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Abstract The relationship between executive functions (inhibitory control and working memory) and metacognitive skills was investigated by applying correlational and regression analyses to data collected from two groups of children. To date, research in this area has lacked a theoretical model for considering these relationships; here we propose and test such a model. Our model hypothesises that if metacognitive skills are either monitoring or control processes, depending on the direction of information flow between the meta- and object-level, then each executive function should relate to one of these processes. Further, the contribution that executive functions and metacognitive skills make to educational achievement was examined. Results indicated that executive functions were more related to metacognitive skills in 5-year-olds than in 7-year-olds, and metacognitive skills were the most important predictors of educational achievement across both age groups. These data support an interpretation that the two skills are not identical to one another, and that executive functions could be 'necessary but not sufficient' antecedents to metacognitive skills, i.e. younger children's immature executive functions may limit their metacognitive skill use.

Keywords Executive functions · Metacognitive skills · Development · Inhibitory control · Working memory · Mathematical reasoning · Word reading

Introduction

Understanding how children learn to become independent problem-solvers who can adapt their behavior flexibly in response to making an error or using an inappropriate strategy is of vital

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importance in both developmental psychology and education. These domain-general skills can affect a child's approach to all types of learning and as such could serve as the building blocks for further gains in education. There are two main bodies of psychological literature that investigate these skills, related to metacognition and executive function. These areas of research have different origins, have maintained different foci in their practical applications and have developed very different methods of assessment. However, recent research has suggested that executive functions may be antecedents to metacognitive skills (Fernandez-Duque, Baird, and Posner 2000; Garner 2009) or the related construct self-regulation (Hofmann, Schmeichel, and Baddeley 2012), although the nature of these relationships require further investigation. The present study aimed to examine the relationships among metacognitive skills and two executive functions, and how these develop, as well as how each skill contributes to educational achievement.

Metacognitive skills

Metacognition research is focused on characterizing what people know about their own cognition (often referred to as metacognitive knowledge) and how people monitor and control their cognition on-task (often referred to as metacognitive skills). There are many models of metacognitive skills (and related constructs, such as self-regulation and metacognitive awareness), each with slight theoretical variations and different terminology (Efklides 2008; Fletcher and Carruthers 2012; Pintrich 2000; Schunk 2001; Winne and Hadwin 1998; Zimmerman 2000). In this study we have adopted the Nelson and Narens (1990) model of metamemory processes. This model defines monitoring processes as those that serve to update the meta-level (one's mental representation of a cognitive task), and control processes as those that assert some action at the object-level (the level of the cognitive task).

Some research investigating metacognitive skills in young children has been limited by methodological weaknesses, such as a reliance on verbal self-report, and the use of offline measures that are collected prospectively (e.g. predictions regarding performance) or retrospectively (e.g. estimating the number of correct answers already given). While offline measures vary with respect to their remoteness from the cognitive task and the disruption they cause to it, they are usually considered less reliable than online measures (e.g. thinking aloud during task completion, Veenman, Van Hout-Wolters, and Afflerbach 2006). One online measure of metacognitive skills that can offer a more accurate representation of children's skills is observational coding of their behavior and speech during a problem-solving task (e.g. Bryce and Whitebread 2012; Perry 1998; Pino Pasternak, Whitebread, and Tolmie 2010). While most observational coding schemes only score 'positively' for evidence of successful metacognition, it is also possible to observe notable failures to use metacognitive skills. 'Distraction' is considered a failure of monitoring processes, as it manifests as a participant losing their place in the task. Failures of control processes are evidenced by a participant persisting with an incorrect response even when task rules or instructions can be recalled and are referred to as 'perseveration' (Deak and Narasimham 2003; Morton and Munakata 2002; Zelazo, Muller, Frye, and Marcovitch 2003), or goal neglect (Duncan, Emslie, Williams, Johnson, and Freer 1996). In the present study, metacognitive skills were assessed by the method reported in Bryce and Whitebread (2012) which provides data on the rate of behaviors reflecting Monitoring, Control and failures of metacognitive skills (perseveration and distraction, PD) shown during a problem-solving train-track construction task. This method of assessing metacognitive skills is developmentally sensitive within the 5–8 years age-range – both quantitative and qualitative improvements were observed in monitoring and control in the previous study (Bryce and Whitebread 2012). Additionally, school teachers provided information on the children's self-regulation through the Children's Independent Learning Development (CHILD) questionnaire (Whitebread et al. 2009, 2011).

Executive functions

Executive functioning encompasses a range of cognitive functions used to maintain and achieve a goal in problem-solving situations. For a long time executive functioning was considered to be largely composed of three separable but related component executive functions – inhibitory control,[1] working memory,[2] and task shifting (Huizinga, Dolan, and van der Molen 2006; Miyake et al. 2000). More recently, Miyake and Friedman (2012) have established that adults' performance on executive function tasks can be decomposed into a Common Executive Function ability, which is indistinguishable from inhibitory control, and two separate updating-specific and shifting-specific abilities. In contrast, the structure of component executive functions is less differentiated in children under 15 years of age – some have found evidence for a single executive function factor (Willoughby, Blair, Wirth, Greenberg, and Family Life Project Investigators 2012) while others have found evidence for a two-factor structure in which inhibitory control and shifting are combined (Lee, Bull, and Ho 2013). Regardless of the number of factors supported in these studies, they tend to be highly related in young children. Therefore, separating the component executive functions can prove to be a challenge. Further, these studies have highlighted the role of processing speed as potentially underlying the relationship among executive functions. As the present study concerned executive functions in young children, it is appropriate that two component executive functions, inhibitory control and working memory, were the foci.

