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Correlates of metacognitive control in 10-year old children and adults

Nike Tsalas[1] · **Beate Sodian**[1] · **Markus Paulus**[1]

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Abstract Metacognitive control is an important factor for successful learning and has been shown to increase across childhood and adolescence. Only few studies have attempted to investigate the cognitive processes and psychological mechanisms that subserve metacognitively-based control and the development thereof. Accordingly, the aim of the current study was to gain an insight into the cognitive and psychological correlates that relate to metacognitively-based control processes. Specifically, we were interested in two measures of metacognitive control: learners' ability to self-regulate their study time in a study time allocation paradigm, as well as the efficiency with which they allocated their study time. It was of particular interest to explore the relation between declarative metamemory and procedural metacognitive skills. In addition, we assessed learners' general cognitive and executive abilities. We tested a group of 10-year olds and a group of adults. Surprisingly, and in contrast to previous studies, the current study does not support a relation between declarative metamemory and procedural skills, or executive functions and intelligence and procedural skills. We interpret our results in line with a dual systems view of metacognitive abilities and further speculate whether procedural skills might become increasingly independent and automated with age.

Keywords Metacognitive control · Study time allocation · Efficiency · Self-regulation · Declarative metamemory

Introduction

Metacognition, defined as the knowledge about, and the monitoring and control of one's own cognitive processes (Flavell 1979), plays an important role in successful learning and for academic achievement (Wang et al. 1990). A common taxonomical distinction has been made between a declarative component and a procedural component. The declarative component

✉ Nike Tsalas
Nike.Tsalas@psy.lmu.de

[1] Ludwig-Maximilian University of Munich, Leopoldstr.13, 80802 Munich, Germany

refers to the knowledge people have about memory and memory processes. The procedural component describes the metacognitive skills that are at play during task performance (e.g., Lockl and Schneider 2003) and involves bottom-up monitoring processes, which guide subsequent top-down control (Nelson and Narens 1990). Notwithstanding the importance of metacognitive control for successful memorisation during learning, surprisingly few studies have attempted to investigate the cognitive processes and psychological mechanisms that subserve metacognitively-based control and the development thereof.

Gaining a better understanding of the factors that relate to metacognitive control processes is important and interesting for at least three major reasons. First, from a theoretical and conceptual point of view, such an understanding is a necessary step in illuminating the nature of metacognitive development. Is the ability to effectively control ones' own cognitive processes during learning a domain general achievement enabled by more general improvements in intelligence and information processing? Or is this a very specific ability that develops largely independently? Veenman and Spaans (2005) for example suggested that metacognitive skills might initially develop separately on different islands of tasks and become integrated later on. Second, might there be developmental differences in the extent to which particular factors influence metacognitive control processes at different ages? This would support developmental theories according to which the amount of cognitive resources needed by metacognitive processes change in the course of development (Bjorklund 1985; Case 1985; Demetriou 1988). Lastly, from an applied point of view, a better understanding of the factors that relate to and influence metacognitive control abilities during learning will provide valuable insights into the processes that affect learners' self-regulation. This might ultimately inform future research on ways to improve such abilities through specifically targeted interventions. Only few empirical advances have tried to answer what processes relate to metacognitive monitoring and control and these advances have yielded inconclusive results (e.g., Bryce et al. 2014; Roebers et al. 2012). Our aim was therefore to contribute to this area of research.

Relations between declarative metamemory and procedural metacognition

An integral component of metamemory is the declarative knowledge about memory processes and memory strategies (Flavell and Wellman 1975). Much of early research explored the deliberate application of explicit knowledge about memory strategies for the strategic regulation of cognitive processes during task performance (procedural skills) (e.g., Kuhn 2000; Schneider et al. 1987a, b). Such relations have been found for example between metacognitive knowledge about text and text processing, as well as relations between knowledge about memory strategies and actual memory behaviour, i.e. strategy use (for a review see Schneider and Pressley 1997). Moreover, and from a developmental perspective most interesting, such a relation was frequently obtained for older children, but not for children under the age of 7 years (Schneider and Pressley 1997).

From a theoretical point of view, it is possible, that one's knowledge base has an influence on information processing and strategy use (cf. Bjorklund 1985). Following such an account, more knowledge about memory and memory processes (declarative metamemory) might enable quicker processing, thereby leaving more mental space for strategic capacity (i.e. monitoring and control). Knowledge about strategies (e.g. associative strategies) for example, might lead to quicker overall processing of study material. In addition, one could also expect a relation between declarative knowledge about strategies and procedural skills, because more efficient procedural skills might inform about the usefulness of a strategy which in turn expands the theoretical knowledge base, i.e. declarative metamemory (e.g. Ghatala 1986; Ghatala et al. 1986).

