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Metacognition predicts critical thinking ability beyond working memory: Evidence from middle school and university students

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ABSTRACT

Previous studies have shown that metacognition is closely related to critical thinking ability. However, it remains unclear whether the effect of metacognition on critical thinking ability is unique or merely due to the variance shared with working memory. The present research investigated whether metacognition predicted critical thinking ability above and beyond working memory. Measures of these variables were administrated to both university students (n = 362) and middle school students (n = 247). The SEM results showed that metacognition made unique contributions to critical thinking ability even when working memory was controlled for. Further, there was no significant difference regarding the predictions from metacognition and working memory to critical thinking ability between the university and middle school students. Our findings provide a first step toward understanding metacognition as a distinct construct from working memory in relation to critical thinking ability.

1. Introduction

Critical thinking is widely regarded as a vital skill in the 21st century and has long been of interest in educational and psychological research (Meneses, Pashchenko & Mikhailova, 2023). Critical thinking ability enables students to achieve academic success, solve real-life problems, and function effectively in the modern world (Akpur, 2020; Hwang, Hand & French, 2023; Ku et al., 2019; Vidal et al., 2023). Developing students' critical thinking ability is not only essential for their social adjustment but also enhances the overall quality of their education (Chen, Wang & Zheng, 2024; Li, Ren, Schweizer, Brinthaupt & Wang, 2021). Therefore, an increasing number of countries worldwide have placed special importance on the cultivation of critical thinking abilities at all levels of education (Alpizar, Vo, French & Hand, 2022; Fan & See, 2022; Hwang et al., 2023). A deeper understanding of the factors influencing students' critical thinking ability is undoubtedly important and can help in designing interventions to increase their capabilities. There is already theoretical and empirical research revealing a close relationship between metacognition and performance on critical thinking tests (e.g., Akcaŏglu, Mor & Külekçi, 2023; Dwyer, Hogan & Stewart, 2014; Teng & Yue, 2023). However, it remains unclear whether the contribution of metacognition to critical thinking ability is unique or merely due to the variance that is shared with working memory (Ku & Ho, 2010; Teng & Yue, 2023). Therefore, the current research aimed to examine whether metacognition predict critical thinking ability above and beyond working memory based on data from middle school and university students.

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1.1. Metacognition and critical thinking ability

1.1.1. Theoretical accounts of metacognition and critical thinking ability

Critical thinking is often described as a high-order cognitive process that focuses on an individual's ability to comprehend a problem and devise reasonable solutions for it (Dwyer et al., 2014; Ennis, 2018). One influential definition proposes that critical thinking includes several crucial cognitive skills, such as identifying assumptions, inductive reasoning, deductive reasoning, analyzing arguments, and evaluating arguments (Dwyer et al., 2014; Ennis, Millman & Tomko, 2005). Building upon this conceptual framework, standard scales such as the Test of Critical Thinking Skills for Adults (TCTS-A, Yeh, Chen, Hsieh & Yeh, 2001) and Cornell Critical Thinking Test-Level X (CCTT-X, Ennis et al., 2005) were developed to assess cognitive skills of critical thinking. Another common operationalization of critical thinking underscores the cognitive ability to evaluate arguments and evidence without influence from one's own prior beliefs and experiences (West, Toplak & Stanovich, 2008). Drawing on this operational account of critical thinking, researchers have mainly employed syllogistic reasoning paradigms with belief bias to tap into the ability to reason independently of prior beliefs involved in critical thinking (Heijltjes, van Gog, Leppink & Paas, 2014; Li et al., 2021; West et al., 2008). Despite different theoretical structures of the critical thinking ability, all conceptualizations suggest that critical thinking demands the deliberate and strategic utilization of these cognitive skills that are most effective in a given context, along with active regulation of one's own thinking processes to arrive at well-founded and justified conclusions (Dwyer et al., 2014; Ennis et al., 2005; Halpern, 2014; West et al., 2008). These conceptions imply evidently that critical thinking is a product of metacognition which provides a direction in the prediction of these two psychological constructs.

Although metacognition has been implicated in a range of important developmental outcomes, it is inconsistently defined and operationalized in the literature (Drigas, Mitsea & Skianis, 2022; Flavell, 1979; Manzar et al., 2018). Metacognition is often described as individuals' awareness and the regulation of their own cognitive or thinking processes (Flavell, 1979; Norman et al., 2019). However, differences in theoretical conceptualizations and measurement have resulted in multiple definitions of the metacognition construct. According to conceptualization developed by Flavell (1979), metacognition involves two major components: knowledge about cognition and regulation of cognition. The knowledge component encompasses the awareness and understanding of an individual's cognitive processes, including self-knowledge as a thinker, the attributes of the current task at hand, and the requisite strategies needed for achieving optimal performance (Flavell, 1979; Ku & Ho, 2010). The regulation component pertains to the practical application of strategies aimed at controlling cognitive processes, such as formulating task approaches through careful planning, monitoring comprehension and understanding during task execution, and evaluating one's progress and performance (Flavell, 1979; Ku & Ho, 2010). Another prevalent conceptualization highlights that metacognition involves two important aspects: metamemory and metaconcentration (Klusmann, Evers, Schwarzer & Heuser, 2011; Manzar et al., 2018). Metamemory refers to one's awareness and control over their memory processes (Drigas et al., 2022; Klusmann et al., 2011; Manzar et al., 2018). It encompasses knowledge about one's own memory abilities, such as knowing when and how to employ effective memory strategies, as well as awareness of memory strengths and weaknesses (Drigas et al., 2022; Klusmann et al., 2011; Manzar et al., 2018). On the other hand, metaconcentration is the capacity to monitor and regulate one's attention and concentration levels (Klusmann et al., 2011; Manzar et al., 2021). It involves awareness of attentional resources, the ability to sustain focus on a task or goal, and the skill to redirect attention when necessary. Metaconcentration also includes strategies for managing distractions and maintaining optimal levels of cognitive engagement during tasks requiring sustained attention (Klusmann et al., 2011; Manzar et al., 2021). The present study employed two measures based on the aforementioned theoretical frameworks to comprehensively assess various aspects of metacognition.