In the present study, inhibitory control was assessed using an age-appropriate Stroop-like task called the animal Stroop. There is some debate regarding whether Stroop tasks really measure inhibitory control or some other skill such as resistance to interference or conflict monitoring (Blais, Robidoux, Risko, and Besner 2007; Botvinick, Cohen, and Carter 2004; Lansbergen, van Hell, and Kenemans 2007). However, it is increasingly accepted that two processes contribute to performance on Stroop tasks – interference suppression and response inhibition (Bunge, Dudukovic, Thomason, Vaidya, and Gabriela 2002; Jongen and Jonkman 2008). This animal Stroop task was used previously in an electroencephalography (EEG) study to distinguish between these two processes and examine their development (Bryce, Szucs, Soltesz, and Whitebread 2011). It was found that the early interference suppression process was mature by age 5, while the later response inhibition process was still developing after age 8. Therefore, the behavioral measures that are elicited from this task can be considered the amalgamation of both interference suppression and response inhibition processes. Verbal and visuo-spatial working memory and short-term memory were measured in the present study using the Automated Working Memory Assessment (Alloway, Gathercole, and Pickering 2007). Both working memory and short-term memory were assessed, as short-term memory only involves the maintenance of information, while working memory involves both the maintenance and manipulation of information. We investigated whether metacognitive skills were specifically related to working memory, as opposed to short-term memory which is not considered an executive function.

[1] Note, in executive functioning literature the term 'inhibition' is also used.

[2] Sometimes also referred to as 'updating'.

Educational achievement

There is evidence in the literature that both metacognitive skills and executive functions are important for academic achievement. Research into metacognitive skills developed predominantly with an educational focus and there is evidence that metacognitive skills make a contribution to educational achievement over and above the effects of intelligence (Veenman, Wilhelm, and Beishuizen 2004; Vukman and Licardo 2010); however, this may depend on the academic subject studied (van der Stel and Veenman 2010). Further, while there is some debate regarding the type of intervention that has the greatest and longest lasting impact (e.g. de Jager, Jansen, and Reezigt 2005; Kistner et al. 2010), there is evidence that metacognitive skills can be improved by both implicit and explicit instruction (Dignath and Buettner 2008; Dignath, Buettner, and Langfeldt 2008).

Increasingly, executive functions are also being investigated in an educational context (Blair and Razza 2007; Meltzer 2007). It has been found that high scores on complex executive function tasks, which are dependent on more than one executive function, are related to educational achievement in young children (Best, Miller, and Naglieri 2011), as are high aggregate scores from simple executive function tasks (Neuenschwander, Cimeli, Rothlisberger, and Roebers 2013). Further, training in executive functions seems to result in greater improvements on other executive function and academic tasks in young children, than an early literacy intervention (Diamond, Barnett, Thomas, and Munro 2007).

As yet the mechanisms of any contribution of metacognitive skills or executive functions to education are not well understood. Indeed, in order to consider the relative contributions that metacognitive skills and executive functions make to successful early learning, measures of these skills must be collected within one study. Therefore, in the present study we also collected a measure of educational achievement from the children (two scales from the WIAT II UK).

How are metacognitive skills and executive functions related?

Previous attempts to investigate how executive functions relate to metacognitive skills, reviewed here, have tended to focus on either monitoring or control processes. Most studies that have examined monitoring processes have used paired-associate memory tasks. Three such studies (Bekci and Karakas 2006; Perrotin, Belleville, and Isingrini 2007; Perrotin, Tournelle, and Isingrini 2008) found evidence for a relationship between monitoring and executive functions in cognitively typical adults. The measure of monitoring used in these studies was the feeling of knowing, which requires participants to estimate the probability that they will later recall a previously learned item (Souchay, Isingrini, and Espagnet 2000). However, the precise nature of this relationship remains unclear because complex executive function tasks were used. Further, these results may not be generalizable to other aspects of monitoring, as other measures of monitoring (accuracy of prediction and uncertainty awareness) have shown no association with executive functions (Pennequin, Sorel, and Mainguy 2010; Rhodes and Kelley 2005). To date, there have been few attempts to investigate how executive functions relate to control processes. However, strategy use (such as the tendency to adjust study time according to task difficulty, or the use of internal memory strategies) is an indicator of control processes, and there is evidence that performance on the Wisconsin Card Sorting Task is related to strategy use (Souchay and Isingrini 2004; Taconnat et al. 2009) while verbal fluency is not.

