. As a result, eye movements can represent attentional operations to show the cognitive processes in different tasks (Just & Carpenter, 1984). Grant and Spivey (2003) also suggested that the visual environment, attention, and mental operations are interactive and intertwined. Accordingly, eye movement recording provides an opportunity to explore the detailed processes in solving insight problems.

Although a limited number of studies have suggested that attention and eye movement can predict insight problem solving, few studies have employed insight tasks with complex visual representations. It has been suggested that the shared selection of saccade and pursuit targets is an effective way of handling environments containing multiple targets (Kowler, 2011). Whether individuals with different insight problem solving abilities show different patterns of eye movements when solving insight problems was a concern of this study.

4. Hypotheses of this study

In this study, we sought to understand the relationships among eye movements, WM capacity, and insight problem solving in addition to how WM capacity influences insight problem solving in situation-based contexts with multiple visual representations. Based on the aforementioned literature, we proposed that WM capacity would influence eye movements and that WM capacity would influence insight problem solving via attention, which can be revealed via eye movements. In addition, past studies have suggested that the restructuring of problems and the achievement of insight involve different types of thinking in different stages (Abraham & Windmann, 2007) and that visual environment, attention, and mental operations are interactive and intertwined (Grant & Spivey, 2003). One of the advantages of the eye-tracking method is that it can record eye movements for the whole experimental period in a task. The on-line measure of eye movements in different

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phrases could show the time course of different stages while achieving insights. Based on these assumptions, we proposed the following hypotheses:

1. Individuals with different levels of WM capacity will show different patterns of eye movements during the completion of WM tasks.
2. Individuals with different level of WM capacity will demonstrate different patterns of eye movements when they respond correctly vs. incorrectly during the completion of WM tasks.
3. Individuals with different insight problem solving abilities will show different patterns of eye movements during the completion of insight problems.
4. Individuals will demonstrate different patterns of eye movements when they respond correctly vs. incorrectly during the completion of insight problems.
5. Individuals with different levels of WM capacity will demonstrate different patterns of eye movements during the completion of insight problems.
6. Individuals with different levels of WM capacity will demonstrate different patterns of eye movements in different stages of solving insight problems.

5. Methods

5.1. Participants

This study employed an experimental design. Twenty graduate students registered to participate in this study. Since six participants could not either pass the first calibration before the experiment or had serious head motions during the experiment, only 14 of them (seven female and seven male) were included in this study. With a mean age of 23.07 years (*SD* = 1.94 years), all qualified participants had a normal or corrected to-normal vision as well as had a good sleep at the night before participating in the experiment. Written informed consent was obtained from all participants prior to the experiment. After completing the experiment, the participants received compensation of US$7 for their participation.

5.2. Stimuli

5.2.1. Situation-based creativity task

This study tried to understand the process by which WM capacity influences situation-based insight problem solving that involves the employment of multiple visual representations. Past studies have seldom used situation-based WM tasks and insight problem tasks. The situation-based creativity task (SCT) and the situation-based WM task (SWMT) meet our needs and they have been proved to be good instruments for understanding the cognitive process of creativity (Lin, Yeh, Hung, & Chang, 2013). We therefore adapted the SCT and the SWMT to measure insight problem solving and WM ability in this study. The original SCT is composed of situation-based insight tasks developed for Flash. The SCT includes three runs of situation-based tasks (30 tasks in total) in which the goal is to escape from three situations: the living room, the kitchen, and the bathroom. Considering the adaptability and time limits of the experimental design, we selected eight tasks from the kitchen and eight tasks from the bathroom situations; we also adapted the tasks from a flash interface to an image format. In our adapted SCT, two instruments provided in the situation had to be correctly combined to solve each of the problems. The time limit for each problem was 60 s. The participant was asked to provide the solution by moving the mouse pointer and clicking on two instruments provided in the task (Fig. 1). The selected instruments could not be changed and the participant would not know the correct answer, so the participant was encouraged to think carefully before the decision was made. The selected answers were recorded in the iView X Eye-tracking system. Incorrect answers were scored as "0" points, and correct answers were scored as "1" point. The highest possible total score was 16 points (8 points in each run).

5.2.2. Situation-based WM task

The situation-based WM task (SWMT) is related to the SCT, and its use as an instrument to evaluate WM capacity was developed by Yeh (2011). The original SWMT includes three runs (five trials in each run) of WM tasks corresponding to the insight tasks involving the living room, the kitchen, and the bathroom. Participants were instructed that some answers to the SCT tasks were primed in the SWMT tasks. To match the adapted insight tasks, only four trials from the kitchen and four trials from the bathroom situations were included in this study. In each trial, three key instrument and accessory instrument pairs (e.g., can + knife; can + clothes hanger; can + electrical screw driver) were displayed on the screen for 10 s. There were a total of four key instruments, so 12 pairs were displayed for the participants to memorize (Fig. 2). Next, participants' WM capacities were tested using a four-back test with a matrix of 20 instruments and one key instrument that was displayed for 10 s. The participants gave answers by directing the mouse pointer to the three accessory instruments that had been shown in the matrix (Fig. 3). A total of four matrices were displayed, and the selected answers were recorded in the iView X -tracking system. In each run, an incorrect answer received "0" points, and a correct answer received "1" point. The highest possible score was 24 points (12 points in each run).

