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The Intercorrelation Between Executive Function, Physics Problem Solving, Mathematical, and Matrix Reasoning Skills: Reflections from a Small-Scale Experiment

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ABSTRACT

There are now many studies in the disciplines of psychology, neuroscience, and education concerning the contribution of executive function skills to the student learning process during school. Less work has been conducted on links with executive function skills and science, especially physics, compared to other school subjects. Here, we focus on physics problem solving skills because they are core elements of physics instruction in secondary education. In addition, teachers are concerned that students are not reaching the desired level of physics problems solving ability by the end of formal schooling. Physics problem solving skills seem to rely on strong mathematical skills, an area where there is robust evidence of links to executive function skills. In addition, matrix reasoning skills seem to impact executive function and mathematical skills. However, little is known about the complex links between these skills. Such work would elucidate cognitive processes underlying physics problem solving. In this small-scale study, 20 Greek high school students (Mage = 16.81 years, SD = 1.87) completed a battery of tasks measuring executive function, physics problem solving, mathematics, and matrix reasoning skills. The results indicated strong positive correlations between physics problem solving skills and mathematical skills. One of the executive function skills (i.e., switching) had significant positive correlations with physics problem solving and mathematical skills. Matrix reasoning skills positively correlated with physics problem solving and mathematical skills, and two of the executive function skills (i.e., switching and working memory). These findings suggest complex intercorrelations between executive function, physics problem solving, mathematical, and matrix reasoning skills. These findings could be the springboard for further studies involving more detailed measurements of these skills. In the long run, results from this type of work could lead to designing pedagogical interventions in physics education based on executive function skills to address teachers' concerns about students' acquisition of physics problem solving skills.

KEYWORDS

executive function skills, physics problem solving skills, mathematical skills, matrix reasoning skills, science achievement

Introduction

Teachers and parents are increasingly aware that cognitive skills are fundamental for learning across all school ages (e.g., Zelazo et al., 2016). There are now many studies showing links between executive function skills and mathematics and literacy knowledge (e.g., Blair & Razza, 2007; Bull et al., 2008). However, there is limited research concerning their influence on science learning, especially physics (Chen & Whitehead, 2009; Thibault & Potvin, 2018; Vosniadou et al., 2018). Recent

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studies suggest that executive function skills could have different links with different science domains. As such, it is important for work in this area to focus on a specific science discipline instead of science achievement in general (e.g., Mason & Zaccoletti, 2020; Rhodes et al., 2016). Consequently, we selected the science discipline of physics and, more specifically, physics problem solving.

We selected physics problem solving for this project for two key reasons. First, physics educators report that students' skills in physics problem solving are not reaching the desired level during their school years (e.g., Docktor et al., 2015; Reif, 1995). Second, there is a steady decrease in the percentage of students who select physics courses during secondary education (e.g., Docktor et al., 2015; Williams et al., 2003). As such, further studies are needed to examine possible cognitive factors that may affect students' physics problem solving skills and their preference for selecting physics courses.

There are a handful of studies linking executive function skills with physics reasoning (Brookman-Byrne et al., 2018; Vosniadou et al., 2018) or physics problem solving (Kozhevnikov et al., 2007). However, executive function skills might not be alone in contributing to physics problem solving. For example, mathematical skills could be important because physics content relies on arithmetic computations and manipulating algebraic equations (e.g., Heron & Meltzer, 2005). Executive function skills seem reliably correlated to mathematical skills (e.g., Partanen et al., 2020; Ropovik, 2014), and mathematical skills are reliably correlated to physics problem solving (e.g., Docktor et al., 2015). In addition, matrix reasoning skills seem to be correlated to executive function skills (e.g., Ellefson et al., 2021) as well as mathematics (e.g., Latzman et al., 2010). Given that multiple cognitive and academic skills might be contributing to physics problem solving, it is important to investigate how these skills intercorrelate with each other to better understand the cognitive processes that underlie physics problem solving skills. The findings from such studies could lead to physics education interventions based on cognitive skills that could enhance physics problem solving skills and better prepare students for challenging academic events.

Executive Function Skills

Although there is not one universal definition of executive function skills, they usually include the ability to evaluate different approaches, control internal or external stimuli, and design a plan for the solutions to everyday life or advanced problems (e.g., Ellefson et al., 2017). An ongoing debate exists about exactly what skills are included; there is consensus that the three core skills are working memory, inhibition, and switching (e.g., Diamond, 2013; Miyake et al., 2000). In addition, definitions can include higher-order skills like planning, reasoning, and problem solving (e.g., Collins & Koechlin, 2012; Lunt et al., 2012).