The afore-mentioned studies have examined the relationships between metacognitive skills and executive functions in adults, and given that one hypothesis states that executive functions are precursors to metacognitive skills, it seems likely that this limits our understanding. A recent study by Roebers et al. (2012) conducted both cross-sectional and longitudinal analyses of the relationships among metacognitive monitoring, metacognitive control, executive function, self-concept and educational achievement in 7 to 8-year-olds. Because of a large sample size (n=206), they were able to conduct structural equation modelling and found, in the cross-sectional analysis of data from 8-year-olds, that (i) executive functions were only related to metacognitive control and not monitoring, (ii) metacognitive control and executive functions contributed to language abilities, and (iii) only executive functions contributed to mathematical abilities. In the longitudinal analyses they found that executive function at age 7 contributed to metacognitive control a year later. While this is an enlightening study with the advantage of a large sample size and longitudinal data on some measures, there are naturally some disadvantages to such a large sample size in terms of the measures used, as discussed by the authors themselves. First, the latent executive function variable represented the shared variance of three different executive functioning tasks, which possibly reduced the specificity of the conclusions drawn as it is not clear which exact executive function processes are reflected in the latent variable. Second, the metacognitive measures were elicited only from a spelling task, which might have limited the generalizability of the findings. Third, there were indications that the monitoring measure was not sensitive for the age-range involved, which could have concealed the true role of monitoring in relation to other constructs. Considering that adult studies (previously mentioned) did find a link between monitoring and executive functions, the nature of this relationship remains unresolved. Therefore, it seems that our current study, which has the advantages of using measures of two separate executive functions, and assessing metacognitive skills during general problem-solving (rather than one academic activity), could complement the findings of Roebers et al. (2012).

Proposed theoretical model in the present study

An additional issue in this research area is the lack of theoretical frameworks through which to view the relationships among executive functions and metacognitive skills. As such, there is no basis for making and testing predictions regarding these relationships. We propose a simple theoretical model that extends the Nelson and Narens (1990) model, already described. This model hypothesizes that if metacognitive skills are either monitoring or control processes, depending on the direction of information flow between the meta- and object-level, then each component executive function should relate to one of these processes. Hypotheses relating to how each executive function assessed in the present study could be related to each metacognitive process are outlined here.

The two processes of which inhibitory control is thought to be composed, interference suppression and response inhibition (Bunge et al. 2002; Jongen and Jonkman 2008), may relate to metacognitive skills differently (for a similar argument related to self-regulation, see Hofmann et al. 2012, Box 2). That is, the more 'passive' interference suppression process (which involves resisting interference initially) may be more related to monitoring processes, while the more 'active' response inhibition process (which involves overcoming inappropriate responses) may be more related to control processes. Interference suppression may contribute to a child's ability to engage in monitoring by preventing them from being distracted by environmental factors while they update their representations; response inhibition may allow a child to actively inhibit less advanced strategies in order to switch strategies when necessary, as noted by Kuhn (2000) and Kuhn and Pease (2010). Indeed, Miyake and Friedman (2012) refer to the Common Executive Function component having two aspects – to maintain goal-related information, and to use this information to affect processing. These two aspects are strikingly similar to the definitions of monitoring and control processes. Thus, the theoretical framework presented here would predict that inhibitory control measures would relate to both monitoring and control processes.

Working memory tasks (both verbal and visuo-spatial) require simultaneous maintenance and manipulation of information, while short-term memory tasks require only maintenance (Alloway and Archibald 2008; Baddeley and Hitch 1974). Maintenance of items in short-term memory stores is considered a mental capacity that is crucial for nearly all cognitive activities. While short-term memory most probably supports metacognitive skills in some ways, individual differences in short-term memory beyond a certain minimal level are unlikely to predict individual differences in metacognitive skills in children. Therefore, short-term memory is not expected to relate to either monitoring or control. However, the manipulation of information (required in working memory tasks) is considered to be a function that would contribute to control processes. For instance, in the backwards digit span task, the information manipulation required is to reverse the order of digits. This is an active process that could be utilized in metacognitive control when a person must change their approach to a task or conduct some mental calculation. It is a prime example of the meta-level (the mental representation of the digits) passing information (the digits in reverse order) to the object-level (the level of the task, to provide the reversed digits). Thus, the theoretical framework presented here predicts that working memory will be related to control, but not monitoring abilities.

The development of the relationship

This theoretical framework makes specific predictions which can be tested as long as the two executive functions measured here (inhibitory control and working memory) are indeed separate skills in young children. If measures of inhibitory control and working memory are still undifferentiated in young children, we would expect them to relate to other measures in the same way. Further, some researchers have noted that the relationship between monitoring and control processes is still developing in young children, and that a failure to effectively use the information provided via monitoring processes can contribute to metacognitively unskillful behavior (Hacker, Dunlosky, and Graesser 1998; Schneider and Pressley 1997; Schneider, Vise, Lockl, and Nelson 2000; Whitebread 2013). Given that the structure of executive functions and the processes that contribute to metacognitive skills may still be changing in young children, generating clear predictions regarding the precise nature of relationships among them and how these relationships develop is a challenge. Therefore, this aspect of the present study was somewhat exploratory.