Alternatively, one might speculate that declarative metamemory and procedural metacognitive processes employed during metacognitive control do not relate to each other and are subserved by different cognitive substrates. This would be in line with recent theoretical advances that have proposed a dual systems view of metacognitive abilities (e.g., Balcomb and Gerken 2008; Kentridge and Heywood 2000; Proust 2013; Shea et al. 2014). From this perspective, there are two kinds of processes that underpin metacognitive abilities: one kind, which is informed by deliberate, and reflective knowledge that can be verbalised (including declarative knowledge about memory), and one kind, which is more implicit and informed by the experience of one's own cognitive processes and does not rely on metarepresentational and declarative knowledge. Such a differentiation between explicit and implicit abilities is not unlikely, given that recent research on the development of social-cognitive functions for example has suggested the existence of two systems for mentalising abilities (i.e., understanding the mental states of others, e.g., Apperly and Butterfill 2009; Frith and Frith 2012), which in turn have been considered to be metacognitive abilities as well (e.g., Kuhn 2000; Schneider and Lockl 2008). If therefore dual processes exist in social cognitive mentalizing skills, which are conceptually similar to metacognitive skills, then likewise, such distinct processes might underpin different kinds of metacognitive abilities. Such an account would suggest that a distinct set of processes support deliberate and analytical metacognitive reasoning (relevant for declarative based metacognition) and procedural skills, which involve a (self-) evaluative loop that is based on experience and metacognitive cues (such as ease of processing) and does not require awareness (Kentridge and Heywood 2000; Kim et al. 2016; Paulus et al. 2014; Proust 2013).

General cognitive abilities

Executive functions

A comprehensive approach to understanding metacognitive control should take into account the role that general cognitive processes might play. As described at the beginning, one line of work that has attempted to illuminate possible cognitive mechanisms that influence procedural metacognition has focused on the way in which executive functions (EF) might relate to monitoring and control processes. Such an approach seems natural, given the theoretical framework proposed by Nelson and Narens (1990). This model presumes that monitoring affects control processes and, despite the fact that more recent notions suggest that the directionality of monitoring-control processes might also work the other way around (e.g., Koriat 2012), both considerations imply executive coordination of these processes (Shimamura 2008). Indeed, on a theoretical level, several researchers have highlighted the similarities between EF and metacognitive skills (Fernandez-Duque et al. 2000; Roebers and Feurer 2016; Shimamura 2000). Moreover, the prefrontal cortex supports both EF and metacognition (e.g. Shimamura 2000) and patients with lesions to the prefrontal areas show impairment in the performance on tasks measuring EF and metacognition (e.g., Schacter et al. 1984; Janowsky et al. 1989).

Only few developmental studies have approached the question of how EF relate to metacognitive *control*. Roebers et al. (2012) for example investigated monitoring-control processes in a longitudinal design in which children were 7.5 years old at the first and 8.5 years at the second measurement point. They found that EF (measured as a latent variable) was only related to metacognitive control but not monitoring processes. Bryce et al. (2014) on the other hand, tested 5- and 7-year old children and specifically investigated the way in which inhibitory control and working memory relate to monitoring and control. In contrast to

Roebers et al. (2012), these authors found evidence that inhibitory control was related to monitoring but not control processes, whereas working memory was related to metacognitive control. Interestingly, Bryce et al. (2014) found that EF were more strongly related to metacognitive control in 5-year olds than in 7-year olds, highlighting that there might be a developmental difference in the relative contribution of executive functions for metacognitive skills. Whereas these studies do suggest that executive processes are at play in monitoring and control, the exact nature of this relation is far from clear. The inconsistency in the findings, which might be due to the different operationalization of monitoring and control and the focus on different age groups, highlights the need for more studies.

Intelligence

Finally, further basic cognitive processes which are part of intelligence, such as working memory and processing speed for example, might affect the extent to which learners at different ages engage in metacognitive control. Indeed, from a theoretical point of view, a close link has been suggested between the ability to regulate one's own cognitive processes and intelligence (e.g., Sternberg 1985). In his triarchic theory of intelligence, Sternberg (1985) for example describes metacognitive abilities as an essential component of intelligence. Such a link between intellectual abilities and metacognitive abilities seems to be most convincingly demonstrated by research showing that gifted children possess better metacognitive skills (for a review see Alexander et al. 1995). Indeed, this is in line with theoretical notions which suggest that higher intellectual capacities involve quicker information processing, thereby leaving more cognitive capacity for strategic operations (e.g. Bjorklund 1985; Case 1985; Demetriou 1988; Schneider and Pressley 1997). From such a theoretical perspective it is therefore plausible to assume that metacognitive control skills are inherently related to general cognitive ability and that the development of monitoring-based control processes is the result of domain general cognitive development. However, it should be noted that alternative models have been proposed. These suggest either the independence of metacognitive abilities compared to intellectual abilities, or offer a mixed account in that these abilities are indeed related, but cannot be collapsed into the same construct, as it has been shown for example that metacognitive abilities contribute to performance on top of intelligence (cf. Veenman et al. 1997).

Taken together, despite increasing research interest in procedural metacognitive abilities, there is little understanding of the psychological mechanisms and the cognitive processes that relate to metacognitive control. Moreover, from a developmental point of view, understanding which factors relate to metacognitive-based control might help us recognise the factors that drive such development. Therefore, the aim of the current study was to take a comprehensive approach to these questions by including domain specific knowledge on memory, as well as executive functions and intelligence.