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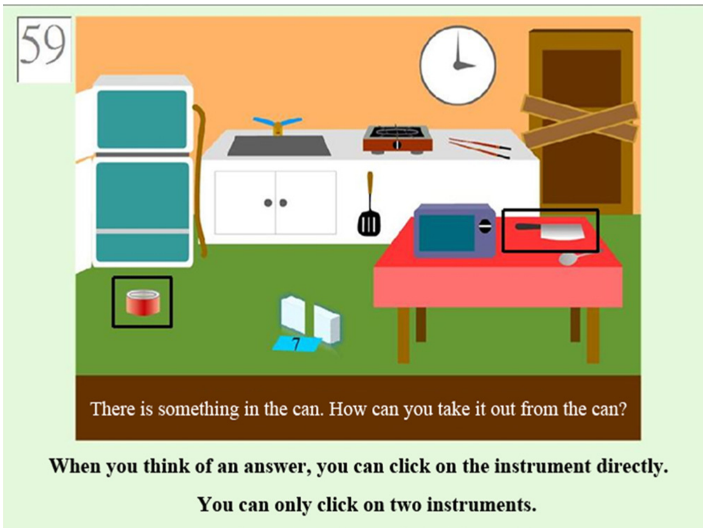

Fig. 1. An example of the adapted situation-based creativity task.

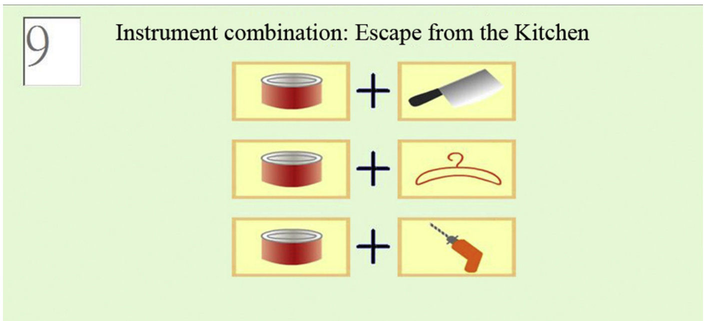

Fig. 2. An example of the instrument combinations.

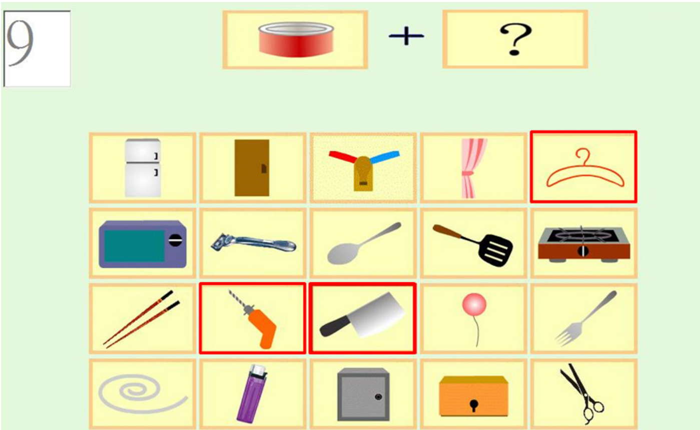

Fig. 3. An example of the WM capacity test.

5.3. *Apparatus*

Eye movements were recorded using an iView X Hi-Speed 1250 eye-tracking system manufactured by SensoMotoric Instruments (SMI). Eye positions were sampled at 500 samples/s. In this study, the visual stimuli were presented on a screen (CRT 19 in., 1024 × 768 pixels, 39 cm × 29 cm, 85 Hz) using the Experiment Center 2.5 software (SMI). The screen was orthogonal to the line of sight at a distance of 70 cm and subtended 31° (H) and 23° (V) of the visual angle. The recorded eye positions had an average error of .5° to 1.0° of visual angle.

