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Evidence for a Role of Executive Functions in Learning Biology

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Research examining cognition and science learning has focused on working memory, but evidence implicates a broader set of executive functions. The current study examined executive functions and learning of biology in young adolescents. Fifty-six participants, aged 12–13 years, completed tasks of working memory (Spatial Working Memory), inhibition (Stop-Signal), attention set-shifting (ID/ED) and planning (Stockings of Cambridge), from the Cambridge Neuropsychological Test Automated Battery. They also participated in a biology teaching session, practical and assessment on the topic of DNA designed specifically for the current study that measured (a) memory for biology facts taught and (b) understanding of information learned in the practical. Linear regression analysis revealed that planning ability predicted performance on the factual assessment, and both spatial working memory and planning were predictive of performance on the conceptual assessment. The findings suggest that planning ability is important in learning biological facts but that a broader set of executive functions are important for conceptual learning, highlighting the role of executive functions in understanding and applying knowledge about what is learned within science teaching.

Key words: executive function; working memory; planning; science learning; biology; CANTAB

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Executive functions are widely believed to be a compendium of constructs comprising three core, dissociable components: inhibition, working memory and set-shifting (Diamond, 2013; Lehto, Juujärvi, Kooistra, & Pulkkinen, 2003; Miyake et al., 2000), and a number of higher level functions such as planning and problem solving (Diamond, 2013). Separation into these three core components has been identified in both child (Hughes, Dunn, & White, 1998; Lehto et al., 2003; Schoemaker et al., 2012) and adult samples (Miyake et al., 2000), although some argue that inhibition and working memory are a single system (Pennington, Bennetto, McAleer, & Roberts, 1996). Of the core constructs, most research that has examined executive functions and science learning has focused on the role of working memory. Researchers examining science learning have varied in how working memory has been defined with some examining 'mental capacity' (e.g. Danili & Reid, 2004) and others referring specifically to 'working memory' (St Clair-Thompson & Gathercole, 2006). A recent study (St Clair-Thompson, Overton, & Bugler, 2012) reported dissociation between the cognitive resources underlying performance on tests of mental capacity and working memory with the latter highlighted as the best predictor of problem solving and science grades. The current paper will therefore focus on studies that have assessed working memory. Numerous models of working memory have been proposed (e.g. Baddeley, 2006; Cowan, 1995, 1999; D'Esposito, 2007; Miyake, Friedman, Rettinger, Shah, & Hegarty, 2001; Oberauer, 2009), but the most popular model in the literature supported by strong evidence is Baddeley's theoretical working memory component model (Baddeley, 1986, 2006; Baddeley & Hitch, 1974). This model includes a phonological loop (for storing verbal information) and a visuo-spatial sketchpad component (for storing visuo-spatial information). A key component of the model is a 'central executive' that is for conditions of high level processing, such as the control and manipulation of stored information.

It is now well established that working memory develops across childhood and into adolescence (DeLuca et al., 2003; Luciana & Nelson, 1998; Rhodes, Murphy, & Hancock, 2011). Gathercole and colleagues (Gathercole, Pickering, Ambridge, & Wearing, 2004), for example, reported increases in working memory performance between ages 4 and 15 years. Rhodes et al. (2011) also reported that children were not at adult levels of verbal or spatial working memory at the age of 11 years. Furthermore, Luciana, Conklin, Hooper, and Yarger (2005) found that performance on complex spatial working memory tasks, such as self-ordered search tasks, continues until 16 years of age. The development of strategic working memory into mid-adolescence suggests implications for learning of science subjects into the middle secondary school years. There is indeed an established link between working memory and other areas of academic learning such as reading (Christopher et al., 2012), language (Daneman & Merikle, 1996) and mathematics (Bull & Scerif, 2001).

Research that has examined working memory and science learning has varied in relation to whether they have examined storage alone or storage and processing. Studies that have focused on storage aspects (i.e. tapping the phonological loop or visuo-spatial sketchpad) of working memory have provided inconsistent evidence for a role of storage-based memory in science learning. Chen and Whitehead (2009) examined the relationship between visuo-spatial short-term memory capacity and learning physics in Taiwanese pupils who were aged 13–15 years. Physics learning was assessed across a number of topics using structural communication grids that place a low load on memory capacity. Chen and Whitehead (2009) reported a significant relationship between visual–spatial short-term memory capacity and physics understanding in their sample. Jarvis and Gathercole (2003), in contrast, failed to report a significant relationship between science learning with

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either verbal or visuo-spatial short-term memory storage. Their findings in a UK sample of 14-year-old pupils question the significance of more basic short-term memory processes in science learning.