The current study

In the current study we chose to investigate metacognitive-based control processes in a standard study time allocation paradigm (e.g., Metcalfe and Finn 2013; Souchay and Isingrini 2004) using picture pairs as learning material. This is a classical measure of metacognitive control, allowing us to integrate our findings into a rich body of literature (e.g., Destan et al. 2014; Dufresne and Kobasigawa 1989; Dunlosky and Hertzog 1998; Lockl and Schneider 2003; Metcalfe 2002; Metcalfe and Kornell 2003).

More specifically, we aimed to investigate two measures of metacognitive control. First: self-regulation during study time allocation, that is the extent to which participants allocate their study time in line with their monitoring judgements. Second: the efficiency with which participants allocate their study time. We included a group of 10-year olds, because studies that have looked at learners' monitoring-based control in paired-associate learning suggests that this skill is in place at 10 years of age (Waters and Schneider 2010). In addition, we included a group of adults, because even though 10-year olds might be considered to already be mature in their metacognitive control skills, recent empirical studies suggest that metacognitive skills in different domains, including learning, continue to develop across adolescence (e.g. Weil et al. 2013; Koriat et al. 2014). As such, we also tested a group of adults who are considered mature in their use of metacognitive skills.

Based on the previous literature review, we devised the following hypotheses: If explicit declarative metamemory and procedural metacognitive processes during study time allocation are indeed supported by similar processes, then we would expect a relation between these two skills. If however, procedural metacognitive skills are rather implicit and work independent of explicit knowledge, then we might not find such a relation (H1). Concerning general cognitive processes, we asked whether EF are related to metacognitive control as suggested by several authors (e.g. Fernandez-Duque et al. 2000; Roebers and Feurer 2016; Shimamura 2000). As such we would expect a relation between performance on executive function tasks and metacognitive skills. In particular, we wanted to investigate two kinds of executive functions, which might specifically relate to our two measures of metacognitive control. Metacognitive self-regulation, similar to cognitive planning, requires you to monitor and regulate your goal attainment, and therefore we hypothesised that cognitive planning would relate to metacognitive self-regulation in study time allocation (H2a). Efficient study time allocation involves the differential allocation of study time to easy and difficult learning items, but importantly, it also requires the ability to inhibit investing study time into one item (when for example no learning is taking place) and to continue investing study time into the next item (Metcalfe and Kornell 2003). Therefore, we hypothesised that inhibitory control would relate to efficiency in study time allocation (H2b). Further, in line with theoretical notions that suggest a close link between intelligence and metacognitive skills, we would expect a relation between measures of intelligence and metacognitive control (H3). Moreover, from a developmental point of view, metacognitively-based control processes might become increasingly automated with age and experience (cf. Shiffrin and Schneider 1977), and therefore with age procedural metacognitive skills should be less dependent on, or related to general intelligence and executive functions. These processes should carry more weight in accounting for control processes in children compared to adults (H4).

Method

Participants

The total sample consisted of 149 participants, 78 ten-year olds ($M_{\text{Age}} = 10.44$, $SD = 0.33$; 38 girls) and 71 adults ($M_{\text{Age}} = 28.27$, $SD = 9.35$, 47 women). Families were contacted via letter and received a travel compensation and a small gift for the child as a thank you for participating. Eighty percent of the mothers, and 78% of the fathers had completed high school. Adult participants were recruited with flyers around university and a mailing list. They either received course credit or a monetary compensation of 10 Euros. The institutional ethics committee approved the study and informed consent was obtained from adult participants or from the parent who accompanied the child to the study.

Material and procedure

Measures of metacognitive control A standard paired-associate learning task was used to measure metacognitive control (e.g., Lockl and Schneider 2003). The learning task was administered on a standard laptop and was presented using Psychopy software (Peirce 2009). In this task, 20 picture pairs of coloured line drawings depicting familiar objects (e.g. football, chair), animals (e.g. dog, cat), and fruit and vegetables (e.g. strawberry, tomato) were used as learning material. In order to ensure that there would be variance in the judgments of learning (JOL) given by participants, we were keen on including pictures pairs with varying degree of association. Therefore, for children, we included ten pairs with only weakly associated pictures and ten pairs with highly associated pictures. For adults, we piloted 20 picture pairs in order to define pictures which were considered as either easy or hard to remember in this age group. Note that different pictures pairs were used for children and adults. One could either keep all materials the same across age-groups, but given that the age-groups have different abilities, this would lead to severe methodological problems (most notably, ceiling effects in adults). The other possibility is to slightly modify tasks to be adequate for each age group, which is the approach we followed. A 5-point smiley scale served to collect JOL. A frowning smiley on the left indicated low confidence and a smiling smiley on the right end of the scale high confidence. The smileys were coded as 1–5 from left to right and could be chosen by pressing the keys 1–5 on the keyboard of the laptop. The keys were marked with stickers of 5-smileys that corresponded to the scale presented on screen. A paper protocol was used for each participant to note down their verbally given answers during the recall phase.