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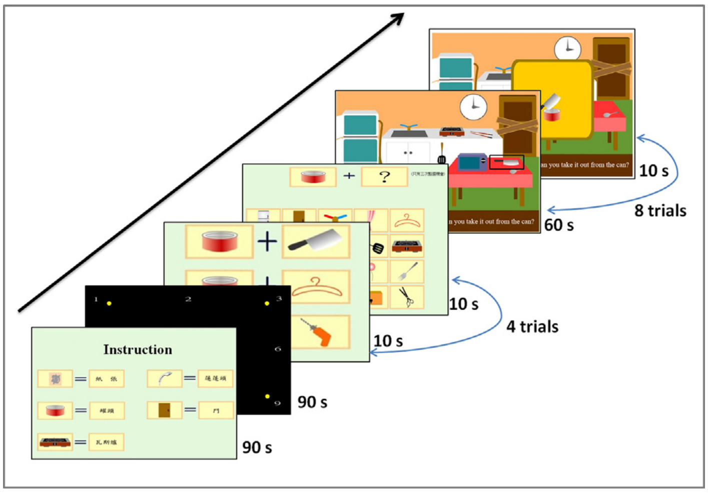

Fig. 4. Procedure for the first run.

5.4. Experimental design and procedures

This study included an instruction session, an experimental session with two runs, and a debriefing session; the participants were tested individually in these sessions. The entire procedure took approximately 70 min to complete. The first run included the adapted WM and insight tasks from the kitchen situation, and the second run included the same tasks from the bathroom situation. Before using the eye-tracer system, participants were instructed to inform us of their dominant eye. Next, participants were instructed to sit at an eye-to-screen distance of approximately 57 cm in front of a 19 in. CRT monitor with their chins and foreheads on the rests that were integrated into the eye-tracking system.

Before each run of the tasks, a standard nine-point calibration procedure was conducted. During the calibration, the participant viewed nine randomly presented small and white fixation crosses on a black background. The fixation crosses were then removed, and the first run of the WM tasks was displayed. The adapted WM tasks consisted of the memorization of three different pairs of instrument combinations displayed on four consecutive screens (12 pairs and 40 s in total) and the recognition of the correct combinations from four matrices (40 s in total). Then, the participant proceeded to complete the eight insight tasks in the first run. The maximum response time for each of the insight tasks was 60 s, but when the participants finished the task before the time limit, they continued to the next task. Upon completion of the first run, the participants rested for 2 min, followed by the second calibration and the second run. The procedure for the second run was the same as that of the first run (Fig. 4) The only difference between the first and second runs was the content of the WM and insight tasks.

5.5. Data analysis

During the experiments, the accuracy, response times, and eye movements for the WM and insight tasks were recorded and preprocessed using the Experiment Center 2.5 and BeGaze 2.4 software from the iView X Eye-tracking system. Subsequent analyses were conducted in MATLAB. To analyze the eye movement data, we first defined the area of interest (AOI) to analyze gaze location. The AOIs were the objects displayed in the recognition matrices from the WM tasks (Fig. 3) and the objects displayed in the insight tasks (Fig. 1). We then categorized the gaze locations into all-object and target AOIs.

We separately calculated the following six eye movement parameters for the AOIs: total number of fixations on all-object AOIs (total fixations), total gaze duration on all-object AOIs (total gaze duration), total number of saccades to all-object AOIs (total saccades), total number of fixations on target AOIs (fixations on targets), total gaze duration on target AOIs (gaze duration on targets), and total number of saccades to target AOIs (saccades to target). In addition, we analyzed response times. Based on these parameters, we further analyzed the effects of WM capacities, WM responses (incorrect vs. correct), insight problem solving abilities, and insight problem solving responses (incorrect vs. correct) with one-way univariate analysis of variance (one-way ANOVA) and repeated-measures analysis of variance (repeated measures ANOVA).

6. Results

6.1. Effects of WM capacity on eye movements in WM tasks

We used the median WM scores as a threshold to divide the participants into the Low and High groups. We then used the WM group as an independent variable and each of the six eye movement parameters and WM response time as dependent

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Table 1
The effects of WM capacity on eye movements in WM tasks.

Source	Descriptives			ANOVA $F(1, 12)$			
	M	*SD*	*N*	*MS*	*F*	*p*	η_p^2
Response time							
Low	9.353	1.115	7	.192	.180	.679	.015
High	9.118	.942	7				
Total fixations							
Low	37.750	3.394	7	4.715	.646	.437	.051
High	36.589	1.755	7				
Total gaze duration							
Low	9.365	.831	7	.145	.215	.651	.018
High	9.568	.807	7				
Total saccades							
Low	37.500	3.895	7	1.215	.075	.789	.006
High	36.910	4.148	7				
Fixations on targets							
Low	1.125	.224	7	.240	4.918*	.047	.291
High	1.386	.195	7				
Gaze duration on targets							
Low	.540	.104	7	.131	6.934*	.022	.366
High	.733	.164	7				
Saccades to targets							
Low	6.464	1.859	7	11.161	4.044	.067	.252
High	8.250	1.436	7				

* $p < .05$.

variables in one-way ANOVAs. The results revealed significant effects of WM capacity on fixations on targets ($F(1, 12) = 4.918$, $p = .047$, $\eta_p^2 = .291$) and gaze duration on targets ($F(1, 12) = 6.934$, $p = .022$, $\eta_p^2 = .366$; Table 1).