Research that has examined central executive aspects of working memory (i.e. with tasks that measure storage and processing) has provided much more consistent evidence than studies examining storage only for a role of central executive processes in science learning. A study that examined verbal executive working memory in a sample of 101 Scottish biology school pupils (aged 16–17 years) revealed that those with superior working memory were more accurate on a biology grid assessment (Bahar & Hansell, 2000). The task used in the study required pupils to store and manipulate phonological information in memory and thus went beyond simple storage processes assessed in previous studies. Danili and Reid (2004) similarly examined the relationship between science learning and performance on a verbal executive working memory task (in this case, a backward digit span task). The authors reported a significant correlation between verbal working memory and performance on a chemistry test in Greek pupils aged 13–15 years. A recent study examined the relationship between both storage tasks and storage and processing tasks and algorithm problem solving from a chemistry exam in undergraduate students (St Clair-Thompson et al., 2012). The storage and processing task employed (counting recall) but not the storage only tasks (digit and block recall) correlated with problem solving. These findings, on biology and chemistry assessments, suggest that a relationship between executive working memory and science learning may be evident across science disciplines.

A study that incorporated both verbal storage and central executive tasks has suggested that the relationship between working memory and science learning may be stronger for central executive aspects of working memory than for storage processes. Gathercole, Pickering, Knight, and Stegmann (2004) examined the relationship between verbal short-term and central executive working memory and science achievement in a UK sample of pupils aged 14–15 years. While correlations were observed between science level and both short-term (on a digit recall task) and executive working memory (on a backward digit recall task), the relationship was stronger for the executive task. A number of other studies have indeed emphasized the role of executive working memory in science learning (Jarvis & Gathercole, 2003; St Clair-Thompson & Gathercole, 2006).

Evidence for modality differences has also been reported. Jarvis and Gathercole (2003) reported that spatial central executive scores, but not verbal working memory performance, were significantly correlated with science grades in a UK sample of 14-year-old pupils. St Clair-Thompson and Gathercole (2006) similarly examined the relationship between verbal and spatial working memory and science achievements in a UK sample of 11- to 12-year-old pupils. Again, the relationship between working memory and science achievement was domain specific; spatial, but not verbal, working memory was related to performance on the science test. These findings suggest that spatial executive working memory may be critically important in science learning. The aforementioned studies examined science learning in relation to a generic science exam where different science discipline aspects were assessed. A recent study reported a significant relationship between spatial executive working memory and science learning in pupils aged 12–13 years (Rhodes et al., 2012). Spatial working memory in fact predicted both performance on a generic science school exam and on a study-specific chemistry assessment. Furthermore, the assessment comprised both factual and conceptual components, and the relationship with working memory was specific to conceptual aspects of learning. In the current study, we aimed to examine

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whether spatial executive working memory was similarly predictive of conceptual learning of biology where pupils had to show their understanding and application of the concepts learned.

Recent research suggests that a broader set of aspects of executive function contributes to science learning than working memory. As with the development of working memory, there is consistent evidence for profound changes in other aspects of executive functions across the period of adolescence (Anderson, Anderson, Northam, Jacobs, & Catroppa, 2001; DeLuca et al., 2003, Levin, Eisenberg, & Benton, 1991; Luciana & Nelson, 1998). Anderson et al. (2001) reported the most significant age-related changes in attentional flexibility between 7–9 and 15 years of age, and Davidson, Amso, Anderson, and Diamond (2006) showed that cognitive flexibility was still not at adult levels at 13 years of age. Planning ability also appears to mature around this age with reports of maturation around 12 years of age (Davidson et al., 2006). Research on the development of inhibition has been more inconsistent; one study reported that inhibition develops up to age 17 (Leon-Carrion, Garcia-Orza, & Perez-Santamaria, 2004). As science learning requires strategic thinking—from the ability to plan solutions to problems, to engage in hypothesis making, to examine and evaluate data, to think flexibly between different options and to speculate on the influence of experimental manipulations—it seems likely that continued development of these processes will influence science learning into the secondary school years.