At the outset, participants were instructed that in this task they would have to study picture pairs so that in a final recall phase they would remember the right target picture when only presented with the left cue picture. Overall, the paired-associate learning task consisted of five phases. In a familiarisation phase, participants were presented with 40 single pictures one after the other showing two-dimensional line drawings of objects and animals. Participants were asked to name these pictures and were corrected if a wrong or no answer was given. In the second phase, 20 picture pairs were presented one after the other for a fixed duration of 1.5 s and participants were instructed to try to remember the pairs. In the third phase, only the cue pictures of the previously presented pairs were presented and participants were instructed to make a JOL indicating how sure they were that they would remember the second picture in about 10 minutes time. A smiley scale was presented on screen and participants could give their JOL. After making their JOL, participants had the opportunity to re-study the 20 picture pairs again. Participants were instructed that they could only look at the list once. They were told that they could study the picture pairs in a self-paced manner; however it was emphasised that a good performance would involve remembering as many items as possible and studying for as little time as possible.

Directly after the study phase, participants performed the symbol search task and the number symbol code task. These two tasks also served as a distractor for the learning task. In the fifth and final phase of the paired-associate task, the cues were presented on screen, on an item-by-item basis, and participants were asked to give a verbal response which target picture had previously been presented with the cue. There was no time limit for responding.

We calculated two measures of metacognitive control. Similar to other studies in the literature, for each participant we calculated a gamma correlation between JOL (1–5) and the study time allocated to each item as a measure of metacognitive self-regulation (e.g., Metcalfe and Finn 2013). Gamma correlations can take a value from −1 to +1. If participants act in a self-regulated way, we expect items judged as likely to be remembered to receive less study time and items judged not to be remembered to receive more study time, leading to a negative correlation. Put differently, self-regulated behaviour would be indicated by a negative correlation. The second measure of metacognitive control was the efficiency with which learners studied the learning material (e.g. Ackerman and Goldsmith 2011; Metcalfe and Kornell 2003). To this end we divided the proportion of correctly remembered items from the recall test by the mean time (seconds) invested into learning overall.

Intelligence In order to assess children's and adults' basic cognitive abilities we administered the following subscales from the Wechsler Intelligence Scale for Children (WISC-IV, German adaptation, Petermann and Petermann 2007) and the Wechsler Adult Intelligence Scale (WAIS_III, German adaptation, von Aster et al. 2006) respectively. These tests are well established and widely accepted in the field and enabled us to directly compare IQ performances of children and adults. Moreover, these tests allowed us to differentiate between more verbal based intelligence (verbal IQ) and non-verbal intelligence (performance IQ). As an estimation of participants' verbal IQ we administered the vocabulary subscale and the digit-span and letter number task. Moreover, as an estimation of participants' performance IQ, we administered the matrix reasoning task and the digit-symbol coding task, as well as the symbol search task. For all subscales the test and scoring procedures closely followed the procedures described in the manual of the respective tests and were translated into age corrected points. Because we were interested in participants' skills relative to each other and not their normative IQ, we used the standard scores for the statistical analysis.

Executive functions

Inhibition. As a measure of inhibition, the well-established paper based German version of the Stroop task was used (Bäumler 1985). As a dependent measure we calculated the difference in time taken to read the colour-words (interference condition) and the time taken to read the words.

Planning. We used the German adaptation of the Tower of London task (ToL, German adaptation, Tucha and Lange 2004). This task consists of a wooden model with three balls of different colours, which can be placed on three rods of different heights. In a specified amount of moves participants have to arrange the three balls according to a visually presented configuration from an initial state into a goal state. A trial was coded as successfully solved if it was solved on the first try with the minimum amount of moves. The dependent variable consisted of the total amount of problems solved by each participant.

Declarative metamemory We administered the Würzburger test-battery (Schlagmüller et al. 2001) to assess declarative metamemory. This test battery consists of three different subscales assessing general declarative metamemory, knowledge of text-related metamemory and, importantly, knowledge about mnemonic strategies (such as semantic categorisation and clustering) which are likely to be relevant for the successful memorisation of paired associates. This questionnaire has been validated as a reliable instrument to measure declarative metamemory in school children and can be economically administered (Schlagmüller et al. 2001). In the three subscales there were two types of questions, each with three answer possibilities. In one type of question the best answer had to be selected. In the second type of question, participants were asked to give a grade from 1 to 5 to each answer option, 1 indicating a good option and 5 a bad one. We closely followed the coding procedure suggested by Schlagmüller et al. (2001). Schlagmüller et al. (2001) indicated a test-reliability of Cronbach's $\alpha = .77$. In the current sample, Cronbach's alpha for 10 year olds was $\alpha = .69$ and for adults $\alpha = .67$.

Both, 10-year olds and adults were tested individually in a room on university premises. During the testing of children, one of the parents was present in the room, but did not interact with the child during the session. The procedure for 10-year olds and adults was the same. Note that for the children, the experimenter read out loud all questionnaires to ensure that children would understand the questions and clarifications were given if needed. Adults completed the questionnaires themselves but could ask clarification questions if needed. At the beginning of the testing session for children and after signing informed consent, parents filled out a demographic questionnaire. The testing session for 10-year olds and adults took about 1½ h. Small breaks between tasks could be taken if needed. The testing session started with the paired-associate learning task. The remaining tests were administered in the following sequence: Questionnaire on general declarative metamemory, matrix reasoning, questionnaire on knowledge of semantic clustering strategies, vocabulary task, digit-span (forward- and backward), number letter task, Stroop task, questionnaire on knowledge of text related metamemory, Tower of London.