6.2. *Effects of WM response on eye movements in WM tasks*

We conducted within-subject analyses to examine whether the participants displayed different eye movements during the WM tasks when they responded incorrectly vs. correctly. Specifically, we used the response group (incorrect vs. correct) as an independent variable and each of the six eye movement parameters and response times as dependent variables to conduct repeated-measure ANOVAs. The results revealed that WM responses (incorrect vs. correct) significantly affected all parameters, particularly gaze duration on targets ($F(1, 12) = 5.402$–20.195, p's < .05, $\eta_p^2 = .294$ to .608; Table 2).

6.3. *Relationship between insight problem solving ability and eye movements during insight tasks*

We conducted one-way ANOVA to examine whether the participants with different insight problem solving abilities would show different patterns of eye movements during the completion of insight problems. We used the median insight problem solving score as a threshold to divide the participants into the Low and High groups. We then used these groups as an independent variable and each of the six eye movement parameters and response times as dependent variables in one-way ANOVAs. The results revealed no significant effects (Table 3).

6.4. *Relationship between insight problem solving responses and eye movements during insight tasks*

We conducted within-subject analyses to examine whether the participants displayed different eye movements during the insight tasks when they responded correctly vs. incorrectly. Specifically, we used the response group (incorrect vs. correct) as an independent variable and each of the six eye movement parameters and response times as dependent variables to conduct repeated-measure ANOVAs. The results revealed that, with the exception of total gaze duration, the type of insight problem solving responses (incorrect vs. correct) affected all eye movement parameters ($F(1, 12) = 5.060$–35.113, p's < .05, $\eta_p^2 = .280$ to .730; Table 4).

6.5. *Effects of WM capacity on eye movements during insight tasks*

We used the median WM score as a threshold to divide the participants into the Low and High groups. We then used the WM group as the independent variable and each of the six eye movement parameters during insight problem solving as dependent variables to conduct one-way ANOVAs. The results revealed significant effects of the WM ability on fixations

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Table 2
The effect of WM responses on eye movements in the WM tasks.

Source	Descriptives			ANOVA $F(1, 12)$			
	M	SD	N	MS	F	p	η_p^2
Response time							
Incorrect	6.236	4.544	14	69.029	8.011*	.014	.381
Correct	9.376	.977	14				
Total fixations							
Incorrect	26.464	17.67	14	844.082	6.340*	.026	.328
Correct	37.445	2.767	14				
Total gaze duration							
Incorrect	6.632	4.479	14	56.914	5.402*	.037	.294
Correct	9.484	.710	14				
Total saccades							
Incorrect	27.035	18.53	14	757.640	5.896*	.030	.312
Correct	37.439	3.691	14				
Correct							
Incorrect	.813	.588	14	1.511	7.253*	.018	.358
Correct	1.278	.292	14				
Gaze duration on targets							
Incorrect	.207	.223	14	.539	20.195***	.001	.608
Correct	.485	.154	14				
Saccades to targets							
Incorrect	4.839	3.681	14	49.806	6.493*	.024	.333
Correct	7.506	1.997	14				

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

Table 3
The effects of insight problem solving ability on eye movements during insight tasks.

Source	Descriptives			ANOVA $F(1, 12)$			
	M	SD	N	MS	F	p	η_p^2
Response time							
Low	20.081	5.820	6	2.744	.075	.789	.006
High	20.976	6.201	8				
Total fixations							
Low	62.573	19.706	6	14.555	.038	.848	.003
High	64.633	19.345	8				
Total gaze duration							
Low	15.601	4.825	6	1.878	.079	.783	.007
High	16.341	4.894	8				
Total saccades							
Low	59.470	18.176	6	89.221	.218	.649	.018
High	64.571	21.562	8				
Fixations on targets							
Low	2.553	.715	6	.086	.068	.798	.006
High	2.711	1.332	8				
Gaze duration on targets							
Low	.712	.269	6	.013	.130	.725	.011
High	.774	.352	8				
Saccade to targets							
Low	9.677	2.737	6	5.790	.302	.593	.025
High	10.976	5.242	8				

Note. The group size was different due to identical scores in the calculation of the median.

on targets ($F(1, 12) = 8.173$, $p = .014$, $\eta_p^2 = .405$), gaze duration on targets ($F(1, 12) = 5.923$, $p = .032$, $\eta_p^2 = .330$), and saccades to targets ($F(1, 12) = 5.525$, $p = .037$, $\eta_p^2 = .315$). The results reveal that participants with higher WM capacities made more saccades to targets, fixated the targets more frequently, and looked at the targets for longer times than participants with lower WM capacities (Table 5).