A number of research studies have examined a broader set of executive functions beyond working memory, and all implicate other processes in science learning. St Clair-Thompson and Gathercole (2006) examined the relationship between inhibition and attention shifting with mathematics, English and science learning in 11- to 12-year-old pupils. Inhibition was reported to be correlated with science learning. Another study with a sample of 11- to 16-year-old boys reported a relationship between science ability and both inhibitory control and attention flexibility (Latzman, Elkovitch, Young, & Clark, 2010). Rhodes et al. (2012) reported correlations between planning ability and both performance on a generic science exam and on a chemistry-specific assessment. Linear regression analyses revealed that attention set-shifting predicted performance on a chemistry assessment that required the 12- to 13-year-old pupils to show understanding of and apply the knowledge they had gained from a chemistry practical. These findings suggest the role of executive functions in science learning may be broader than the historical focus on working memory in the literature. Most research in this area has examined science learning on generic science exams that are not discipline specific and which will involve a combination of factual and conceptual understanding of science material. The current study will investigate whether inhibition, attention set-shifting and planning, in addition to working memory, predict performance in the area of biology and will examine both retrieval of factual knowledge and conceptual understanding of the discipline in early adolescence.

The principal aim of the current study was to examine the relationship between core aspects of executive function and the factual and conceptual learning of biology. In the current study, we assess aspects of executive functions considered as core in the literature, namely inhibition, working memory and attention set-shifting. As there have been reports in the literature of a role for planning in science learning, we also included an assessment of planning ability. Planning is of course central to key aspects of science learning such as the experimental process. We chose to assess science learning and executive functions in a young adolescent sample, as working memory and other aspects of executive function are still under development at this stage. Adolescents who participated in the study were aged 12–13 years and had been attending secondary level education for approximately 18 months.

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The current study examined science learning at the point of the introduction of a new curriculum in Scotland in 2009, the Curriculum for Excellence (Scottish Executive, 2004). The curriculum focuses on active learning and peer collaboration, and the use of a broad range of approaches (labelled 'experiences and outcomes') is emphasized, which allows children to demonstrate what they 'know, understand, and can do'. In relation to science, the focus of the curriculum within the primary school years (up to age 12) is on investigative aspects of science but, in the early secondary years, shifts more to content and skills, including both acquiring knowledge through learning facts, planning investigations, and examination and evaluation of data. We will focus on conceptual learning, which requires the pupil to think flexibly about the knowledge they acquire weighing up multiple options, each of which may be complex, to arrive at a solution and would therefore seem likely to rely more heavily on executive function skills than basic retention of facts. The current study hypothesized that executive functions would specifically predict conceptual understanding rather than factual learning. Relatively few studies in this area have examined executive functions in relation to biology and those that have focus on working memory. We therefore sought to examine this gap in the literature. Based on existing literature, it was predicted that performance on the biology assessment would be predicted by working memory. A lack of data on broader aspects of executive function made prediction difficult, but based on previous research (Latzman et al., 2010; Rhodes et al., 2012; St Clair-Thompson & Gathercole, 2006), we hypothesized that inhibition, planning and attention set-shifting would predict biology learning. In particular, we predicted that executive functions would relate to performance on the conceptual part of the biology assessment where pupils had to reflect and think strategically in applying the knowledge they had acquired.

METHOD

Participants

Sixty-three pupils (aged 12–13 years) were recruited to the study from four secondary schools within the North Lanarkshire Council area of Scotland. Schools were all located in urban areas spread across the authority and followed the National Curriculum independently. The schools were chosen as they are representative of having an average level of deprivation (average deprivation score indicated by free school meal data is 16% vs Scotland average of 19.8%). The study received ethical approval from the Departmental Ethics Committee, and consent was obtained from parents of all participating adolescents. No pupils refused to participate. Teachers of all consenting pupils completed the Strengths and Difficulties Questionnaire (SDQ; Goodman, 2001) to screen for any potential psychiatric/behavioural disorder known to be associated with impaired executive functions (e.g. the common developmental disorder ADHD). Fifty-six pupils were rated within the normal range (Total Difficulties score < 15) on the SDQ ($N = 20$ boys, 36 girls), and their data were included in the statistical analyses. Pupils had a mean age of 13.38 ($SD = 0.35$). All pupils also completed the British Picture Vocabulary Scale II (Dunn, Dunn, Whetton, & Burley, 1997) to provide a measure of general ability that is known to be less heavily confounded with executive function skills. All pupils scored within the normal range on this verbal ability test.

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Materials

Cognitive tasks

All participants completed four cognitive tasks taken from the Cambridge Neuropsychological Test Automated Battery (CANTAB) (Morris, Evendon, Sahakian, & Robbins, 1987): the Spatial Working Memory (SWM; working memory), Stockings of Cambridge (SOC; planning), Stop-Signal (inhibition) and ID/ED (attention set-shifting). These tasks were chosen because they have been extensively validated in both child and adult populations (Curtis, Lindeke, Georgieff, & Nelson, 2002; Luciana & Nelson, 1998; Rhodes, Coghill, & Matthews, 2004, 2005, 2006; Robbins et al., 1994), and typical developmental trajectories of performance have been reported (Curtis et al., 2002; Luciana & Nelson, 1998; Robbins et al., 1994). Tasks are performed on a touch-screen computer and are highly suitable for use with children and adolescents (Rhodes, Riby, Matthews, & Coghill, 2011; Rhodes et al., 2005).