Participants additionally filled out two questionnaires, one on self-efficacy and self-regulation and children's parents filled out a questionnaire on parental style.[1]

Results

Statistical approach

For the examination of our main question of interest, i.e. the relation of metacognitive control with declarative metamemory and other predictor variables, we conducted bivariate Pearson's correlations. Further, we complemented classical null hypothesis testing with statistical inference procedures using the Bayes factor (see Wagenmakers 2007). The Bayesian statistical approach is an alternative approach to hypothesis testing which considers the probabilities of the obtained evidence of having occurred either under the alternative or the null hypothesis. An advantage of Bayesian statistical analysis compared to null hypothesis testing, which merely allows us either to accept or reject the null hypothesis, is that it allows us to interpret the data in terms of how much evidence they provide for the alternative hypothesis and the null hypothesis, respectively. A Bayes factor of 1 neither supports the alternative hypothesis nor the null hypothesis—it is *inconclusive.* If $BF_{10} > 1$, the data are more likely to have occurred under H_1 than under H_0. If $BF_{10} < 1$, the data are more likely to have occurred under H_0 than under H_1 (Jeffreys 1961). In order to make interpreting Bayes factors even more convenient, descriptive

[1] Based on recommendations provided by two reviewers and the editor we decided to focus on declarative metamemory, executive functions and intelligence and to leave these questionnaires out.

classification schemes have been proposed. Here, the following classification will be adopted (Lee and Wagenmakers 2013): anecdotal evidence ($1 < BF \leq 3$), moderate evidence ($3 < BF \leq 10$), strong evidence ($10 < BF \leq 30$), very strong evidence ($30 < BF \leq 100$), extreme evidence ($BF > 100$). For Bayesian analysis, JASP software was used using default prior scales (Jamil et al. 2015).

Descriptive results

Table 1 presents the descriptive results on the experimental tasks for children and adults.

Inferential analysis

In order to compare children's and adults' IQ scores, as well as their absolute performance on the experimental tasks, we conducted independent sample *t*-tests on the means. These *t*-tests showed that that 10-year olds and adults did not differ in terms of their performance IQ ($p = .240$) and verbal IQ ($p = .351$). There was a significant difference in the number of problems solved in the Tower of London (ToL) task, $t\ (147) = -3.16$, $p < .001$, $d = .59$. Adults solved on average more problems than children.

An independent sample *t*-test for the Stroop task showed that adults were better at inhibiting prepotent responses compared to 10-year olds, $t\ (147) = 12.58$, $p < .001$, $d = 2.06$. Adults scored significantly higher on the declarative metamemory questionnaires compared to 10-year olds, $t\ (143) = -5.43$, $p < .001$, $d = .9$. Note that we did not directly compare the performance between the metacognitive control measures and recall, because children and adults studied different learning material.

Relations between the predictor and the outcome variables

In order to investigate our main research questions, that is, the relations between measures of metacognitive control and the other variables, we first conducted bivariate Pearson's correlations between the investigated variables for both age groups. Tables 2 and 3 present Pearson's

Table 1 Valid cases, mean and standard errors on experimental tasks for children and adults

Variable	Adults			10-year olds			Potential range
	n	Mean	SE	*n*	Mean	SE	
Recall (% correct)	71	83.87	1.98	78	85.7	1.32	0–100
Metacognitive skills							
Control (Gamma)	71	−.46	.04	78	−.56	.04	(−1)–(+1)
Efficiency	71	17.07	1.46	78	31.49	1.79	0–100
Cognitive abilities							
Verbal IQ	71	34.59	.81	78	35.57	.67	3–57
Performance IQ	71	33.98	.58	78	32.99	.61	3–57
Executive functions							
Tower of London (planning)	71	11.46	.18	78	10.52	.19	0–14
Stroop (inhibition)	71	39.75	1.59	78	78.48	2.55	(−∞)–(+∞)
Declarative metamemory	69	56.06	.60	75	50.8	0.7	0–62

Scores on cognitive ability measures represent standard scores and are age corrected. A low score on the Stroop task indicates better inhibitory ability correlations as well as Bayes factors for adults and children, respectively. In view of the fact that there was a considerable variance in age for adults, we additionally correlated age with the other variables.

Adults Missing data led to pairwise deletion. Correlational analysis for adults revealed that there were significant intercorrelations between the performance on the recall task and both metacognitive control measures (metacognitive self-regulation and efficiency). Adults who showed higher metacognitive self-regulation performed better on the recall test. Moreover, those learners who recalled more items had allocated their study time in a more efficient manner. Further, there was a significant relation between metacognitive self-regulation and efficiency; adults who showed higher self-regulation were also more efficient. No significant correlations were found however between the two metacognitive control measures and performance IQ and declarative metamemory, and between performance and other predictor variables.