The theoretical accounts suggest that metacognition is crucial for critical thinking ability (Dwyer et al., 2014; Halpern, 2014; Ku & Ho, 2010). Metacognitive knowledge, such as understanding the factors that impact an individual's cognitive processes (person variables), comprehending how to approach and interpret various problems based on their unique characteristics (task variables), and knowing when and why to employ certain skills (strategy variables) can enhance critical thinking performance (Dwyer et al., 2014; Halpern, 2014). In addition, metacognitive regulation, such as planning, monitoring, and evaluating, also plays a pivotal role in critical thinking process. Planning activities involve determining the critical thinking procedures, selecting appropriate strategies, and allocating available resources (Ku & Ho, 2010; Schraw, 1998). Monitoring enables students to continuously be aware of task comprehension, which includes checking task information for validation, focusing attention on important ideas, and identifying information ambiguities (Dwyer et al., 2014; Halpern, 2014). Evaluating contributes to examine and correct one's critical thinking processes, such as evaluate reasoning, goals, and conclusions and make necessary revisions (Facione, 1990). In sum, theoretical accounts emphasize the importance of metacognition as an executive control system used to supervise and control the critical thinking process.

1.1.2. Empirical findings on metacognition and critical thinking ability

Previous empirical studies have shown evidence favoring an integrated critical thinking framework, positing that metacognition is closely related to critical thinking ability. For instance, Ku and Ho (2010) found that university students with a high level of critical thinking engaged in more metacognitive regulation activities, especially high-level planning and high-level evaluating strategies. Magno (2010) used structural equations modeling to determine the effect of metacognition on critical thinking ability as latent variables and found that metacognition significantly predicted college students' critical thinking ability. Sun, Xie and Lavonen (2022) collected data from junior high school students and reported that metacognition was significantly correlated with performance on critical thinking task ($r = .547$). A recent study based on university students by Akcaöglu et al. (2023) revealed that metacognition awareness made a significant contribution to critical thinking ability. In addition, Teng and Yue (2023) conducted a study in the English as a foreign language context and showed that metacognitive writing strategies (metacognitive knowledge and metacognitive regulation) significantly predicted university students' critical thinking ability measured by Watson-Glaser Critical Thinking Appraisal. This collection of results provides sufficient evidence that there is a close link between metacognition and critical thinking ability. However, existing research predominantly focuses on university students, and there is a need for further investigation into the effect of metacognition on critical thinking during other important stages of cognitive development, such as adolescence. Moreover, the studies mentioned above have not taken into account other control variables such as working memory while examining the relationship between metacognition and critical thinking ability.

1.2. Working memory as a confounding variable

Working memory must be considered when estimating metacognition's ability to predict critical thinking as its overlap of executive processes with metacognition (Conte, Fairfield, Padulo & Pelegrina, 2023; Cowan, 2017; Dwyer et al., 2014). Working memory refers to the cognitive system responsible for temporarily holding and manipulating information required for complex cognitive tasks (Baddeley, 2021). Both theoretical accounts and empirical evidence suggest a substantial relationship between working memory and critical thinking ability. For example, the integrated critical thinking framework suggests that critically thinking about information relies on processing that simultaneously actively keeps goal- or task-related representations in mind (Dwyer et al., 2014). Applying critical thinking to problem solving is also directly affected by a person's ability to engage in a controlled, planful search of memory and effortful retrieval of additional goal- or task-related information as needed (Dwyer et al., 2014). Some studies have directly investigated the relationship between working memory and critical thinking ability. Noone, Bunting and Hogan (2016) found that working memory measured by tone monitoring and letter-memory tasks predicted university students' critical thinking ability, including argument analysis, verbal reasoning, and hypothesis testing skills. Evidence from cognitive training has shown that adolescents' deductive reasoning improved significantly after four weeks of working memory training (Ariës, Ghysels, Groot & Maassen Van Den Brink, 2016). Additionally, research has shown that working memory significantly contributes to adults' one subskill of critical thinking, i.e., to override the belief bias when completing syllogistic reasoning tasks (e.g., Ding et al., 2020; Schubert, Ferreira, Mata & Riemenschneider, 2021).