Working memory

The SWM task places heavy demands on central executive functioning. It is a self-ordered searching task (Petrides & Milner, 1982) that assesses the participant's ability to retain spatial information and to store and simultaneously manipulate information in working memory while working towards a goal. Participants are required to 'search through' a spatial array of coloured boxes presented on the screen to collect 'blue tokens' hidden inside the boxes. Returning to a box where a token has already been found constitutes a 'Between Search Error' (BSE). Participants must keep searching through all the boxes until they find the blue token at which point they proceed to find the next hidden blue token. The task therefore requires the participant to hold information in working memory (storage) while simultaneously continually updating their memory (additionally requiring processing). Ultimately, participants will find a blue token behind each of the boxes. Experimental trials commence with a four box search, and the highest difficulty level involves eight box trials. Participants can use a (self-initiated) strategy to aid performance, for example always starting at top left of the array of boxes moving across to bottom right. A higher error (BSE) score indicates poorer working memory performance.

Inhibition

The Stop-Signal task provides an assessment of response inhibition. This task measures the ability of an individual to inhibit a prepotent motor response, requiring participants to respond or withhold responding dependent on receiving an auditory signal. This test consists of two parts. In the training component, the participants are told to press the left-hand button when they see a left-pointing arrow and the right-hand button when they see a right pointing arrow. In the experimental component, the participants are told to continue pressing the buttons on the press pad when they see the arrows, as before, but if they hear an auditory signal (a beep), they should withhold their response and not press the button. The stop-signal paradigm allows a sensitive estimate of inhibitory control—the stop-signal reaction time (SSRT)—reflecting the time it takes to suppress a response. Longer SSRT reflects poorer inhibitory control.

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Attention set-shifting

The executive ID/ED (Intra-Dimensional/Extra-Dimensional) task assesses attention set-shifting, involving the ability to shift flexibly from focusing attention on one aspect of a stimulus to another (e.g. Intra-Dimensional: from one solid shape to another, Extra-Dimensional: from a solid shape to a line). Specifically, the task measures a participant's ability to focus attention on specific attributes of compound stimuli (intra-dimensional stages) and to shift attention when required to a previously irrelevant stimulus dimension (extra-dimensional stages). At each stage of the task, two different stimuli are presented (e.g. a solid shape), and participants are instructed to choose the stimulus they think is the correct one after which they receive feedback. Once the participant correctly chooses the same stimuli over six trials, the task moves to the next stage. The intra-dimensional stages involve shifting from one solid shape to another, whereas the executive extra-dimensional stages require shifting from one type of stimulus to another (a solid shape to a line). The key measure on this task is the Stage Reached score; reaching the final stages indicates the ability to engage in executive set-shifting (reaching stage eight). Participants are also required to show reversal of this rule whereby the correct exemplar (the line they have chosen) changes to another shaped line presented (reaching stage nine). A higher Stage Reached score reflects superior attention set-shifting ability.

Planning

The SOC task measures planning ability and makes substantial demands on executive function. This task was derived from the 'Tower of Hanoi' task (Shallice, 1982). Participants must move balls to match a 'goal' arrangement. The balls hang in 'socks' akin to snooker balls in pockets. Problems can be solved in a certain 'Minimum Number of Moves' (two, three, four or five moves). Initial and Subsequent 'Thinking' Times during trials are recorded to provide estimates of cognitive speed during the preparatory and execution phases of task performance. Participants need to plan out the full set of moves prior to executing a move to be successful on trials (particularly at the harder four and five move stage problems). For each trial, a yoked control condition is also executed to enable estimates of 'movement times' in order to provide an estimate of cognitive deliberation/planning times in the test conditions. The key measure on this task is the number of Problems Solved in the Minimum Number of Moves. The higher the number of problems solved, the better the planning ability observed.

Procedure

The pupils in the current study were enrolled in a number of science-specific classes at school, namely physics, chemistry and biology. In order to establish whether executive functions underlie the acquisition of factual knowledge about science and/or the ability to conceptually understand and apply knowledge to new problems, we conducted a biology teaching session on the topic of DNA with an associated practical and assessment. This biology session required the pupils to show retention of the facts they had acquired in addition to the ability to apply their knowledge to show understanding of the topic on a conceptual level. Participants completed the cognitive tasks, and approximately 3 weeks later, they took part in the biology teaching session and practical. A related assessment was undertaken immediately after the practical (see Appendix). Performance on the practical assessment was also related to performance on a recent school generic

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science exam (across the areas of biology, chemistry and physics) conducted 1 month prior to the current study. This exam mainly involved retrieval of fact-based scientific knowledge.