Children Missing data led to pairwise deletion. Correlational analysis revealed significant relations between recall performance and metacognitive control. More specifically, recall was negatively correlated with metacognitive self-regulation, indicating that those children who

Table 2 Intercorrelations between outcome and predictor variables for adults

		1.	2.	3.	4.	5.	6.	7.	8.
1. Age	Pearson's r	–							
	BF_{10}	–							
2. Verbal IQ	Pearson's r	0.17	–						
	BF_{10}	0.41	–						
3. Performance IQ	Pearson's r	0.09	0.391***	–					
	BF_{10}	0.19	38.28	–					
4. ToL (planning)	Pearson's r	−0.15	0.336**	0.00	–				
	BF_{10}	0.30	8.18	0.15	–				
5. Stroop (inhibition)	Pearson's r	0.276*	−0.243*	−0.09	−0.11	–			
	BF_{10}	2.12	1.15	0.19	0.22	–			
6. Declarative metamemory	Pearson's r	−0.11	0.276*	0.09	0.03	−0.11	–		
	BF_{10}	0.22	1.98	0.20	0.16	0.23	–		
7. Recall	Pearson's r	−0.305**	0.19	0.26*	0.20	−0.08	−0.05	–	
	BF_{10}	3.91	0.52	1.54	0.57	0.18	0.16	–	
8. Self-regulation	Pearson's r	0.01	−0.14	−0.13	−0.02	−0.03	0.11	−0.485***	–
	BF_{10}	0.15	0.30	0.25	0.15	0.15	0.23	1184.37	–
9. Efficiency	Pearson's r	−0.11	−0.09	0.16	−0.22	−0.05	−0.19	0.254*	−0.371**
	BF_{10}	0.22	0.19	0.36	0.83	0.16	0.48	1.38	21.15

The table shows Pearson's *r* and Bayes factors for intercorrelations between the variables. Significance levels were assessed by means of two-tailed tests

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

Table 3 Intercorrelations between the outcome and predictor variables for children

			1.	2.	3.	4.	5.	6.	7.
1.	Verbal IQ	Pearson's r	–						
		BF_{10}	–						
2.	Performance IQ	Pearson's r	0.348**	–					
		BF_{10}	14.88	–					
3.	ToL (planning)	Pearson's r	0.324**	0.352**	–				
		BF_{10}	8.23	18.14	–				
4.	Stroop (inhibition)	Pearson's r	0.11	−0.325**	0.10	–			
		BF_{10}	0.22	8.49	0.20	–			
5.	Declarative metamemory	Pearson's r	0.248*	0.14	0.305**	−0.08	–		
		BF_{10}	1.37	0.29	4.88	0.18	–		
6.	Recall	Pearson's r	0.01	0.06	0.01	0.11	0.11	–	
		BF_{10}	0.14	0.16	0.14	0.23	0.22	–	
7.	Self-regulation	Pearson's r	−0.06	−0.17	−0.16	−0.06	−0.21	−0.395***	–
		BF_{10}	0.16	0.43	0.38	0.16	0.73	74.81	–
8.	Efficiency	Pearson's r	−0.11	−0.17	−0.14	0.22	−0.02	0.371***	−0.06
		BF_{10}	0.23	0.40	0.28	0.87	0.15	34.17	0.16

Pearson's r and Bayes factor for intercorrelations between the variables. Significance levels were assessed by means of two-tailed tests

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

acted in a more self-regulated manner had a higher proportion of recall. Moreover, recall was positively correlated with efficiency, indicating that those children who were more efficient in their allocation of study time, remembered a higher proportion of items. The two measures of metacognitive control did not correlate for children. Similar to adults, no significant correlations were found however between the two metacognitive control measures and performance IQ and declarative metamemory, and between performance and other predictor variables.

Post hoc and exploratory analyses

Because there might be stronger relations between declarative metamemory and recall and the two measures of metacognitive control for difficult compared with easy items respectively, we conducted post hoc analyses for children and adults. That is, we conducted six further correlational analyses between declarative metamemory and recall, self-regulation and efficiency for both easy and difficult items for children and for adults. However, these analyses did not yield any significant results (all p's between .22 and .85 for children and all p's between .064 and .949 for adults).

Because we wanted to more closely investigate the idea whether a larger capacity of working memory might leave more mental space for strategic actions, we conducted further bivariate correlations for children and for adults. Specifically, we correlated digit span, as a measure of working memory, and the two measures of metacognitive control. For adults, this yielded a significant negative correlation between metacognitive self-regulation and digit span ($r = -.268$, $p = .024$) suggesting that adults who were more self-regulated also did better on the digit span task. There was no significant correlation between digit span and efficiency ($r = -.045$, $p = .711$). For children, there was neither a significant correlation between metacognitive self-regulation and digit span ($r = .080$, $p = .489$) nor digit span and efficiency ($r = -.131$, $p = .253$).

Discussion

Despite increasing interest in the development of the interplay between metacognitive monitoring and control processes, surprisingly little research has explored the psychological correlates of metacognitive control. Accordingly, the aim of the current study was to gain a better understanding of the factors that relate to metacognitive control processes: the extent to which learners allocate their study time in line with their metacognition (metacognitive self-regulation) and the efficiency with which they allocate their study time. We tested a group of 10-year olds and a group of adults in a standard, paired-associate paradigm in which they could allocate their study time in a self-paced manner.