Briefly, working memory is conceptualised as maintaining information in mind while reprocessing that information, if needed. Working memory skills seem to be linked to solving higher-level mathematical equations (e.g., Baddeley & Hitch, 1994; Baddeley, 2002) and complicated science problems (e.g., Kozhevnikov et al., 2007; Rhodes et al., 2016). Inhibition involves the ability to cut off prepotent or intuitive responses and focus attention on the immediate task (Miyake et al., 2000). Inhibition can include blocking external ideas and personal thoughts as well as preventing individual experiences and notions from interfering with completing a task, focusing attention only on the immediate objectives of the task (e.g., Friedman & Miyake, 2004; Mason & Zaccoletti, 2020). Switching, also sometimes called cognitive flexibility, is viewed as the ability to move between different perspectives or information while completing a task (e.g., Miyake et al., 2000). Switching can include exploring alternate solutions when initial solutions stop working (e.g., Diamond, 2013).

The higher-order executive function skills are seen as hybrids because they often involve a combination of working memory, inhibition, and switching (e.g., Blums et al., 2017; Miyake & Friedman, 2012). Planning seems to correlate with an ability to focus on a target (inhibition), use organised approaches (working memory), and be able to try various strategies (switching) while solving a problem (e.g., Anderson, 2002; Partanen et al., 2020).

Taken together, these executive function skills are conceptually related to the type of activity involved in physics problem solving – understanding the problem, devising a plan, carrying out the plan, and looking back to evaluate the results and the plan (e.g., Docktor et al., 2015; Pólya, 1957).

Executive Function Skills and Physics

Executive function skills seem to be linked to science achievement (e.g., Mayer et al., 2014; Rhodes et al., 2014; Vosniadou et al., 2018). However, although there is some evidence that executive function skills work differently in different science domains (e.g., Mason & Zaccoletti, 2020; Rhodes et al., 2016), there are still many questions about how they intercorrelate with physics. As such, we focus here on investigating the role of executive function skills in physics, particularly in physics problem solving skills.

Some recent studies have looked at the correlation between executive function skills and naïve conceptions in physics. Briefly, naïve conceptions are ideas about physical phenomena formed based on interactions with the physical environment occurring before starting school. Naïve conceptions usually contradict the correct scientific theories. It could be that executive function skills help students transition from naïve to scientific thinking. For example, Kwon and Lawson (2000) found that scientific reasoning in adolescents (ages 13 to 17 years, $N = 210$) is linked to overcoming naïve conceptions and achieving conceptual change. Brookman-Byrne et al. (2018) found a correlation between inhibition skill and suppressing naïve conceptions of science in adolescents (ages 11 to 15 years, $N = 90$).

Suppressing naïve conceptions is essential for evolving physics reasoning, yet physics achievement in secondary education also requires the development of physics problem solving skills (e.g., Docktor et al., 2015; Hake, 1998). Taking the reliable links between executive function skills and the suppression of naïve conceptions, it seems essential to examine the correlation between executive function skills and physics problem solving skills (Kozhevnikov et al., 2007).

Generally, problem solving does seem to be a skill that is foundational to all science domains (e.g., Scherer & Tiemann, 2012). It is often seen as a process involving multiple cognitive tasks (e.g., Novick & Bassok, 2005; Rhodes et al., 2016; Scherer & Tiemann, 2012). Specific problem solving definitions do differ between cognitive psychology and education. Here, we take a more educational approach to physics problem solving, conceptualising it as the skills students need to solve physics problems.

Heron and Meltzer (2005) suggested completing physics problems involves conceptual understanding along with appropriate mathematical and reasoning skills. Several studies have investigated the links between physics problem solving skills, conceptual understanding, mathematical, and reasoning skills (Docktor et al., 2015; Hake, 1998; Huffman, 1997). Nevertheless, there are few studies looking at the role executive function skills play in this process. For example, Latzman et al. (2010) investigated the role of working memory, inhibition, and switching in science achievement in male adolescents (ages 11 to 16 years, $N = 151$). They found inhibition to be a strong predictor of science achievement. Kozhevnikov et al. (2007) found links between working memory and kinematics problems in university-aged students (ages 18 to 22 years, $N = 60$). Briefly, kinematics refers to the study of object motion without considering the forces acting on objects. They recommend that future studies looking at cognitive skills involved in physics should include mathematical and reasoning skills. In addition, they used several questions from the Force Concept Inventory that we also used but in its full version for the physics problem solving skills measurements.

Although there are only a few studies showing links between executive function skills, physics problem solving, and physics reasoning (see Table 1 for a summary), much more evidence is needed to establish a good understanding of the required cognitive skills. Establishing intercorrelations among executive function, physics problem solving, mathematical, and matrix reasoning skills, will enable a better understanding of the various cognitive skills involved in learning to solve physics problems.

Executive Function Skills and Mathematical Skills

Mathematical skills play an essential role in physics problem solving skills for adolescents (e.g., Docktor et al., 2015; Heron & Meltzer, 2005). In addition, the reliable link between mathematical skills and executive function skills has been replicated over the past decade (Anthony & Ogg, 2020; Nesbitt et al., 2015; Sung & Wickrama, 2018). Generally, working memory, inhibition, and switching are strong predictors of both mathematical skills and science achievement (e.g., Blair & Razza, 2007; Bull et al., 2008).