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Table 4
The effects of insight problem solving responses on eye movements during insight tasks.

Source	Descriptives			ANOVA $F(1, 12)$			
	M	SD	N	MS	F	p	η_p^2
Response time							
Incorrect	22.886	8.424	14	108.161	5.311*	.038	.290
Correct	18.955	5.588	14				
Total fixations							
Incorrect	70.713	24.853	14	912.468	5.060*	.042	.280
Correct	59.295	18.488	14				
Total gaze duration							
Incorrect	17.564	6.596	14	49.633	3.854	.071	.229
Correct	14.902	4.509	14				
Total saccades							
Incorrect	69.049	25.088	14	928.439	5.695*	.033	.305
Correct	57.532	19.124	14				
Fixations on targets							
Incorrect	1.513	.780	14	36.828	35.113***	.000	.730
Correct	3.807	1.655	14				
Gaze duration on targets							
Incorrect	.345	.211	14	4.359	33.309***	.000	.719
Correct	1.134	.536	14				
Saccades to targets							
Incorrect	7.872	4.717	14	204.978	9.970**	.008	.434
Correct	13.283	5.918	14				

* $p < .05$.
** $p < .01$.
*** $p < .001$.

Table 5
The effects of WM capacity on eye movements during insight tasks.

Source	Descriptives			ANOVA $F(1, 12)$			
	M	SD	N	MS	F	p	η_p^2
Response time							
Low	18.020	5.678	7	92.674	3.189	.099	.210
High	23.165	5.085	7				
Total fixations							
Low	55.607	17.986	7	928.449	3.054	.106	.203
High	71.894	16.864	7				
Total gaze duration							
Low	13.824	4.498	7	67.764	3.727	.078	.237
High	18.224	4.015	7				
Total saccades							
Low	53.404	17.616	7	1129.145	3.504	.086	.226
High	71.365	18.278	7				
Fixations on targets							
Low	1.982	.529	7	6.112	8.173*	.014	.405
High	3.304	1.102	7				
Gaze duration on targets							
Low	.576	.223	7	.412	5.923*	.032	.330
High	.919	.298	7				
Saccades to targets							
Low	8.116	2.826	**7**	74.290	5.525*	.037	.315
High	12.723	4.347	7				

* $p < .05$.

6.6. *Effects of WM capacity on eye movements during insight tasks across different time intervals*

To further examine whether participants with different WM capacities displayed different eye movements patterns towards targets across different stages of insight problem solving, we first examined the eye movement data towards targets between 0 and 21 s (the mean response time was 21 s; Fig. 5). Then, we analyzed the aggregate effects of WM capacity group

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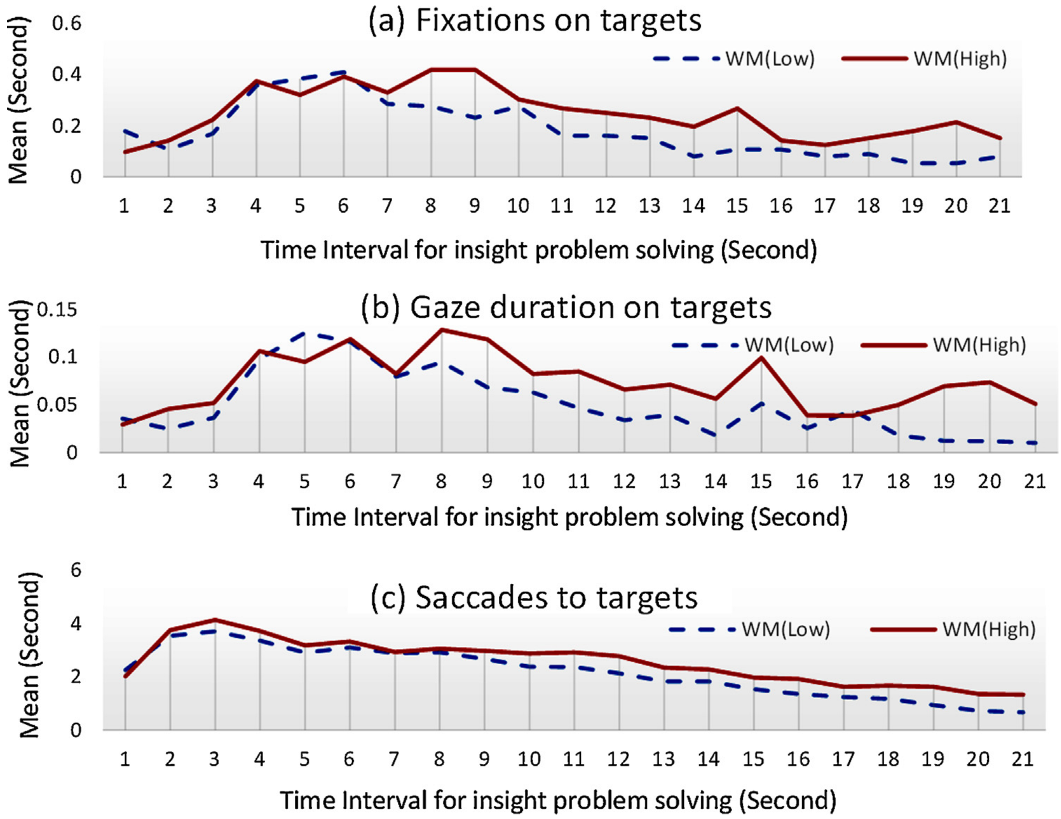