Cognitive testing

The order of the executive function tasks was counterbalanced across participants. Testing was conducted in a quiet room in the participant's school.

Biology teaching session and practical

Pupils attended a 45-min teaching session facilitated by a PowerPoint presentation on the basics of DNA and forensic medical biology. Areas covered included the following: explanation of what DNA is and how similar we are to other species; the definition of base pairs in a DNA sequence and how these make us different to one another; the definition of an amino acid sequence and enzymes being 'chemical scissors' that recognize certain sequences; how DNA is isolated from cells and how much DNA we have in our cells and body; and basics about how DNA bands obtained using enzymes are unique to individuals and the importance of these in forensic science. The presentation was followed by a detailed description of the practical task to be completed and accompanied by a step-by-step set of instructions for isolation of DNA from biological material (bananas in the case of this class). Pupils were shown how DNA would be run on an agarose gel (on a PowerPoint slide) and how patterns of the bands would have to be matched, to find, for example, DNA found at a murder scene, and matched to the DNA from several different suspects. From the results, pupils had to decide which pattern of bands from different individuals matched the pattern found at the scene.

The class was divided into small groups for the practical that was supervised by three research assistants (facilitators). The pupils were supplied with a package containing all the materials required to isolate DNA using common household items such as salt, washing up detergent and alcohol. DNA isolation was completed by the pupils who mashed up a banana and added it to a water solution; added salt and washing up detergent; filtered the mixture through a coffee filter paper; and finally, alcohol was added to observe visible DNA strands. The facilitators circulated through the groups, encouraging discussion on the observations that were being made and questioning whether they understood the presented material. The pupils were then brought together, and the teaching facilitators discussed the results of the practical.

Biology assessment

This assessment comprised seven questions divided into two parts. Part 1 (Questions 1–4) addressed factual-based questions about information presented in the practical requiring a basic level of conceptual understanding. Part 2 (Questions 5–7) assessed conceptual understanding of the material presented in the practical requiring the participant to work out and solve problems based on the information learned (see Appendix A for the full list of questions).

Statistical Analyses

The four outcome measures from the CANTAB have been described as key measures within a wealth of research studies including those with adolescent samples (e.g. Curtis et al., 2002; Luciana & Nelson, 1998; Rhodes et al., 2005). With

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a sample of 56 participants, the use of four key measures was within the recommended guidelines for sufficient power to detect significant effects within a regression analysis (Tabachnick & Fidell, 2007).

In order to assess relationships between the key measures of executive function and performance of the study specific biology assessment, Pearson correlation analyses (two-tailed) were conducted. Performance on each part of the biology assessment was also correlated with performance on a recent school science exam (which assessed biology, physics and chemistry) to examine the relationship between the assessments developed in relation to the practical and routine school science exams. A multiple linear regression analysis was also conducted adjusting for age and with one key outcome measure for each of the four executive function tasks (SWM: Total BSE; SOC: Min Moves; Stop-Signal: SSRT; ID/ED: Stage Reached) in order to examine whether executive function is predictive of science achievement at this age.

RESULTS

Mean scores and standard deviations for the biology assessment and all tasks of executive function are illustrated in Table 1. The mean biology test score did not differ between girls and boys for either Part 1 (fact based) (girls: 55.2%, range = 29–100%; boys: 50%, range = 43–86%) or Part 2 (conceptual based) (girls: 68.7%, range = 22–100; boys: 63.6%, range = 0–89%) (all $p > .05$). Participants were therefore treated as one group for all subsequent analyses (Table 2).

Correlational analyses

Pearson correlations revealed a significant relationship between performance on the factual section (Part 1) of the biology assessment and number of Problems Solved in the Minimum Number of Moves on the Planning task alone ($r = 0.39$, $p = .003$). Correlational analysis between performance of Part 2 of the biology assessment that required conceptual understanding revealed significant correlations between performance on this assessment and both the number of Problems Solved in the Minimum Number of Moves on the Planning task ($r = 0.41$, $p = .002$) and BSEs on the SWM task ($r = -0.45$, $p < .001$).