Moreover, working memory could be significantly associated with metacognition. As depicted in the working memory model proposed by Baddeley and Hitch (1974), there is a domain general "central executive" responsible for the coordination of multiple tasks. In Cowan's embedded-processes model (Cowan, 1999), working memory is defined as all processes necessary for the temporary storage of information, including both passive storage and active processing (e.g., central executive and focus of attention). These theoretical models of working memory highlight that the central executive directs cognitive efforts toward relevant stimuli and concurrently processes several highly integrated items (Baddeley, 2021; Cowan, 2017). Conceptually, there is a notable overlap between the central executive of working memory and the core elements of metacognition (Baddeley, 2021; Norman et al., 2019). The central executive of working memory is responsible for regulating the flow of information within the system, prioritizing tasks, and suppressing irrelevant information (Cowan, 2017). Similarly, metacognition involves a process of cognitive regulation, where individuals actively monitor and adjust their cognitive strategies to optimize performance (Ku & Ho, 2010). When engaging in a critical thinking task, the central executive of working memory is actively engaged in managing the information required for the task (Li et al., 2021). At the same time, metacognition also enables the individual to reflect on the effectiveness of their cognitive strategies and adjusts them accordingly (Dwyer et al., 2014). Therefore, we speculate that there might be a significant overlap between the roles of working memory and metacognition in critical thinking. It is imperative to control for the influence of working memory when examining the effect of metacognition on critical thinking. Empirical work suggests that metacognition and working memory represent distinct, but related constructs, and individual differences in working memory are partly accounted for by variations in metacognition (Bertrand, Moulin & Souchay, 2017; Conte et al., 2023; Sahar, Sidi & Makovski, 2020). Since the metacognitive monitoring or regulation is one of the key processes implicated in completing working memory tasks (Conte et al., 2023), it is assumed that metacognition is related to working memory which should be taken into consideration in examining the role of metacognition in critical thinking ability. However, little previous work has directly examined the unique contribution of metacognition to critical thinking ability when considering the role of working memory.

1.3. Unaddressed questions

In spite of the research described earlier, it remains to be seen whether metacognition is able to predict critical thinking ability over and above working memory. Theoretical accounts postulate that metacognition and working memory operate as two separate psychological constructs, individually imparting their unique influence on the process of critical thinking (Dwyer et al., 2014; Halpern, 2014). Nonetheless, given that working memory serves as one of the most powerful predictors of critical thinking (Ariës et al., 2016; Ding et al., 2020; Dwyer et al., 2014; Noone et al., 2016; Schubert et al., 2021) and working memory is also related to metacognition (Baddeley, 2021; Bertrand et al., 2017; Conte et al., 2023; Norman et al., 2019; Sahar et al., 2020), there might be an overlap between the contribution of metacognition and working memory to critical thinking. However, prior empirical research has solely examined the effect of either metacognition or working memory on critical thinking ability, without simultaneously investigating how these two psychological factors interact to contribute to critical thinking (e.g., Akcaŏglu et al., 2023; Ariës et al., 2016; Noone et al., 2016; Schubert et al., 2021; Sun et al., 2022; Teng & Yue, 2023). Apparently, there is a gap between theoretical assumptions and empirical research regarding the unique role of metacognition in critical thinking when taking consideration of the working memory. Investigating this issue can provide support for theoretical hypotheses, further elucidating the specific roles of metacognition and working memory in critical thinking ability. Additionally, it can provide some insights into designing more effective strategies for fostering critical thinking, i.e., better metacognition or working memory training for students to enhance their critical thinking ability.

Another unaddressed question concerns whether the relationships between metacognition, working memory, and critical thinking ability vary across developmental stages. According to Piaget's theory, adolescence is a period of marked change in an individual's cognitive or thinking development (Piaget, 1952). Adolescents' thoughts start taking more of an abstract form and egocentric thoughts decrease which allows them to solve problems through abstract concepts and utilize high order cognitive skills (Barrouillet et al., 2015). Indeed, empirical research suggests cognitive abilities such as metacognition, working memory, and critical thinking exhibit a prominent ascending trend during adolescence (Ahmed, Ellis, Ward & Davis-Kean, 2022; Alpizar et al., 2022; dos Santos Kawata et al., 2021; Lin & Shih, 2022). The neural research also shows that the prefrontal cortex matures rapidly during adolescence and early adulthood and these brain changes generate cognitive growth (Schalbetter et al., 2022). The prefrontal cortex is responsible for cognitive functions such as metacognition, working memory, and critical thinking (Friedman & Robbins, 2022; Li et al., 2021; Vaccaro & Fleming, 2018). In addition, brain structures continue to become more specialized, with a separation of functional neural modules over the course of adolescence and early adulthood, supporting the specialization and separation of cognitive functions (Baum et al., 2020; Fair et al., 2007). These results imply that relationships among metacognition, working memory, and critical thinking might undergo changes during adolescence and early adulthood due to the development of brain functions and cognitive abilities. However, very few studies have investigated the contributions of metacognition and working memory to critical thinking ability from a developmental perspective. It remains unclear whether the relations among metacognition, working memory and critical thinking ability are different between young adults and adolescents.

1.4. *The present study*

The first aim of the current study is to provide an answer to the question whether metacognition uniquely predict critical thinking ability when working memory is statistically controlled. The second aim is to investigate whether there are differences in the relationships among metacognition, working memory, and critical thinking ability between young adults and adolescents. To achieve the above aims, we collected data on metacognition, working memory, and critical thinking ability from samples of middle school and university students. In order to capture the multifaceted nature of variables, reduce task-specific biases, and enhance the reliability of results, we employed two measures to tap into metacognition, working memory, and critical thinking ability, respectively. Participants' metacognition and critical thinking ability were assessed by standard tests. Working memory was assessed by visual-spatial updating task and running memory task, both of which are derived from established paradigms of working memory.