In summary, this study brings together two major areas of research that have focused on how people are able to make and follow a plan, flexibly respond to new ideas, and reflect on their achievements in order to achieve a cognitive goal – metacognitive skills and executive functions. Age-appropriate measures of metacognitive skills, inhibitory control, memory (short-term and working) and educational achievements were collected from 5 and 7-year-old children. According to the theoretical model proposed here, inhibitory control was expected to relate to both metacognitive monitoring and control, and working memory was expected to relate to control. The pattern of relationships across the age groups could shed further light on the nature of the relationships among executive functions and metacognitive skills.

Materials and methods

Participants

Participants were 34 five-year-olds (mean age 5.7 years, 19 female) and 32 seven-year-olds (mean age 7.8 years, 10 female[3]) recruited through schools in the city of Cambridge, UK.

Tasks and variables

Metacognitive skills: the train-track task

Children's behavior during a problem-solving task was coded for verbal and non-verbal evidence of metacognitive skills and a lack of metacognitive skills (named perseveration and distraction, PD). The task required the children to build a train-track from wooden pieces to match a shape in a plan. Each child attempted two plans, an easy and a hard one, and in one attempt the plan was removed to challenge their memory (for details of the coding schemes, see Bryce and Whitebread 2012). The shapes were closed-circuits – younger children attempted an oval (easy) and 'goggles' (hard) shape, and older children attempted a 'goggles' (easy) and P (hard) shape. The coding scheme aimed to fairly represent, by numerical counts, examples of metacognitive monitoring (e.g. checking plan, reviewing, error detection), metacognitive control (e.g. sorting, seeking, changing strategy) and perseveration and distraction (e.g. persisting with an inferior strategy, going off-task). Reliability indices for this coding scheme were good; inter-rater agreement was κ=0.90 and intra-rater agreement was κ=0.98. Instances of behaviors were converted to rates by dividing the number of occurrences by the number of minutes the child spent on the task. Thus, the resulting variables were rate of Monitoring, rate of Control and rate of PD (rates per minute).

Metacognitive skill: CHILD questionnaire

School teachers of the children completed the Children's Independent Learning Development (CHILD) questionnaire (Whitebread et al. 2009, 2011). The questionnaire consists of a list of behaviors that children never, sometimes, usually, or always show (translated to numerical scores 1 to 4). There are two factors in this questionnaire – self-regulation (mean of 9 items), and social-regulation (mean of 4 items) – but since this study focused on cognitive regulation we only report the self-regulation score. The internal consistency of the self-regulation factor, as measured by the Cronbach's alpha within this sample, was high: α=.98.

Inhibitory control: animal stroop

The children's inhibitory control abilities were assessed using the animal Stroop task (Bryce et al. 2011; Szucs, Soltesz, Bryce, and Whitebread 2009). In this task, children select the animal that is larger in real life, from two animals presented on the screen that are physically different sizes. Some trials are congruent (e.g. a large elephant and a small mouse), while some are incongruent and require inhibitory control (e.g. a small elephant and a large mouse). Accuracy and reaction time (RT) data are available from this task and proportionally transformed scores were used to account for differences in processing speed, as it has been

[3] Please note: Within each age group, there were no significant differences between the genders in any of the outcome scores.

suggested that processing speed underlies the relationships among executive functions. Mean RTs were proportionally transformed using the formula: (incongruent RT – congruent RT) / congruent RT. Likewise, the proportional accuracy variable was calculated using the formula: (congruent % – incongruent %) / congruent %. Lower scores in each variable reflect superior inhibitory control.

Memory: AWMA

Measures of both working memory (WM) and short-term memory (STM) were collected from the children via the Automated Working Memory Assessment (AWMA, Alloway et al. 2007). Each type of memory was assessed by one verbal and one visuo-spatial task – WM was assessed by backwards digit recall (verbal) and odd one out (visuo-spatial), STM was assessed by non-word recall (verbal) and dot matrix (visuo-spatial). This automated assessment has been widely validated as a reliable measure and produces raw and standardized scores. The resulting variables were mean WM and mean STM scores (raw and standardized).

Educational achievement: WIAT II UK

Two subtests of the WIAT II UK (Wechsler 2005) were administered to the children to gauge their educational achievements to date – Mathematical Reasoning and Word Reading. Raw and standardized scores are produced from these measures.

Procedure

Children were administered the train track task, four tests from the AWMA, and the Mathematical Reasoning and Word Reading scales from the WIAT II UK in two sessions in school. The order of administration was quasi-randomized to avoid order effects, and each session took approximately 15 min. The children completed the animal Stroop task in a third session in which they attended an EEG laboratory at the University of Cambridge. Teachers completed the CHILD questionnaire at a time that was convenient to them over the testing period.