Table 1. Summary of executive function data (means, *SD*)

Measure*	Mean (*SD*)
Biology assessment Part 1 (factual)	66.84% (15.67)
Biology assessment Part 2 (conceptual)	53.37% (18.76)
SWM Total Between Search Errors	28.37 (14.53)
SWM Strategy	33.58 (4.90)
SOC Problems Solved in Min Moves	8.09 (1.99)
SST SSRT (last half)	202.60 (68.60)
ID/ED Total Trials	87.22 (19.90)
ID/ED Errors at ED Shift	11.52 (9.90)
ID/ED Stage Reached	8.57 (0.80)

Note:
*SWM, Spatial Working Memory; SOC, Stockings of Cambridge; SST, Stop-Signal Task; ID/ED, attention set-shifting task; SSRT, stop-signal reaction time.

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Table 2. Correlational data for key measures

Measure	1	2	3	4	5
(1) Biology Part 1 (facts)					
(2) Biology Part 2 (conceptual)	.52***				
(3) Working memory: SWM Between Search Errors	−.25	−.445***			
(4) Planning: SOC Problems Solved in Min Moves	.39**	.405**	−.23		
(5) Inhibition: SST SSRT	−.18	.01	.01	−.14	
(6) Attention set-shifting: ID/ED Stage Reached	.08	.07	.16	.06	.02

Note:
**indicates significance at $p < .01$, ***$p < .001$; SWM, Spatial Working Memory; SOC, Stockings of Cambridge; SST, Stop-Signal Task; ID/ED, attention set-shifting task; SSRT, stop-signal reaction time.

In addition, a significant positive correlation emerged between a recent school-devised science test and Part 1 of the biology assessment ($r = 0.30$, $p = .028$). However, while a positive correlation emerged between the school science assessment and part 2 of our biology assessment, this was not statistically significant ($r = 0.16$, $p > 0.05$), therefore demonstrating the largely factual content of standard school assessments at this stage.

Regression analyses

A multiple linear regression analysis conducted with biology performance Part 1 (factual part) as the dependent variable with age and the four key measures of executive function as predictors revealed there was a significant model [$F(5, 54) = 2.58$, $p = .04$]. This model explained 13% of the variance in biology Part 1 performance ($R^2 = 0.21$, Adjusted $R^2 = 0.13$). Performance on the factual part of the biology assessment was predicted by the number of Problems Solved in Minimum Moves on the Planning task alone ($\beta = 0.33$, $p = .02$, R^2 change = 0.15).

A multiple linear regression analysis conducted with biology performance Part 2 (conceptual part) as the dependent variable with age and the four key measures of executive function as predictors revealed there was a significant model [$F(5, 54) = 4.48$, $p = .002$]. This model explained 24% of the variance in biology Part 2 performance ($R^2 = 0.31$, Adjusted $R^2 = 0.24$). Performance on the conceptual part of the biology assessment was predicted by both SWM total number of BSEs ($\beta = -0.40$, $p = .002$, R^2 change = 0.15) and the number of Problems Solved in Minimum Moves on the Planning task ($\beta = 0.31$, $p = .02$, R^2 change = 0.16). See Tables 3 and 4 for details of the final model.

DISCUSSION

This study reveals that conceptual understanding of biology is significantly predicted by the executive function abilities of working memory and planning. Both working memory and planning were predictive of a conceptual understanding of biology when other aspects of executive functions were controlled. Planning also predicted science learning in relation to an assessment that required retrieval of facts learned in the biology practical, showing that this executive ability may be important in learning facts but that a broader set of executive functions is critical when adolescents have to understand and apply information they are taught. Previous studies of executive functions have not differentiated between these aspects of

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Table 3. Standardized regression coefficients predicting biology factual scores

	B	*SE B*	β
Constant	76.75	86.37	
Age (months)	−2.51	6.00	−0.06
ID/ED	1.70	2.59	0.09
SOC	2.53	1.04	0.33*
SWM	−0.22	0.151	−0.19
SST	−0.03	0.03	−0.13

Note:
*indicates significance at $p < .05$; ID/ED, attention set-shifting task; SOC, Stockings of Cambridge; SWM, Spatial Working Memory; SST, Stop-Signal Task.

Table 4. Standardized regression coefficients predicting biology conceptual scores

	B	*SE B*	β
Constant	−14.65	96.14	
Age (months)	2.36	6.68	0.04
ID/ED	3.00	2.89	0.13
SOC	2.89	1.15	0.31*
SWM	−0.55	0.17	−0.40**
SST	0.012	0.03	0.05

Note:
*indicates significance at $p < .05$,
**$p < .01$; ID/ED, attention set-shifting task; SOC, Stockings of Cambridge; SWM, Spatial Working Memory; SST, Stop-Signal Task.

learning within their assessments. The current findings build on previous research by confirming the role of executive spatial working memory in science learning and extending to other aspects of executive function, namely planning ability. The current results contrast a recent study that highlighted the role of attention set-shifting in chemistry learning (Rhodes et al., 2012), suggesting that different aspects of executive functions may be important in the learning of different science subjects.