Theoretically highly interesting, the results showed that there was no relation between declarative metamemory and procedural task performance for both, children and adults (H1). Moreover, there was no support for a relation between both measures of metacognitive control (metacognitive self-regulation and efficiency in study time allocation) and the other predictor variables (EF and IQ estimates) in adults and children (H2a, H2b, H3, H4). We interpret our results in line with a dual systems view of metacognitive abilities and further speculate whether procedural skills might become increasingly independent and automated with age.

This study is one of the few to have systematically investigated whether declarative metamemory relates to procedural metacognition as it has been conceptualised by Nelson and Narens (1990) in their highly influential framework. In contrast to early developmental research, which provided empirical support for a relation between knowledge about memory strategies and strategic memory behaviour (e.g., Schneider et al. 1987a, b, see also Schneider and Pressley 1997 for a review), the current study does not lend support to such a relation, neither in adults, nor in children (H1). How can we explain these contradictory findings?

Whilst we are cautious in our interpretation of these results for adults who performed very high on the declarative metamemory task possibly leaving too little variance for conducting correlations, for children we offer two explanations. On the one hand, one could argue that there was no relation between declarative metamemory and metacognitive control, because 10-year olds already have sufficient experience with such memory tasks and their use of explicit strategies during learning is rather automated. If this were the case, and in view of previous findings, one might speculate, that in younger elementary school children declarative metamemory might more readily relate to metacognitive control. For example, in order to successfully memorise picture pairs, one needs to have some sort of strategy at hand to associate these picture pairs. Because such associative strategies might still be new to younger children, and they need to more consciously apply them for memorisation, such knowledge might more readily influence their study time. In contrast, for learners who already have more proficient and automated strategies, this declarative knowledge might not influence their self-regulated study time anymore.

An alternative explanation for the current findings, which contradict earlier findings, might be due to the different methodologies employed in early studies and the current study. Indeed, the kind of memory behaviour captured in early paradigms and which *was* related to declarative metamemory, was arguably more deliberate and reflective in nature. Even though the current paradigm asked participants for explicit monitoring judgments, the interplay of monitoring and control processes during the self-paced learning phase, (a common way in which metacognitive control has been operationalized in a number of studies, e.g., Koriat et al. 2006, 2014; Metcalfe and Finn 2013) were uninterrupted, thereby allowing participants to engage in continual metacognitive processes. In other words, it is possible that these kinds of processes, which were not prompted to be subject of verbal reports or explicit reasoning, might relate to a different system of metacognitive skills than those required for the reasoning on concrete questions related to memory and the more deliberate application of a strategy. Concretely speaking, during study time allocation learners might rely less on verbal processes. Such an interpretation of the results would concede to more recent theoretical discussions on the possibility that there are different kinds of self-referential processes that inform metacognitive behaviour: processes which involve metarepresentational and deliberate reflective abilities, and processes which are part of a self-referential loop that does not give rise to awareness (e.g., Kentridge and Heywood 2000; Proust 2013).

These results would thereby support a dual systems views on cognition that have been proposed for example in social cognition and reasoning (e.g., Apperly and Butterfill 2009; Frith and Frith 2012; Wason and Evans 1975) and more recently also with respect to metacognition (Balcomb and Gerken 2008; Kentridge and Heywood 2000; Proust 2013; Shea et al. 2014). One implication would be that researchers who strive to compare findings from different tasks, should consider whether the metacognitive control processes they are examining require more deliberate and reflective reasoning, or whether they are subject to more automatic processes.

Interestingly, in the current study children's performance on the declarative metamemory questionnaire was positively correlated with their performance on the Tower of London task. That is, those children who scored higher on declarative metamemory solved more problems on the Tower of London task. The Tower of London task requires explicit planning of cognitive action and reasoning skills and thus might have tapped into similar processes that subserve metacognitive reasoning on the questions posed in the questionnaire on declarative metamemory.

Interestingly, both measures of metacognitive control significantly correlated in adults; however this was not the case for children. In other words, those adults who were more self-regulated were also more efficient in their study time allocation. Even though children studied different learning material, we speculate whether there might be a developmental progression in that learner's ability to self-regulate actually results in more efficient learning with age. More specifically, similar to a utilization deficit, even though children show competent metacognitive behaviour and might act in a self-regulated manner, there is still room for improvement when it comes to the efficiency in which this study time allocation results (here efficiency meaning the amount of material memorised per study time).