Analysis

The suitability of all the data (metacognitive skills, inhibitory control, memory and educational achievement variables) for parametric statistical analysis was assessed, both as a whole group and in each age group separately. Because the distribution of some variables violated the assumptions required for parametric tests, nonparametric correlation analyses (Spearman's) were used. Rates of metacognitive skills from each train track plan type (easy and hard) were entered into correlation analyses separately. In order to allow the reader to judge the likelihood of Type 1 errors, we provide 95 % confidence intervals for each correlation coefficient. As there is no nonparametric equivalent of multiple linear regression, square root transformed variables were used in regression analyses. After the square root transformation, all variables that were used in regression analyses were normally distributed. Independent variables were entered hierarchically – age was entered in the first step using the forced entry method, and all other relevant measures were entered in the second step using the stepwise method.

Results

Descriptive statistics

Descriptive statistics regarding all variables are presented and differences between the age groups (results of Mann-Witney test) are indicated by asterisks in Table 1. There was an increase in rates of Monitoring and Control behaviors, and no change in PD behaviors within this age-range. The results from the CHILD questionnaire and the memory scores indicate that each age group was typical for their age in metacognitive skill, working memory and short-term memory. In contrast, the age groups were significantly different in standardized scores of educational achievement, indicating that although the 7-year-olds had normal academic achievement levels for their age group, the 5-year-old group performed better than expected for their age.

How are metacognitive skills and executive functions related, and how does the relationship develop?

The primary aim of this study was to understand if and how two executive functions (inhibitory control and working memory) relate to metacognitive skills in young children. Correlations between metacognitive skills (coding rates in each task and

Table 1 Mean and standard deviations (in parentheses) of each dependent variable for each age group

Measure	5-year-olds	7-year-olds
Metacognitive skills		
Monitoring rate/min*	4.83 (2.72)	6.14 (2.43)
Control rate/min*	4.41 (1.92)	5.21 (1.63)
PD rate/min	1.41 (1.49)	1.05 (1.22)
CHILD self-regulation	2.85 (0.79)	2.71 (0.57)
Inhibitory control		
Animal stroop IC %	0.10 (0.10)	0.06 (0.10)
Animal stroop IC RT	0.13 (0.08)	0.10 (0.10)
Memory		
Working memory (raw)***	9.22 (2.16)	13.8 (2.74)
Short term memory (raw)***	12.51 (3.03)	17.14 (3.09)
Working memory (st)	103.74 (10.77)	106.55 (11.06)
Short term memory (st)	103.74 (13.83)	110.66 (13.15)
Educational achievement		
Word reading (raw)***	50.06 (10.23)	88.53 (16.11)
Mathematical reasoning (raw)***	19.00 (4.74)	32.91 (5.68)
Word reading (st)*	109.41 (10.01)	99.75 (14.92)
Mathematical reasoning (st)**	108.35 (11.33)	99.66 (11.77)

Significant difference between the groups (Mann-Witney test): $^{*}p<.05$, $^{**}p<.01$, $^{***}p<.001$. PD: Perseveration and distraction; Monitoring, Control and PD rates are total rates per minute; Animal Stroop IC %: proportional accuracy score from the animal Stroop task; Animal Stroop IC RT: proportional reaction time score from the animal Stroop task; a smaller animal Stroop IC % and animal Stroop IC RT score represents superior inhibitory control abilities; raw: raw scores; st: standardized scores

CHILD score) and executive functions (all measures of inhibitory control and memory) within each age group can be found in Table 2. In younger children, inhibitory control measures and short term memory were related to both monitoring and general metacognitive skills (CHILD scores and rates of PD), while working memory was only significantly related to general metacognitive skills (CHILD scores). In the older children, only the correlation between inhibitory control and monitoring reached significance.

As well as correlations, multiple linear regressions were run with rates of Monitoring and Control as dependent variables. Executive functions only made a significant contribution to these variables after age in the younger group (see Table 3). The proportional accuracy measure of inhibitory control from the animal Stroop task accounted for 13 % of the variance in Monitoring rates, while working memory accounted for 15 % of variance in the rate of Control demonstrated by younger children. While short term memory correlated with Monitoring in the younger children, it did not enter the relevant regression analyses suggesting that it did not explain any variance over and above the effects of age and inhibitory control. Interestingly, there was a significant correlation between Monitoring rates in the easy plan and the proportional accuracy measure of inhibitory control from the animal Stroop task in the older children, but no inhibitory control measure entered this regression model after age, suggesting that the relationship may have been driven by age.

Table 2 Correlations among metacognitive skills and executive functions, within each age group. Nonparametric (Spearman's) correlation coefficients and the lower and upper limits of 95 % confidence intervals (in parentheses) are presented