Fig. 5. Mean eye movements scores during insight tasks across time intervals.

(Low vs. High) on the three target-related eye movements during insight tasks (i.e., fixations on targets, gaze duration on targets, and saccades to targets) by dividing the eye movement data into three groups of intervals: (1) 0–3 s, 4–18 s, and 19–21 s; (2) 0–5 s, 6–16 s, and 17–21 s, and (3) 0–7 s, 8–14 s, and 15–21 s. Because no previous studies have addressed this question, we compared the results of these analyses to identify the best eye movement patterns for achieving insights.

The ANOVA results showed that the intervals of 0–5 s, 6–16 s, and 17–21 s best described the influence of WM capacity on insight problem solving. Specifically, there were significant WM group effects on “fixations on targets” during the 6–16 s and 7–21 s intervals (F's > 5.920, p's < .05, $\eta_p^2 > .331$), “gaze duration on targets” in the 6–16 s and 7–21 s intervals (Fs > 5.266, p's < .05, $\eta_p^2 > .305$), and “saccades to targets” in the 7–21 s interval ($F = 6.155$, $p = .029$, $\eta_p^2 = .339$; Table 6).

7. Discussion

7.1. The relationship between eye movements, WM capacity, and insight problem solving

This study proposed six hypotheses; with the exception of the third hypothesis, which stated that individuals with different insight problem solving abilities will show different patterns of eye movements during the completion of insight problems, our hypotheses were supported. Our investigation of the relationship between eye movements and WM capacity revealed that participants with higher WM capacities gazed at the targets more frequently and for longer times than participants with lower WM capacities. Furthermore, when participants responded correctly, they took more time to respond, made more fixations on, more saccades to, and displayed longer gaze durations on both the targets and all objects than when they responded incorrectly. Because the response times for correct answers in the WM tasks were longer than those of incorrect answers and because longer fixation durations indicate difficulty in extracting information (Rayner, 1998), our findings reveal that the WM tasks employed in this study were difficult for the participants. Our WM tasks were, essentially, four-back tasks with multiple visual representations in each trial.

Additionally, fixations concentrated in a small area indicate focused and efficient searching (Cowen et al., 2002), and saccades are part of a shared mechanism for selecting targets (Krauzlis, 2005). The significant effects of target-related eye movements in WM tasks lend support to the following claims: WM and attention are intricately related (Cowan, 1999; Majerus et al., 2006); the rehearsal of visuo-spatial information is achieved by eye movements (Tremblay, Saint-Aubin, & Jalbert, 2006); visual WM and selective attention both operate at the interface between perception and action (Awh, Vogel, & Oh, 2006); and focused attention is essential for efficient information processing in WM because this focused attention helps maintaining information in memory and retrieving information from WM (Theeuwes et al., 2009). Accordingly, eye movements, attention, and WM may interact and influence WM capacity.

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Table 6
The effects of WM capacity on eye movements during different time intervals of insight problem solving.

Source	Descriptives			ANOVA $F(1, 12)$			
	M	*SD*	*N*	*MS*	*F*	*p*	η_p^2
Fixations on targets (1–5 s)							
Low	.239	.050	7	.000	.030	.866	.002
High	.232	.097	7				
Fixations on targets (6–16 s)							
Low	.204	.057	7	.027	6.512*	.025	.352
High	.293	.071	7				
Fixations on targets (17–21 s)							
Low	.077	.044	7	.024	5.920*	.031	.331
High	.160	.078	7				
Gaze duration of targets (1–5 s)							
Low	.063	.025	7	.000	.014	.909	.001
High	.065	.023	7				
Gaze duration of targets (6–16 s)							
Low	.057	.021	7	.003	5.266*	.041	.305
High	.086	.024	7				
Gaze duration of targets (17–21 s)							
Low	.020	.015	7	.004	8.796*	.012	.423
High	.053	.025	7				
Saccades to targets (1–5 s)							
Low	.448	.150	7	.002	.071	.795	.006
High	.471	.175	7				
Saccades to targets (6–16 s)							
Low	.387	.126	7	.064	3.634	.081	.232
High	.522	.139	7				
Saccades to targets (17–21 s)							
Low	.284	.118	7	.088	6.155*	.029	.339
High	.442	.120	7				

* $p < .05$.