The findings of the present study build on reports in the literature of a relationship between executive working memory and science learning in a number of ways (Gathercole, Pickering, et al., 2004; Gathercole, Pickering, et al., 2004; Jarvis & Gathercole, 2003; Rhodes et al., 2012; St Clair-Thompson & Gathercole, 2006). First, the findings support reports in the literature of a relationship between spatial executive working memory and science learning (Jarvis & Gathercole, 2003; Rhodes et al., 2012; St Clair-Thompson & Gathercole, 2006), here showing that spatial executive working memory indeed predicts biology learning. Previous studies have linked working memory to performance on generic science class tests. Rhodes et al. (2012) reported that spatial executive working memory selectively predicted conceptual learning of chemistry with no significant relationships observed on an assessment requiring retrieval of facts. The current findings build and extend this finding—here, we similarly report that spatial executive working memory selectively predicts conceptual learning of biology. In the current study, however, planning ability predicted both factual and conceptual learning of biology.

The current findings do not support previous reports of a relationship between inhibition and science learning. St Clair-Thompson and Gathercole (2006) and

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Latzman et al. (2010) reported a relationship between inhibitory control and science learning. In the current study, inhibition was not correlated with science learning and was not a significant predictor of any aspect of the biology assessment within the regression analyses. The sample within the Latzman study included a broader and older age range than in the current study, which may help to address the discrepancy between the two findings, although it should be noted that the samples within the current study and St Clair-Thompson and Gathercole (2006) were of similar ages. There are two clear differences between the studies that may explain the discrepant findings. While both studies employed a Stop-Signal task, they varied in the modality tested. The current study employed an entirely non-verbal task, whereas the task employed in St Clair-Thompson and Gathercole (2006) was verbally based, requiring the participants to categorize words presented as animals and non-animals. As the science assessments in both studies require processing of verbal instructions and a verbal response, this could explain the differential findings. The current study also examined learning of a science discipline, whereas St Clair-Thompson and Gathercole (2006) examined attainment on a generic school science exam. Further research exploring different aspects of inhibition is warranted to clarify its role and the impact of task requirements in science learning.

Previous studies have highlighted the role of attention set-shifting in relation to generic science achievements (Latzman et al., 2010) and conceptual learning of chemistry (Rhodes et al., 2012). This relationship was not observed in the current study and suggests the possibility that different aspects of executive function are important in relation to different science disciplines. The current study instead highlights the role of cognitive planning in learning biology, whether this involves learning factual information or applying that information and showing an understanding of the subject. In the current study, linear regression analysis revealed that planning was predictive of performance on the biology assessment when other aspects of executive function were controlled. This builds on previous research showing the predictive role of both executive spatial working memory and planning in science learning. This pattern of findings highlights the important roles of a range of aspects of executive function in biology learning, emphasizing their broader role in conceptual learning of science in particular. The current findings support previous research that has highlighted the role of executive/strategic aspects of cognitive functioning in academic learning (e.g. Bull & Scerif, 2001; Christopher et al., 2012; St Clair-Thompson & Gathercole, 2006) and highlight the need for further research in a range of science disciplines in this area.

Accumulating evidence suggests that inhibition, working memory and shifting are separable processes (Diamond, 2013; Lehto et al., 2003; Miyake et al., 2000). The current findings support this, providing further evidence from child/adolescent samples (e.g. Lehto et al., 2003). The current findings also suggest that planning is a separable process from other aspects of executive function. Clearly, the planning task employed in the current study (CANTAB SOC task) requires the participant to hold a plan in short-term memory while executing that plan. The lack of significant correlation between the two tasks, however, suggests that this working memory component is different from that required in the SWM task, which requires the participant to hold and simultaneously update information in working memory involving additional processing of information in memory.