	Inhibitory control		Memory	
	IC %	IC RT	WM	STM
5-year-olds				
Monitoring easy	−.50** (−.72, −.19)	−.28 (−.57, .06)	.18 (−.17, .49)	.35* (.02, .62)
Monitoring hard	−.35* (−.62, −.02)	−.11 (−.43, .24)	.08 (−.27, .41)	.02 (−.32, .36)
Control easy	−.20 (−.50, .15)	.01 (−.33, .35)	.32 (−.02, .59)	.02 (−.32, .35)
Control hard	−.10 (−.42, .25)	−.15 (−.20, .47)	.24 (−.11, .53)	−.08 (−.40, .27)
PD easy	.36* (.02, .62)	−.24 (−.53, .11)	−.07 (−.40, .28)	−.24 (−.54, .11)
PD hard	.06 (−.28, .39)	.11 (−.23, .44)	−.14 (−.46, .20)	.16 (−.19, .47)
Self	−.41* (−.69, −.01)	.04 (−.36, .43)	.61** (.29, .81)	.43* (.04, .71)
7-year-olds				
Monitoring easy	−.35* (−.62, 0)	−.06 (−.40, .30)	.05 (−.30, .39)	.26 (−.09, .56)
Monitoring hard	.04 (−.31, .39)	−.03 (−.37, .32)	.02 (−.34, .36)	−.06 (−.40, .30)
Control easy	.00 (−.35, .35)	.04 (−.31, .39)	.15 (−.21, .48)	−.01 (−.36, .34)
Control hard	.23 (−.13, .54)	−.06 (−.40, .30)	.13 (−.23, .46)	.01 (−.34, .36)
PD easy	−.21 (−.52, .15)	−.03 (−.33, .37)	−.31 (−.59, .04)	−.05 (−.39, .30)
PD hard	−.16 (−.48, .20)	.03 (−.33, .37)	.00 (−.35, .35)	.18 (−.18, .50)
Self	−.18 (−.54, .23)	−.10 (−.48, .31)	.20 (−.21, .55)	.24 (−.17, .58)

Significance levels: *p<.05, **p<.01, ***p<.001. IC %: proportional accuracy score from the animal Stroop task; IC RT: proportional reaction time score from the animal Stroop task; A smaller IC % and IC RT score represents superior inhibitory control abilities; WM: working memory score; STM: short term memory score; Monitoring: Monitoring rate; Control: Control rate; PD: Perseveration and distraction rate; Easy/Hard: Rates on an easy or hard plan; Self: Self-regulation factor of the CHILD

Table 3 Regressions with metacognitive skills coding rates as dependent variables

	DV = monitoring rate in the easy plan, 5-year-olds				DV = control rate in the easy plan, 5-year-olds		
Predictors	*b*	*SE b*	*β*		*b*	*SE b*	*β*
Step 1							
Age	.21	.43	.09	Age	−.03	.39	.01
Step 2							
Age	.10	.41	.04	Age	−.21	.38	−.10
IC %	−1.33	.64	−.37*	WM	.50	.23	.40*
R^2=.01 for Step 1, ΔR^2=.13* for Step 2.				R^2=.00 for Step 1, ΔR^2=.15* for Step 2.			

*p<.05. IC %: proportional accuracy score from the animal Stroop task; A smaller IC % score represents superior inhibitory control abilities; WM: working memory score

How do executive functions and metacognitive skills contribute to educational achievement?

Correlation analysis was conducted between each academic measure (raw scores on Word Reading and Mathematical Reasoning) and all other measures in each age group separately (Table 4). In the younger group, measures of general metacognitive skills, working memory and short term memory all correlated significantly with both reading and math ability. In the older group, only general metacognitive skills correlated significantly with reading and math ability.

In order to better understand the relative contribution each skill made to reading and math ability, a series of regressions were run within each age group (Table 5). The self-regulation factor of the CHILD questionnaire was a significant predictor of both Word Reading and Mathematical Reasoning scores in each age group.

Discussion

The relationship between metacognitive skills and executive functions

As already reviewed, previous literature on the relationship between executive functions and metacognitive skills has been rather limited and these limitations were addressed in the present study – participants were young children, both monitoring and control processes in a problem-solving task were assessed, and simple measures of two executive functions were employed. Furthermore, the lack of existing theoretical frameworks within which to understand these relationships was addressed by proposing a model based on Nelson and Narens' (1990). This model predicted that inhibitory control would relate to metacognitive monitoring, control, rates of PD and scores on the CHILD, while working memory would relate to control processes, rates of PD and scores on the CHILD.

The previous literature regarding monitoring and executive functions is mixed. While throughout the discussion we compare the conclusions of Roebers et al. (2012) with our observed results, it should be noted that the two studies are not directly comparable because of fundamental differences in analyses. In particular, their measures of each skill were latent

Table 4 Correlations among educational achievement scores and all other variables, within each age group. Nonparametric (Spearman's) correlation coefficients and the lower and upper limits of 95 % confidence intervals (in parentheses) are presented

	Metacognitive skills			Animal Stroop			Memory	
	Mon	Con	PD	Self	IC %	IC RT	WM	STM
5-year-olds								
Reading	.23 (−.12, .53)	.22 (−.13, .52)	−.08 (−.41, .27)	.57** (.23, .79)	−.28 (−.57, .06)	−.15 (−.47, .20)	.49** (.18, .71)	.34* (0, .61)
Math	.11 (−.24, .43)	.06 (−.28, .39)	−.28 (−.57, .06)	.74*** (.49, .88)	−.30 (−.58, .04)	−.07 (−.40, .28)	.55** (.26, .75)	.54** (.25, .74)
7-year-olds								
Reading	−.07 (−.41, .29)	.03 (−.32, .38)	.07 (−.29, .41)	.66*** (.36, .84)	−.14 (−.47, .22)	−.11 (−.44, .25)	.26 (−.10, .56)	.29 (−.07, .58)
Math	−.06 (−.40, .30)	.18 (−.18, .50)	−.07 (−.41, .29)	.63** (.31, .82)	.14 (−.22, .47)	.15 (−.21, .47)	.25 (−.11, .55)	.23 (−.13, .54)