A further intriguing finding of the current study was that there was no support for a relation between executive functions and general cognitive abilities and measures of metacognitive control for adults and children. Our hypotheses that the extent to which learners engage in metacognitive self-regulation might be related to aspects of cognitive planning, and that the extent to which they efficiently allocate their study time might relate to inhibitory control were therefore not supported by the data (H2a, H2b). This is in contrast to prevalent conceptualisations, which highlight the similarity between executive functions and metacognitive skills (e.g., Fernandez-Duque et al. 2000; Roebers and Feurer 2016; Shimamura 2000). From a developmental perspective highly interesting, it is possible that this independence of skill is related to increased automaticity. Put differently, these different findings might be specifically related to developmental aspects of metacognitive monitoring and control processes and executive functions. Indeed, both, procedural metacognitive skills, as well as different facets of executive functions develop across childhood and adolescence (e.g., Anderson 2002, Krikorian et al. 1994; Lockl and Schneider 2003; Tsalas et al. 2015). Therefore, it is possible that as metacognitive skills and executive functions develop and change, so might their relation with each other (cf. Best et al. 2009). Markedly, this notion is more directly supported by findings by Bryce et al. (2014) who used the same paradigm in two different age groups and found that executive functions played a more prominent role in 5-year olds than in 7-year olds. This suggests, that more studies are needed that systematically try to capture similar monitoring and control processes and, if possible, employ similar tasks in different age groups in order to facilitate comparability.

With respect to general cognitive ability in both, adults and children, the current results support theoretical considerations that metacognitive skills and general intelligence are not integrally related (e.g., Veenman and Spaans 2005) and consist of different processes and skills (H3). Note, that we tested 10-year olds because they have been shown to engage in self-regulated learning during study time allocation, however it is possible that at this age, and under self-paced conditions, metacognitive control processes are already relatively independent, therefore not leading to significant relations with other cognitive measures. However, we cannot generalise these results to younger populations. Indeed, it is possible that a relation between general intelligence and metacognitive control is characterised by a trajectory proposed by the ceiling hypothesis (cf. Alexander et al. 1995). This hypothesis would suggest that intelligence and metacognitive abilities are more closely related early in life, but that this effect diminishes with age. Even though we cannot directly infer evidence for this hypothesis from the results of the current study, previous studies seem to support this notion. The study by Bryce et al. (2014) for example demonstrated that there was a relation between working memory and metacognitive control in younger children. It would therefore be valuable and interesting for future research to systematically explore the relation between executive functions and intelligence with metacognitive control during study time allocation across different ages from early childhood to adulthood. Interestingly, in our post-hoc correlational analysis between digit span and the two measures of cognitive control, for adults, there was a significant correlation between digit span and metacognitive self-regulation. Empirically, this finding concurs with the findings by Bryce et al. (2014) who found that working memory related to metacognitive control. Moreover, from a theoretical point of view, this finding is in line with the view that a larger working memory capacity leaves more mental space for strategic actions (Bjorklund 1985; Case 1985; Demetriou 1988; Schneider and Pressley 1997).

Some limitations of the current study need to be addressed. First, in order to avoid ceiling effects in adults and floor effects in children, we slightly modified the learning material used for the study time allocation task for these two age groups. This modification meant that children and adults studied different types of picture pairs. This enabled us to have sufficient variability in their performances, allowing us to conduct correlational analyses. Yet, it does not allow us to make a direct comparison between metacognitive performances. Such a direct comparison would lead to a better understanding of the relative contribution of the different variables to metacognitive control and should be considered in future research. Second, in the current study we measured metacognitive strategic behaviour through metacognitive self-regulation and efficiency. Whereas we presume that a high performance on metacognitive self-regulation and efficiency would require somewhat good strategy use, the variables we measured captured such skills in a more latent way. For future research it would be desirable to try to capture the actual strategies that participants employ, for example through thinking aloud protocols or retrospective questioning. Third, from a developmental point of view, and considering recent research, which has shown that metacognitive skills continue to develop in adolescence (Koriat et al. 2014; Weil et al. 2013), we deemed it interesting to investigate metacognitive control in 10-year olds to see which abilities might relate to these metacognitive skills. However, for future research it would be interesting to include a wider age range, most notably younger children, in order to tap into possible developmental differences between children who are less competent in their metacognitive control behaviour than the samples we tested in the current study. Finally, with respect to the measure on declarative metamemory, the test battery employed in the current study might not have been adequate in order to capture adults' declarative metacognitive knowledge. We were keen on employing an instrument to capture children's metamemory knowledge, however this instrument might have led to ceiling effects in adults, thereby leading to too little variance for conducting correlation analyses. Future research trying to tackle the relation between declarative metamemory and procedural metacognition should aim for an instrument that is more sensitive for this age group.

In sum, the major aim of the current study was to explore whether declarative metamemory and general cognitive factors relate to procedural metacognitive control processes. The current findings highlight the importance of taking into consideration the kind of task one is using to measure metacognitive control. Our findings suggest that metacognitive control employed during on-going studying might be subject to different processes than those that underpin reflective reasoning in declarative metamemory. This supports theoretical notions of a dual system view on metacognition. Previous research has provided some evidence for implicit processes and the reliance on metacognitive cues that are at play for metacognitive monitoring (e.g., Koriat and Ackerman 2010; Paulus et al. 2014). It would be interesting and theoretically valuable to combine such approaches with tasks capturing metacognitive control, in order to evaluate the hypothesis proposed in this paper, that there a different types of metacognitive control: one based on reflective and one on implicit processes.

Compliance with ethical standards

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Conflict of interest The authors declare that they have no conflict of interest.

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