2. Method

2.1. *Participants*

Participants were 247 middle school students aged between 10 and 15 years old (M = 13.62, SD= 1.06, 94 males), and 362 university students aged between 16 and 23 years old (M = 19.07, SD= 1.11, 165 males). The samples were from two secondary schools and two universities in a central province in China. The distribution of subjectively reported family economic level for secondary school students (1= "very poor" to 5= "very rich") was as follows: 3.6 % rich, 6.9 % rich, 71.3 % middle income, 10.9 % relatively poverty, and 7.3 % very poor. Regarding with family economic level of university students, 4.1 % of participants self-appraisal their family economic level was very rich; 9.9 % of participants' family economic level was rich; 66.2 % thought their family economic level was medium; 13.5 % of participants' family economic level was relatively poverty; 6.3 % of participants' family economic level was very poor. Participants or their parents have given written informed consent before participating in the study. The Institutional Review Board of the corresponding author's university approved this research.

2.2. *Measures*

2.2.1. *Measures of metacognition*

The Metacognitive Awareness Inventory (MAI) was used to assess students' metacognition (Schraw & Dennison, 1994). The Chinese version of this scale has demonstrated acceptable reliability and validity (Xie, 2021). The scale contains 52 items (e.g., "I consciously focus my attention on important information."). Participants rated each item on a five-point Likert scale (1= strongly disagree; 5= strongly agree). The test assesses two metacognition dimensions: knowledge of cognition and regulation of cognition. The score for the MAI was obtained by averaging all the item responses. Higher scores indicated a higher level of metacognition. Cronbach's alpha for middle school and university students was .89 and .91, respectively.

The Brief Metacognition Scale (BMS) was also used to assess metacognition (Klusmann et al., 2011). The Chinese version of the BMS has well-documented content validity and is highly reliable (Zhang, Yu & Zhang, 2020). The BMS contains 9 items (e.g., "I am usually able to remember exactly where I read or heard a specific thing") rated on a five-point Likert scale (1= strongly disagree; 5= strongly agree). The scale assesses two metacognition dimensions: metamemory and metaconcentration. The score for the BMS was computed by averaging all the item responses. Higher scores indicated higher level of metacognition. Cronbach's alpha of this scale among middle school and university students was .86 and .89, respectively.

2.2.2. *Working memory tasks*

Visual-spatial updating task (VUT) was adopted to measure the students' working memory. This task was modified from the original visual pattern test which presents red squares filled in a 4 × 4 matrix (Della Sala, Gray, Baddeley, Allamano & Wilson, 1999). However, instead of presenting the red squares simultaneously as the original visual pattern test, the current task presented the red squares sequentially and asked participants to memorize the location of the red squares and to mark them in an empty 4 × 4 grid in the same order as they were displayed on the screen. Completing this task required participants to actively construct and update mental path configurations from the moving patterns by sequential presentation. Each red square was presented for 1000 ms. The interval between any two red squares was 500 ms. The task included 4 practice trials and 12 test trials that consisted of 4 levels of red squares sequence length (4, 5, 6, and 7). The score of VUT was the total number of red squares recalled in the correct position and correct sequence.

The modified running memory task (RMT) was also employed to assess working memory. This paradigm has been frequently used to measure updating of working memory (Miyake, Friedman, Emerson, Witzki & Howerter, 2000). Participants were presented with a series of digits, with list lengths varying between 5, 7, 9, and 11. The task required the participants to recall the last four digits presented in the list. Each digit was presented for 1000 ms. The interval between any two digits was 100 ms. The four list lengths were varied randomly across trials to ensure that participants continuously updated their working memory representations until the end of each trial. The task comprised 5 practice trials and 28 test trials (7 trials within each list length). The score of RMT was the total number of correctly recalled trials.

2.2.3. Measures of critical thinking ability

Critical thinking ability of university students was evaluated using the Test of Critical Thinking Skills for Adults (TCTS-A, Yeh et al., 2001). As reported by Yeh et al. (2001), the TCTS-A exhibits good psychometric properties with stable reliability and validity results. The test measured five kinds of critical thinking skills, including identifying assumptions, inductive reasoning, deductive reasoning, analyzing arguments, and evaluating arguments, with 30 items total, 6 items for each dimension. Each item had four options to choose from, and the final correctness was recorded. The time limit was set for 25 min. The total TCTS-A score was computed by summing the scores on each item. In the present study, the internal consistency of the total score of TCTS-A was .69 among university students.

The Chinese version of the Cornell Critical Thinking Test-Level X (CCTT-X, Ennis et al., 2005) was used to measure middle school students' critical thinking ability. This test was designed for students in grades 4–12. The CCTT-X describes a fictitious situation followed by a series of alternative inferences and conclusions from which participants must choose. It comprises 71 multiple-choice items and measures different aspects of critical thinking ability: identifying assumptions, inductive reasoning, deductive reasoning, analyzing arguments, and evaluating arguments. Each question has three response options, and only one is correct. The Chinese version of the CCTT-X has good reliability and construct validity (Bi, Dong & Han, 2019). The total CCTT-X score was computed by summing the scores on each item. Higher scores indicate a higher level of critical thinking ability. The Cronbach's alphas were .73 in the present study.

We also adopted the syllogistic reasoning problems with belief bias (SRPBB) to measure middle school and university students' critical thinking ability. This task was adapted from the belief bias questionnaire developed by Markovits and Nantel (1989). The belief bias paradigm assesses one's ability to evaluate evidence and arguments independently of prior beliefs (West et al., 2008), which is a strongly emphasized ability in the critical thinking literature. The current test included four types of reasoning problems in which the logical conclusion was in conflict with one's prior knowledge: (1) All A are B, C are A; therefore, C are B (valid conclusion, e.g., "All things that are smoked are good for health, cigarettes are smoked; cigarettes are good for health."), (2) All A are B, C are not B; therefore, C are not A (valid conclusion, e.g., "All animals love water, cats do not like water; cats are not animals."), (3) All A are B, C are B; therefore, C are A (invalid conclusion, e.g., "All flowers have petals, roses have petals; roses are flowers."), and (4) All A are B, C are not A; therefore, C are not B (invalid conclusion, e.g., "All things that have a motor need oil, bicycles do not have motors; bicycles do not need oil."). Each type of problem consisted of 5 items. In addition, 4 non-conflict items (one item for each kind of logical form) were included to avoid habitual responding. Participants determined whether the conclusion logically followed from the premises by supposing that all premises were true. The score was the number of conflict items judged correctly. In the current study, the internal consistency assessed by Cronbach's α for middle school and university students was .83 and .87, respectively.