Significance levels: *$p<.05$, **$p<.01$, ***$p<.001$. Mon: Total Monitoring rate; Con: Total Control rate; PD: Total Perseveration and distraction rate; Self: Self-regulation factor of the CHILD; IC %: proportional accuracy score from animal Stroop task; IC RT: proportional reaction time score from animal Stroop task; A smaller IC % and IC RT score represents superior inhibitory control abilities; WM: Working memory score; STM: Short term memory score

Table 5 Regressions with educational achievement measures as dependent variables, in each age group

	DV = word reading, 5-year-olds				DV = word reading, 7-year-olds				DV = mathematical reasoning, 5-year-olds				DV = mathematical reasoning, 7-year-olds		
Predictors	*b*	*SE b*	*β*		*b*	*SE b*	*β*		*b*	*SE b*	*β*		*b*	*SE b*	*β*
Step 1															
Age	1.42	.69	.41	Age	1.41	1.07	.28	Age	.88	.57	.32	Age	1.28	.55	.46*
Step 2															
Age	.83	.68	.24	Age	.61	.89	.12	Age	.06	.42	.02	Age	.91	.48	.33
Self	1.31	.59	.44*	Self	3.09	.89	.62**	Self	1.83	.36	.78**	Self	1.44	.49	.52**
R^2=.17 for Step 1, ΔR^2=.16* for Step 2.				R^2=.01 for Step 1, ΔR^2=.36** for Step 2.				R^2=.10 for Step 1, ΔR^2=.51** for Step 2.				R^2=.21* for Step 1, ΔR^2=.25** for Step 2.			

*p<.05, **p<.01, ***p<.001. Self: Self-regulation factor of the CHILD

variables, meaning that they reflect only the shared variance among performance on different tasks, while our measures of each skill were performance scores on each task, which means that they reflect the intended 'pure' skill as well as other skills or processes that contribute to performance on such tasks. Roebers et al. (2012) found that in 8-year-olds the latent executive function variable was not related to the latent variable "metacognitive monitoring" at all (although this could be related to the aforementioned issues with their monitoring measures). Here, the proposed theoretical model predicted that monitoring processes would be uniquely related to our measures of inhibitory control, due to the interference suppression process that contributes to inhibitory control. The results of the present study indicate that monitoring processes did relate to inhibitory control, and this relationship was more consistent in 5-year-olds than 7-year-olds.

The majority of existing literature did not indicate which specific executive functions should relate to metacognitive control. According to the theoretical model proposed in the present study, control processes were expected to relate to both inhibitory control and working memory. The data indicate that working memory showed reliable associations with measures of control only in the younger group. While we found no specific executive functions were related to metacognitive control in the older age group, Roebers et al. (2012) did find that their latent executive function variable was related to the latent variable "metacognitive control" in the relevant cross-sectional analysis. This variation in findings might be attributed to the difference in the measures used and the analyses conducted, as already described.

The present study has generated novel data with regard to how executive functions relate to a lack of metacognitive skills (rate of PD) and CHILD scores. Based on the theoretical model, it was hypothesized that both inhibitory control and working memory would relate to these measures, as they are expected to assess both monitoring and control processes (and failures of these, in the case of PD). This hypothesis was supported by the evidence, but again only in the younger group.

The research findings indicate that the theoretical model must be adapted to show that inhibitory control as measured by the animal Stroop is not related to control processes in either age group. It is not clear why this is the case, and perhaps further investigation using different measures of inhibitory control would provide additional insights. While the mechanisms underlying these relationships are still to be fully elucidated, they will hopefully become clearer with further research using alternative measures and participants of different ages. The results from this exploratory study indicate that further investigations of this type could be very productive and would likely help to further develop and refine a theoretical model of the relationships between executive functions and metacognitive skills.

The developmental pattern of results suggest that executive functions are not exactly the same as metacognitive skills, as there were many more and stronger relationships between specific, online measures of metacognitive skills and executive functions in the younger children than in the older children. This pattern of results is considered reliable as there is no evidence that any of the measures reached ceiling level in either group – both laboratory tests of executive functions (animal Stroop and the AWMA tests) are suitable for use until adulthood, there is no upper limit on the rates of metacognitive skills shown during the train-track task, and scores on the self-regulation scale of the CHILD were also comparable across the age groups (mean score of 2.85 in the younger group and 2.71 in the older group, with a maximum score of 4). It should be noted that the variance was higher in all metacognitive skills measures in the younger group than the older group; in order to ameliorate the risks of Type I error when the assumption of homogeneity of variances was not satisfied, nonparametric correlation analyses were used and a square root transformation was applied for the regression analyses. Therefore, we are confident that the weaker and fewer relationships in the older group cannot be attributed to statistical weaknesses.