Regarding the relationship between eye movements and insight problem solving, we found that when the participants responded correctly, they took less time to respond and produced more fixations and saccades to all objects compared to when they responded incorrectly. Moreover, participants produced more fixations and saccades and longer gaze duration directed toward the targets. These significant effects of eye movements during insight tasks again confirm the close relationship between eye movements and attention (Cowen et al., 2002; Krauzlis, 2005) and lend support to the eye-mind assumption (Just & Carpenter, 1984), which suggests that the eye remains fixated on a piece of visual information as long as that piece of visual information is being processed. In addition, our significant results support the findings that saccades reflect attentional shifts during insight tasks (Hafed & Clark, 2002) and that attention and mental operations are interactive (Grant & Spivey, 2003). Interestingly, we also found that, compared to participants with lower insight problem solving abilities, participants with greater insight problem solving abilities did not show different eye movement patterns in terms of response times, fixations, saccades, and gaze durations towards either the targets or all of the objects. Based on our integration of these results with the representational change theory of insight (Knoblich et al., 2001), the different eye movement patterns that we observed during insight responses, and the effects of WM capacity on insight problem solving that we observed, we suggest that although attention is essential for insight problem solving, the ability to achieve the "attention-insight" link depends on individual differences, and these differences may due to WM efficiency. Achieving a successful "attention-insight" link requires the ability to effectively restructure the problem and change inappropriate initial representations, and these abilities are greatly influenced by the central executive function in WM. Our conclusions here are in line with the finding that performance on the visual-array task does not reflect a multi-item storage system but instead reflects a person's ability to accurately retrieve information in the face of proactive interference (Shipstead & Engle, 2013). Moreover, our conclusions lend support to the argument that WM capacity reflects the domain-general processing abilities of the central executive WM capacity, and more generally the central executive, predicts performance in tasks involving selective attention (Burnham, Sabia, & Langan, 2014).

7.2. *The influence of WM capacity on insight problem solving*

We found that WM capacity affected eye movements during insight tasks. Specifically, we found that participants with higher WM capacities exhibited a greater number of fixations and saccades and had longer gaze duration on the targets.

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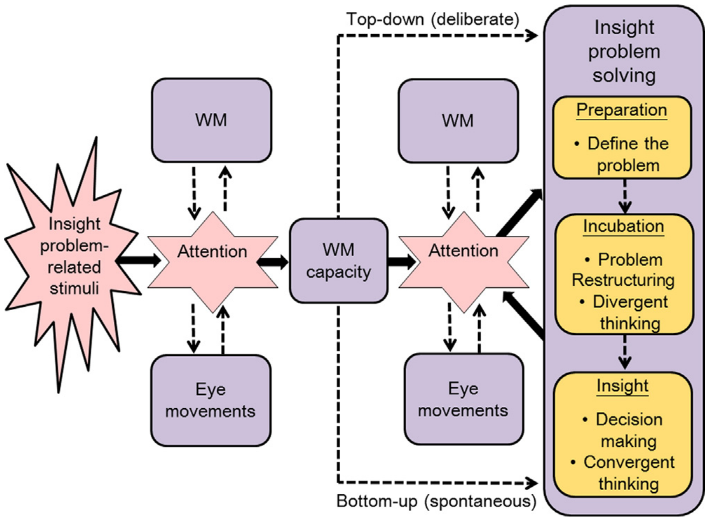

Fig. 6. The process model of the influence of WM capacity on insight problem solving.

These findings lend support to the argument that WM capacity facilitates problem solving because it helps problem solvers to control their attention, resist distraction, and narrow their search through a problem space (Wiley & Jarosz, 2012). Additional support comes from the finding that WM capacity benefits creative insight because it enables the individual to maintain attention on the task and prevents undesirable mind wandering (De Dreu et al., 2012). In addition, it has been suggested that individuals with high WM capacities are more capable of resisting sensory capture and therefore display efficient storage of information in WM (Fukuda & Vogel, 2009). The ability to prevent high cognitive load is especially important for solving the complex insight problems presented in this study.