2.3. Statistical analysis

The preliminary descriptive analyses used SPSS 26 to calculate the correlation between the main study variables. Structural equation models (SEM) examining the relationships between metacognition, working memory, and critical thinking ability using Mplus 7.0, statistically controlling for students' gender and SES. Model fit was evaluated by the ratio of chi-square to degrees of freedom ($\chi2/df$), comparative fit index (CFI), Tucker-Lewis index (TLI), root mean square error of approximation (RMSEA), and standardized root mean square residual (SRMR). The good fit indices were $\chi2/df < 5$, CFI > .95, TLI > .95, RMSEA < .06, and SRMR < .08 (West, Taylor & Wu, 2012).

3. Results

3.1. Measurement invariance testing

Measurement invariance (or equivalence) indicates that a multi-item scale has the same meaning for different groups. It is an important prerequisite for the interpretation of group differences in a scale (Martin, Benjamin, Marcel & Veronika, 2021; Putnick & Bornstein, 2016). To test for measurement invariance of two measures of metacognition (MAI and BMS) and critical thinking (SRPBB), the following procedure was applied (Vandenberg, 2002): First, a confirmatory factor analysis of the construct for two groups was fitted. This model did not have any constraints regarding the equality of item loadings and intercepts over groups (configural model). Second, constraints were sequentially added to the model, and model fit was evaluated at each step. Constraints on loadings (metric or weak invariance) and on intercepts (scalar or strong invariance) were introduced, which represent increasing levels of measurement invariance. Following Cheung and Rensvold (2002) and Chen (2007), changes (Δ) in CFI, RMSEA, and SRMR were used to assess whether there was invariance between progressively constrained models. The hypothesis of measurement invariance was rejected if ΔCFI > .01, ΔRMSEA > .015, and ΔSRMR > .015. As shown in Table 1, model comparison results suggested that MAI, BMS, and SRPBB showed strong measurement invariance across age groups.

3.2. Age differences

In order to analyze the age difference, we conducted independent samples *t*-tests to examine the difference in the scores on measures of metacognition (MAI and BMS), working memory (VUT and RMT), and critical thinking ability (SRPBB). As shown in Table 2, university students showed significantly higher scores than middle school students on MAI, BMS, VUT, RMT, and SRPBB, suggesting that university students might have higher levels of metacognition, working memory, and critical thinking ability than middle school students.

3.3. Correlation results

In order to inspect the relationships between interested variables, we conducted a correlational analysis of measured variables for middle school and university students, respectively. Table 3 presents the bivariate correlations for all variables of two age groups. The results based on data from the university students sample showed that measures of metacognition and working memory were significantly correlated with critical thinking ability. Similarly, measures of middle school students' metacognition and working memory were significantly correlated with their critical thinking ability.

3.4. SEM results

We used SEM to examine whether metacognition predicts a unique portion of critical thinking while controlling for working memory. We constructed three models (Model 1–3) based on data from university students to investigate how metacognition and working memory predict the variance of critical thinking ability. Model 1 reflects the prediction of the latent variable of metacognition to critical thinking ability. The latent variable of metacognition was comprised MAI and BMS. The latent variable of critical thinking ability was loaded by SRPBB and TCTS-A. As shown in Table 4, the standardized regression coefficient of metacognition was significant and explained approximately 13.2 % of the variance of critical thinking ability. Model 2 concerned the prediction of working memory to critical thinking ability. Working memory was a latent variable including visual-spatial updating task and running memory task. The results (see Table 4) showed that working memory explained 3.2 % of the variance of critical thinking ability. In Model 3 (see Fig. 1), both the latent variables of metacognition and working memory were included as predictors. This model showed a good model fit, χ^2/df= 1.29, CFI= .99, TLI= .98, RMSEA= .028, SRMR= .021. As expected, there were significant correlations between the latent variables of working memory and metacognition (r = .21, p < .05). More importantly, metacognition (β= .30, p < .001) was still significantly predictive of critical thinking ability when working memory (β= .17, p < .05) was controlled for, and explained significantly unique variance (11.0 %) of critical thinking ability. Based on results of three models, approximately 16.7 % (i.e., .167= (.132–.110) /.132) of the explained variance by metacognition overlapped with working memory of university students.

We also contrasted three prediction models (Model 4–6) for middle school students. As presented in Table 4, Model 4 including metacognition only indicated that the latent variable of metacognition accounted for approximately 14.6 % of the variance in critical thinking ability. Model 5, containing working memory as the only predictor, showed that the latent variable of working memory accounts for 20.3 % of the variance in critical thinking ability. In Model 6 (see Fig. 2), both metacognition and working memory was

Table 1
Model comparison to tests of measurement invariance by age groups.