It is reasonable to question whether this result pattern simply reflects a general trend towards differentiation of skills with age, as proposed by Lee et al. (2013). However, this seems unlikely, as correlations within domains (i.e. between Monitoring and Control rates, and between working memory and inhibitory control scores) were not stronger in the younger group (r=.36, and r=−.27, respectively) than in the older group (r=.43, and r=−.33). Instead, it seems that the specific relationship between metacognitive skills and executive functions changes with age. These data could be interpreted as suggesting that executive functions are necessary for the development of metacognitive skills but not an integral part of more mature metacognitive skills. Indeed, Apperly et al. (2009) distinguish between skill A (in this case, executive functions) playing a supportive role in the development of skill B (in this case, metacognitive skills) but no longer being necessary for the mature skill B (analogous to scaffolding for a house only being required during the building phase), and skill A being an integral part of a mature skill B (analogous to the cement of a house being necessary to maintain the structure). For instance, perhaps at the younger age, when executive functions are still relatively immature, their absence restricts or limits a child's attempts to perform metacognitively. One could imagine a situation whereby a child tries to monitor their place in a task but becomes easily distracted due to their limited interference suppression abilities. Another interpretation of this pattern of results is that executive functions are necessary for a basic level of metacognitive skillfulness, but after they reach a certain level, other factors (such as emotional regulation, motivation, task expertise) become important determinants of how metacognitively skilfully a child behaves. Further evidence for this interpretation could be sought by including a younger group of children; we would expect that executive functions and metacognitive skills would be even more closely related than in the 5-year-old group.

The shortcomings of this study deserve acknowledgement. The small sample size may not have provided sufficient statistical power for multiple linear regression and correlation analyses. This, and the use of one measure per component executive function, makes this study rather exploratory in nature. Indeed, larger scale investigation assessing all potentially contributing factors could perhaps further uncover the intricacies of how metacognitive skill develops. Alternatively, an intervention study could better address the mechanisms of these relationships – if our interpretation is correct, one would expect executive function training to improve the metacognitive skills of young children more than those of older children.

Educational achievement

The present study also considered how metacognitive skills, inhibitory control and memory all relate to both reading and math abilities. In each age group, the children's self-regulation scores from the CHILD contributed to both Word Reading and Mathematical Reasoning scores, and there was some evidence that in the 5-year-olds working memory and short term memory were also related to both educational measures (although they did not reach significance in the regressions). The regression models indicated that metacognitive skills accounted for between 16 – 51 % of variance in educational achievement scores. Of course, the direction of causality is not established using these techniques, and although unlikely it could be that superior reading and mathematical skills result in more self-regulatory behavior. Again, our results from the older age group deviate from the conclusions of the most relevant results from Roebers et al. (2012, the cross-sectional analyses), which indicated that the latent variables representing executive functions and metacognitive control were related to language abilities, and that only the executive function latent variable was related to mathematical abilities. However, when looking at the present study's age groups separately, it seems that there is a stronger relationship between self-regulation and reading in 7-year-olds than 5-year-olds, whereas there is a stronger relationship between self-regulation and math in 5-year-olds than 7-year-olds. At least the former pattern is in line with the findings of Roebers et al. (2012). These findings highlight the crucial role that this approach to learning plays in attainment and confirm that metacognitive skills are worth investigating within this age-range.

Conclusions

The data presented here seem to illustrate a chain of relationships between executive functions, metacognitive skills and educational achievement. It appears that executive functions contribute to young children's ability to use their metacognitive skills appropriately, which in turn contributes to their educational achievement. These results could be interpreted as suggesting that while executive functions are still maturing (in 5-year-olds) they play a key role in determining how metacognitively skilful children are, and at both ages metacognitive skills contribute to academic achievement. If this interpretation does accurately reflect the nature of the relationships among these skills, these findings have relevance for educational interventions. That is, executive functions have traditionally been considered as being necessary for normal functioning (e.g. you either can or cannot inhibit inappropriate responses) and the lack of them has indicated some developmental disorder (e.g. autism, ADHD). However, metacognitive skill is a more fluid concept. It can be considered a person's propensity to use these skills in everyday situations. As such, it is highly dependent on motivation for the task, emotional state, experience of the task, and so on. This offers a hopeful message for education – a child's abilities may not be predetermined by their executive functions; rather, as long as executive functions are not deficient, a child's metacognitive skills play an increasingly important role with age.

These findings evidently have theoretical significance for the existing literature on the relationship between executive functions and metacognitive skills – they have elicited more specific relationships than previous studies, broadened the age-range being studied allowing for additional developmental trends to emerge, and offered a theoretical framework within which to consider relationships. While more work on this topic is required before we can claim a full and complete understanding of the nature of relationships among executive functions and metacognitive skills, this type of research can contribute to the emerging picture of these undoubtedly complex relationships.

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