Similarly, it has been suggested that the ability to deliberately direct attention to pertinent information is a prerequisite for creative insight (Dietrich, 2004). Creative insight can be the result of two processing modes, deliberate and spontaneous. While the deliberate node searches for insights that are initiated by circuits in the prefrontal cortex and thus tend to be structured and rational, spontaneous insights occur when the attentional system does not actively select the contents of consciousness and allows comparatively more random and unfiltered information to be represented in WM (Dietrich, 2004). In addition, findings surrounding eye movements have suggested that fixations and gaze on targets indicate focused and efficient searching (Cowen et al., 2002) and that the greatest visual abilities regarding thinking or seeing usually occur between successive saccades (Kowler, 2011). Accordingly, the significant differences in fixations, gaze durations, and saccades toward insight targets between the WM groups observed in this study suggest that participants with high WM capacities may employ attentionally top-down and deliberate search strategies that select and find solutions, whereas college students with low WM capacities may unconsciously employ bottom-up and spontaneous search strategies to select and find solutions. Accordingly, WM capacity may influence insight problem solving via attention toward solution-related information.

7.3. *The influence of WM capacity on the insight process*

To further understand how WM capacity influences insight problem solving, we compared eye movement data across three different time intervals (0–5 s, 6–16 s, and 17–21 s) based on the mean response times and eye movements patterns during each second (Fig. 5). We found that participants with better WM capacities gazed at the targets more frequently and for greater durations than participants with lower WM capacities in the 6–16 s interval. Moreover, the participants with better WM capacities displayed more frequent saccades towards targets in the 17–21 s interval. The means also revealed an interesting pattern in which both WM groups decreased the number of fixations, the gaze duration, and the number of saccades toward targets between the 6–16 s interval and the 7–21 s interval. These findings suggest that how WM capacity influences the cognitive process of insight problem solving is quite complicated and there are stages of insight problem solving. Furthermore, these results suggest that the receipt of insight is based on the information that is activated by attention and selected from WM (De Dreu et al., 2012; Wiley & Jarosz, 2012).

In addition, the cognitive process of receiving insight may include the stages of preparation, incubation, and insight (Yeh, 2004), and insight problem solving requires both convergent and divergent thinking (Abraham & Windmann, 2007; DeYoung et al., 2008). Based on our situation-based visual tasks and the literature review presented in this study, the present findings suggest that the 0–5 s interval is the stage of preparation in which the problem is defined, the 6–16 s interval is the stage of incubation in which the problem is reconstructed and divergent thinking is employed to create possible solutions based on the information retrieved from WM, and the 7–21 s interval is the stage of receiving insight in which convergent thinking is employed to make decisions. Therefore, the findings in this study are in line with the claims that WM is important for determining the inadequacy of problem formulation; while divergent thinking may be necessary to generate elements of a novel formulation, convergent thinking allows effective application of logical operators (DeYoung et al., 2008).

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Based on the experimental design and findings of this study, we conclude that when insight-problem related stimuli attract attention, eye movements and WM interact via this attention, which further influences the performance of WM capacity. Subsequently, those with better WM capacities may employ top-down search processes and deliberately direct attention to pertinent information and solve insight problem more efficiently. Conversely, those with poorer WM capacities may be less capable of actively selecting and directing pertinent information and therefore employ bottom-up search processes that take more time, as these processes are based on trial and error, and therefore lead to less efficient insight problem solving. Notably, during insight problem solving, attention, eye movements and WM processing dynamically interact (see Fig. 6).

8. Conclusions and suggestions

Recently, the study of eye movements has become increasingly popular in investigating problem-solving behavior. Eye movements provide numerous and specific clues about the underlying cognitive processes and their interactions with environmental stimuli; these clues help explain the overt behavior or performance of complex thinking. Insight problem solving that requires critical "aha" moments of insight has been the interest of researchers. Although a few studies have been conducted that investigate the relationship between WM and insight problem solving, to date, no studies have employed situation-based WM and insight tasks with multiple visual representations to examine their relationship with eye tracking techniques. Using situation-based visual tasks of WM and insight problem solving, this study first suggests that fixations, gaze durations, and saccades towards targets are eye movement parameters that are effective in increasing our understanding of the cognitive processes of WM and insight problem solving. Second, attention, eye movements, and WM capacity interactively influence insight problem solving, and the influence patterns vary with WM capacity and insight stages. Notably, an original and integrative process model of the influence of WM on insight problem solving that is based on the findings in this study was proposed. This model helps uncover the mysterious process of receiving insight, and it should provoke thoughts regarding further studies.

As a pioneering study in the field of WM during insight problem with complex visual representation and situation-based tasks, this study is more an exploratory study than a confirmatory study. Although the sample size of this study was small, the findings were significant and stimulating. Further studies may manipulate the incoming stimuli (e.g., insight problem-related vs. not insight problem-related) to investigate whether the patterns of influence or eye movements patterns would be different. Recently, the employment of functional magnetic resonance imaging (fMRI) has become more popularly in cognitive studies, and some studies have integrated fMRI and eye tracking techniques to explore complex cognitive processes. Further studies should consider integrating these two cognitive neuroscience techniques to provide a clearer picture the influences of WM on insight and insight problem solving.

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