	$\chi2/df$	CFI	TLI	RMSEA	SRMR	ΔCFI	ΔRMSEA	ΔSRMR
Metacognitive awareness inventory								
Configural invariance	3.89	.963	.963	.069	.024			
Metric invariance	3.56	.962	.962	.065	.026	−.001	−.004	.002
Scalar invariance	3.14	.963	.963	.059	.026	.001	−.006	.000
Brief metacognition scale								
Configural invariance	3.86	.954	.930	.069	.043			
Metric invariance	3.55	.953	.938	.065	.046	−.001	−.004	.003
Scalar invariance	3.24	.952	.946	.061	.046	−.001	−.004	.000
SRPBB								
Configural invariance	2.62	.988	.975	.052	.040			
Metric invariance	2.73	.982	.982	.053	.055	−.006	.001	.015
Scalar invariance	2.81	.974	.974	.055	.055	−.008	.002	.000

Note. SRPBB, Syllogistic reasoning problems with belief bias.

Table 2
Descriptive statistics of metacognition, working memory, and critical thinking ability.

	University students $n = 362$	Middle school students $n = 247$	*t*	*Cohen's d*
Metacognition				
Metacognitive awareness inventory	3.86 ± .49	3.43 ± .46	10.73***	.87
Brief metacognition scale	3.32 ± .58	2.91 ± .33	10.99***	.89
Working memory				
Visual-spatial updating task	39.80 ± 10.51	35.66 ± 9.09	5.18***	.42
Running memory task	18.88 ± 4.65	17.98 ± 4.31	2.47*	.20
Crtitical thinking ability				
SRPBB	13.27 ± 4.05	11.86 ± 2.43	5.32***	.44
TCTS-A	18.02 ± 5.76	–	–	–
CCTT-X	–	30.13 ± 4.28	–	–

Note. SRPBB, Syllogistic reasoning problems with belief bias; TCTS-A, Test of Critical Thinking Skills for Adults; CCTT-X, Cornell Critical Thinking Test-Level X.
*** $p < .001$.

Table 3
Correlation coefficients between metacognition, working memory, and critical thinking ability.

	1	2	3	4	5	6	7
University students							
1. Gender	—						
2. SES	.01	—					
Metacognition							
3. Metacognitive awareness inventory	.07	.13*	—				
4. Brief metacognition scale	.01	.07	.46***	—			
Working memory							
5. Visual-spatial updating task	−.03	.06	.08	.13*	—		
6. Running memory task	.15**	.02	.05	.15**	.60***	—	
Crtitical thinking ability							
7. SRPBB	.04	.01	.18**	.25**	.16**	.18***	—
8. TCTS-A	−.04	.06	.17**	.14**	.12*	.15**	.38***
Middle school students							
1. Gender	—						
2. SES	−.03	—					
Metacognition							
3. Metacognitive awareness inventory	−.07	.09	—				
4. Brief metacognition scale	−.12	.11	.58***	—			
Working memory							
5. Visual-spatial updating task	.06	−.09	.11	.05	—		
6. Running memory task	.03	−.09	.19**	.16*	.37***	—	
Crtitical thinking ability							
7. SRPBB	.09	−.07	.16*	.15*	.19**	.24***	—
8. CCTT-X	−.01	.07	.19**	.21**	.14*	.20***	.36***

Note. SRPBB, Syllogistic reasoning problems with belief bias; TCTS-A, Test of Critical Thinking Skills for Adults; CCTT-X, Cornell Critical Thinking Test-Level X.
*$p<.05$, **$p<.01$, ***$p<.001$.

Table4
R^2 values for regression analyses predicting critcal tinking ability for various predictor variables.

	University students			Middle school students		
	Model 1 β	Model 2 β	Model 3 β	Model 4 β	Model 5 β	Model 6 β
Predictor variables						
Metacognition	.36***		.30***	.38**		.29**
Working memory		.18**	.17*		.45***	.35**
R^2	.132	.032	.142	.146	.203	.262
ΔR^2			.110			.059

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

added to the prediction model. This model also displayed a good degree of fit, χ^2/df= 1.16, CFI= .99, TLI= .98, RMSEA= .025, SRMR= .029. Metacognition was significantly correlated with working memory ($r = .26$, $p < .01$). According to the standardized regression weights, the latent variable of metacognition (β= .29, $p < .01$) contributed significantly to critical thinking ability even when

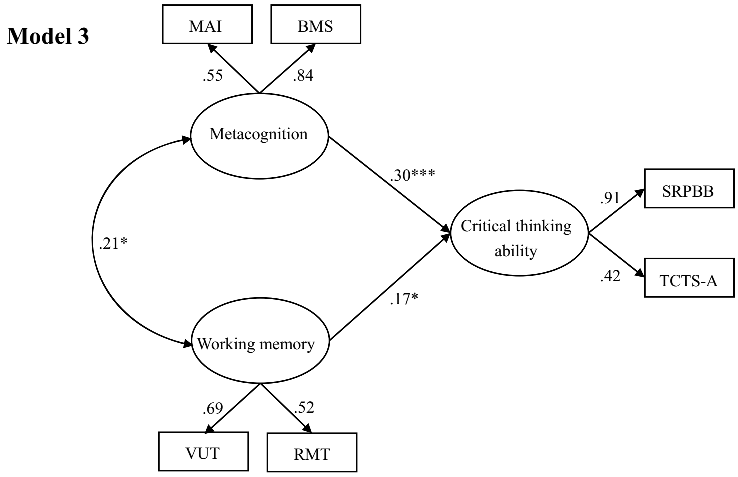

Fig. 1. Illustration of the prediction model for university students including metacognition and working memory as predictor variables and critical thinking ability as predicted variable. *Note.* MAI, Metacognitive Awareness Inventory; BMS, Brief Metacognition Scale; VUT, Visual-spatial updating task; RMT, Running memory task; SRPBB, Syllogistic reasoning problems with belief bias; TCTS-A, Test of Critical Thinking Skills for Adults. **p* < .05, ***p* < .01, ****p* < .001.