The current study has implications for science learning in classrooms, in relation to both teaching materials and practice. Participants in the current study were aged 12–13 years and in their second year of secondary school. Research suggests

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that the cognitive performance on executive function tasks of young people of this age is not yet at adult levels (e.g. Anderson et al., 2001). Importantly, we found that planning was predictive of factual learning of biology, and both planning and working memory were predictive of conceptual learning of this subject. The current findings suggest that in order to ensure optimal learning, developmental restrictions in working memory and planning should be taken into account when designing science curriculum/materials during the early secondary school years. There is some recent evidence that tailored working memory interventions may improve mathematics learning in the classroom in children with poor working memory (Holmes, Gathercole, & Dunning, 2009). The children in the Holmes et al. (2009) study undertook intensive working memory training involving adaptive training that maximally taxed working memory for 35 min within each school day for at least 20 days. The children showed significant improvements in working memory over this time, which was still evident at 6 months post-training assessment. The improvements further generalized to independent working memory tasks, and the study also reported a significant improvement in mathematics ability 6 months post training. A recent study similarly reported improvements in working memory following working memory training but found that these improvements did not extend to academic learning assessed on standardized tests of reading, arithmetic and mathematics 5 months after training (St Clair-Thompson, Stevens, Hunt, & Bolder, 2010). The authors concluded that the standardized tests used may not, however, have particularly loaded working memory. Research is warranted to examine the relationship between working memory training and science learning. It has been noted in the literature that science assessments can be particularly taxing on working memory (e.g. Danili & Reid, 2004), suggesting that training may improve performance on science tests.

While evidence is inconsistent for the role of working memory training on academic learning, the current findings suggest the possibility that a targeted intervention on discrete aspects of executive functions may improve science learning. In particular, the current study suggests that the areas that seem to be related to science learning include the ability to store and concurrently manipulate information and to think out solutions to problems before attempting to answer a problem. Teaching effectiveness may be optimized by tailoring the curriculum, teaching materials and practices to be targeted at the appropriate developmental level for these aspects of cognitive functioning. For example, teachers need to be aware that their pupils of this age may not yet have the ability to plan as expected of adults and may not be able to hold and manipulate a series of information in memory at the same time, to the same degree, as adults. Visual and written aids can help compensate developmental limitations in working memory. Planning limitations may be compensated for by encouraging pupils to stop and spend time working out a problem prior to carrying out a task when, for example, undertaking stages of an experiment.

Limitations

The current study was conducted at one developmental time point in early adolescence. Children commence learning science prior to the age at which they were assessed in the current study (aged mostly 13 years). Further research is warranted to identify if different aspects of executive functions, which are of course known to develop across childhood and into adolescence, are important at different developmental stages for science learning. In the current study, we

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specifically examined learning of biology in relation to executive functions. Findings of a role for planning in the current study may be specific to the biology discipline given a previous report that planning did not predict chemistry understanding or performance on a generic science grade exam when other aspects of executive function were controlled. Further research can identify if learning of different science disciplines is associated with different executive function requirements. The current study was able to go beyond the existing literature to show that a broader set of executive functions are important for strategic application and understanding of information learned in science classes.

Conclusions

The current findings build on existing research showing that relationships between science learning and cognitive functioning include, and go beyond, working memory to other aspects of executive functions, namely planning ability. The findings also show that spatial working memory ability and planning are predictive of science achievements in the area of biology. These findings may have implications for the way in which biology is taught in secondary schools.

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APPENDIX A

Q1 DNA is a mix of which bases? Please circle the right answer:

a) A and C
b) T and G
c) A, T, and C

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d) A, C, T, and G

Q2 What do we use chemical scissors for?

Q3 How long is your DNA? Please circle the right answer:
a) From here to George Square
b) From here to Motherwell
c) From here to next classroom
d) From here to the moon and back

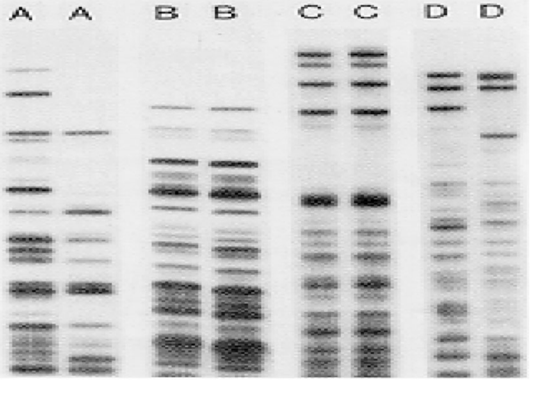
Q4 Name four things you can use DNA for
a)
b)
c)
d)

Q5 During World War II, there was displacement of children all around the UK. After the War, in order to match siblings to their parents, DNA was extracted and run on a gel to match brothers and sisters. Only identical twins have 100% DNA match, everyone else has 99.9% similarity. When the scientists analysed the data, they concluded several things. Please help them out!

i) Name 3 ingredients that scientists can use to extract DNA

a)
b)
c)

ii) Which sets of twins are identical? Please circle the correct answers



iii) Which set of data A, B, C, or D, has the DNA with the biggest DNA fragments?

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