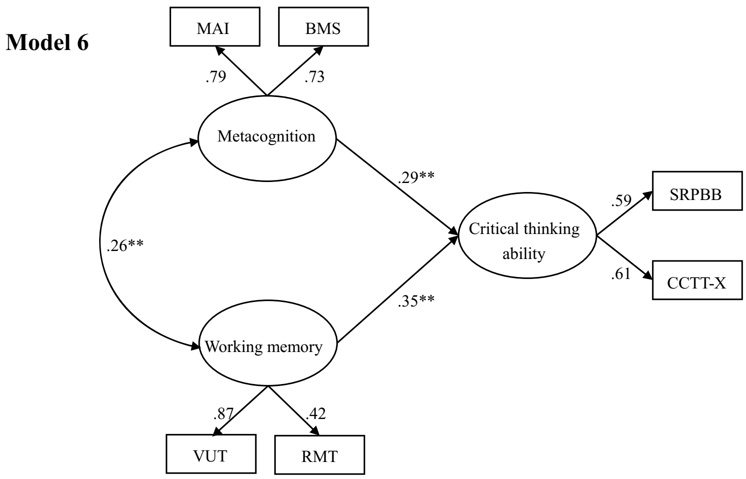

Fig. 2. Illustration of the prediction model for middle school students including metacognition and working memory as predictor variables and critical thinking ability as predicted variable. *Note.* MAI, Metacognitive Awareness Inventory; BMS, Brief Metacognition Scale; VUT, Visual-spatial updating task; RMT, Running memory task; SRPBB, Syllogistic reasoning problems with belief bias; CCTT-X, Cornell Critical Thinking Test-Level X. ***p* < .01.

controlling for working memory (β= .35, p < .01). Moreover, metacognition predicted unique portions (5.9 %) of critical thinking ability in addition to working memory. A further computation showed that 59.5 % (i.e. .595= (.146–.059) /.146) of the explained variance by metacognition overlapped with working memory.

Next we examined whether the magnitudes of the prediction from metacognition and working memory to critical thinking ability were different between university and middle school students samples. Wald tests were conducted to determine if the standardized regression coefficients of metacognition and working memory changed during development. First, the path between metacognition variable and critical thinking ability was constrained to be equal for university and middle school students. The results indicated that there was no group difference in the prediction of metacognition on critical thinking ability, $\Delta\chi^2 = 1.41$, $\Delta df = 1$, p= .235. Second, the prediction from working memory to critical thinking ability constrained to be equal across two age groups. The results showed that paths were invariant across age groups, $\Delta\chi^2 = .01$, $\Delta df = 1$, p= .974.

4. Discussion

The present research investigated the prediction of metacognition on critical thinking ability by controlling for working memory. We were particularly interested in exploring whether metacognition predicted critical thinking ability over and above working memory and whether such relationship is sensitive to age-related changes. Data on self-reported metacognition, working memory, and critical thinking ability were collected from both middle school and university students. T-test results revealed that, compared to middle school students, university students had higher levels of metacognition, working memory and critical thinking ability. SEMs that linked metacognition and working memory to critical thinking ability showed that metacognition made a unique contribution to critical thinking ability even when controlling for working memory. Further analysis indicated that there was no significant difference regarding the predictions from metacognition and working memory to critical thinking ability between the university and middle school samples. In addition, we showed tentative evidence that metacognition and working memory may become gradually distinct as age increases regarding their relations to critical thinking ability. In the following we begin with discussing the contribution of metacognition to critical thinking ability before moving on to compare the similarity and difference of the results between the age groups. We then discuss the research and practical implications of the findings, as well as limitations of the research.

4.1. The contribution of metacognition to critical thinking ability

This study took as a starting point the question whether metacognition contributes to the prediction of critical thinking ability independent of working memory. To our knowledge, little empirical work has directly examined the unique contribution of metacognition when considering other well-established correlates of critical thinking performance such as working memory. Our findings filled this gap by showing metacognition predicted significantly critical thinking ability after controlling for working memory. Such findings extended existing literature by providing direct evidence supporting the unique role of metacognition in critical thinking ability. The revelation of importance of metacognition for solving problems of critical thinking tests is consistent with theories proposing that metacognition is required to activate and regulate the cognitive process and resources to ensure good critical thinking performance (Dwyer et al., 2014; Halpern, 2014). It is also in line with empirical evidence that individual differences in metacognition are related to critical thinking ability (Akcaŏglu et al., 2023; Ku & Ho, 2010; Magno, 2010; Samsudin & Hardini, 2019; Sun et al., 2022; Teng & Yue, 2023). According to Halpern (2014), during the critical thinking process, students monitor their thoughts and evaluate whether they have reached their goals, the efforts they put into during the process, how they use time and the effectiveness of their decisions. Individuals who are more efficient in regulating and evaluating their own thought processes are more likely to outperform individuals who are less efficient when applying critical thinking skills to solve problems.

Besides the unique prediction of metacognition on critical thinking ability, we also found that metacognition overlapped with working memory in predicting critical thinking ability. Our results did reveal that metacognition shared around 16.7 % of the explained variance in critical thinking ability with working memory among university students and shared around 59.5 % among middle school students. Such an overlap is also suggested by theoretical models related to metacognition and working memory which integrate cognitive control process as the backbone of both metacognition and working memory (Baddeley, 2021; Flavell, 1979). This finding echoes the research suggesting that metacognition is associated with the performance on working memory task (Bertrand et al., 2017; Conte et al., 2023; Sahar et al., 2020). The present study constituted the first step towards revealing that how metacognition and working memory simultaneously contribute to critical thinking ability. Our finding extended the previous research by suggesting that there is indeed overlap in the roles of metacognition and working memory on critical thinking. Given this, further development of critical thinking theories is suggested to provide a clearer elucidation of how these two psychological constructs independently and collectively influence the process of critical thinking.

4.2. Similarity and difference between findings from two age groups

In this study we included a middle school adolescents sample in addition to the university young adults sample in order to examine whether the prediction of metacognition and working memory on critical thinking ability is stable or sensitive to age-related changes. Such a developmental perspective is especially informative for generalizing the findings to large groups of students. Our results showed that there were significant differences between the middle school students and university students in scores of metacognition measures, working memory tasks, and syllogistic reasoning problems. Previous studies have demonstrated that the developmental level of metacognition, working memory, and critical thinking skills tends to be higher in young adults compared to young adolescents (dos Santos Kawata et al., 2021; Linares, Bajo & Pelegrina, 2016; Markovits, de Chantal, Brisson & Gagnon-St-Pierre, 2019; Spronk & Jonkman, 2012; Weil et al., 2013), suggesting adolescents' cognitive capability continues to mature through adolescence and into adulthood. This might be because adolescence is a key period for frontal cortex maturation necessary for the development of cognitive ability (Thillay et al., 2015). During adolescence, increases in white matter volume and decreases in gray matter volume in the frontal cortex accompany aging (Dumontheil, 2014), ultimately impacting their cognitive capacity for abstraction and self-control.

We found in both age groups that metacognition predicted critical thinking ability beyond the working memory. Importantly, further analyses showed that there was no significance of the difference regarding the predictions from metacognition and working memory to critical thinking ability between the university and middle school students. These results might suggest the existence of simultaneously developing process of metacognition, working memory, and critical thinking ability and adolescents' metacognition and working memory is sufficiently developed to influence critical thinking ability (Ellerton, 2020; Toplak, West & Stanovich, 2014; Weil et al., 2013). In contrast to the similarity of the prediction power from metacognition to critical thinking across university and middle school students, we found that metacognition overlapped more with working memory in predicting critical thinking ability in the younger sample (59.5 %) than in the adults' sample (16.7 %). This provides some tentative evidence that metacognition and working memory may become gradually distinct with development regarding their relations to critical thinking ability. According to neural evidence (Baum et al., 2020; Fair et al., 2007), during development, brain structures become higher level of specialization or separation of functional neural modules to support cognitive functional specialization and separation. This suggests that the relation between metacognition and working memory might decrease and the separation between them might increase with development of brain structures, which may explain the finding that metacognition overlapped more with working memory in predicting critical thinking in middle school students than in university students.

4.3. Limitations and implications

Some limitations of the present study should be considered. First, employing a self-report scale as a method for assessing metacognition might not afford a comprehensive depiction of students' metacognition. The utilization of scales primarily captures participants' subjective perceptions of their own knowledge and behaviors, thus potentially limiting the scope of evaluation. Future research may combine self-report scales with other methods such as experimental techniques to assess metacognition. Second, data presented in our research are cross sectional and we cannot establish causal directions on the relationships among metacognition, working memory, and critical thinking ability. Longitudinal research is required to provide more insight into the dynamic interactions among three variables. However, though our data are correlational in nature, they provide an important step toward an increasing understanding of metacognition as a distinct construct from working memory in relation to students' critical thinking ability. Third, there are few critical thinking ability scales suitable for both Chinese adolescents and adults; therefore, we employed different tests among the two age groups to measure sub-skills of critical thinking, such as identifying assumptions, inductive reasoning, and evaluating information. Despite using another identical task, i.e., SRPBB, to measure critical thinking among both university and middle school students, these preliminary results regarding age differences in critical thinking warrant careful consideration, pending further substantiation through additional empirical evidence.

Despite these limitations, the findings of the current study have meaningful implications for research. The results of the current research contribute to relevant literature by providing further understanding of the relationship between students' metacognition and their critical thinking ability. We showed that metacognition overlapped with working memory while it also uniquely predicted the critical thinking ability. Furthermore, the trend of a decreasing overlap between metacognition and working memory with development regarding their predictions on critical thinking ability is informative for understanding the dynamic interactions between metacognition, working memory, and critical thinking. Our findings have also important practical implications for current instructional programs that aim to improve students' critical thinking ability by cultivating their metacognition. Learners need explicit instruction to foster the development of metacognitive awareness and strategies. It is incumbent upon teachers to cultivate students' abilities to reflect on, monitor, control, and evaluate their thinking process so that they may become more efficient in utilizing critical thinking to solve problems.

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CRediT authorship contribution statement

Shuangshuang Li: Conceptualization, Investigation, Methodology, Writing – original draft. **Ziyue Wang:** Investigation, Methodology, Writing – review & editing. **Jingwen Wang:** Investigation, Methodology, Writing – review & editing. **Jiahuan He:** Data curation, Formal analysis, Investigation.

Declaration of competing interest

The authors declare no conflict of interest.

Data availability

Data will be made available on request.

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