Working memory seems to play an essential role in mathematical skills throughout the school years (e.g., Bull & Lee, 2014; Cragg & Gilmore, 2014) and is important for mathematical outcomes (for a review, see Raghubar et al., 2010). Inhibition does correlate with mathematical skills (e.g., Bull & Scerif, 2001; Espy et al., 2004), but it depends on the specific skill studied.

Planning skills seem to correlate with mathematical skills (e.g., Gerst et al., 2017), but there are not as many studies looking into these links. Partanen et al. (2020) reported that working memory, reasoning, and planning correlated with solving mathematical problems among children (ages 6 to 16 years, $N = 62$) with low mathematical skills. These findings are in line with previous suggestions that low mathematical skills link with poor planning skills (e.g., Kroesbergen et al., 2003; Toll et al., 2011).
Vosniadou et al. (2018) found that inhibition is activated when primary school children (ages 9 to 12 years, $N = 133$) encounter mathematics problems requiring suppression of naïve conceptions, while switching is linked to overall mathematics performance. Switching seems to be important for shifting among different strategies and solutions when completing mathematical problems (Andersson, 2008; Van der Sluis et al., 2007).

Other Well-Established Links

There seems to be robust evidence that mathematical skills are correlated to physics problem solving (e.g., Kozhevnikov et al., 2007; McDermott & Redish, 1999; Thacker, 2003) and executive function skills (e.g., Blair & Razza, 2007; Bull et al., 2008; Vosniadou et al., 2018). However, only limited investigation has been done concerning the relative contributions of both executive function and mathematical skills to physics problem solving skills within individuals. In addition, matrix reasoning skills are reliably correlated to executive function skills (Blair et al., 2005; Ellefson et al., 2021) and academic performance in mathematics and physics (Ellefson et al., 2021; Vosniadou et al., 2018). Again, little is known about how these variables intercorrelate, making it important to study all these

Table 1

Summary of Existing Evidence of Correlations of Executive Function Skills with Physics Problem Solving and Physics Reasoning

Study	**Kwon & Lawson (2000)**	**Kozhevnikov et al. (2007)**	**Latzman et al. (2010)**	**Brookman-Byrne et al. (2018)**
Participants	*N* = 210 Ages 13-17 years	*N* = 60 Ages 18-22 years	*N* = 151 (male) Ages 11-16 years	*N* = 90 Ages 11-15 years
Executive Function Skills	Switching	Working memory	Working memory Inhibition Switching Planning	Inhibition
Other Cognitive Skills		Reasoning	Reasoning Problem Solving Sorting	
Physics Tasks	Air pressure concepts	Kinematics problem solving	Iowa Tests of Educational Development	Items evoking naïve conceptions
Key Findings	Inhibition correlates with conceptual change	Correlation between spatial visualisation ability & solving kinematics problems	Inhibition and switching correlate with science achievement	Inhibition correlates with suppression of naïve conceptions

Notes. Test of air pressure concepts (Kwon & Lawson, 2000), Kinematics Problems Solving Test (Hestenes et al., 1992), Iowa Tests of Educational Development (Forsyth et al., 2001; Hoover et al., 2001).

skills together (Docktor et al., 2015; Kozhevnikov et al., 2007).

The Current Study

Establishing the intercorrelations between executive function, physics problem solving, mathematical, and matrix reasoning skills is important for better understanding the cognitive processes that underlie physics achievement. As such, we designed this small-scale study as a pilot to a larger project. Our main research question concerns how well these skills intercorrelate in Greek high school students. Based on previous findings, we do expect to find statistically significant correlations.
In the Greek curriculum, students learn advanced concepts in physics and mathematics during the high school years. At the beginning of high school (Year 11, 15-year-olds), students decide between courses that include physics content or not. Consequently, this age is important for understanding the cognitive skills linked to physics problem solving.

We administered our study in school settings to have a fuller range of individual abilities. Collecting multiple cognitive and academic measures is time consuming, so it is important to first establish how well any given task can be administered in school settings. For executive function skills, there are multiple ways to look at individual performance. We focus on three key metrics: accuracy, response time, and efficiency (i.e., a combined accuracy-time metric). Commonly used executive function tasks often have skewed accuracy rates (due to ceiling effects) and response times (due to longer times). The efficiency metric does a good job of balancing out the two, but fully understanding performance requires looking at all three metrics.

Method

Participants

We recruited 15- to 17-year-old high school students from Greece ($N = 20$, $M_{age} = 16.81$ years, $SD_{age} = 1.87$). All the participants were native Greek speakers. They completed the tasks online due to Covid-19 restrictions. We recruited students from a Greek school where we had existing contacts to complete tasks administered only online. In Greece, adolescents are familiar with using computers.

The University of Cambridge Faculty of Education ethics committee reviewed our research protocol. The school staff sent invitations to 236 students of the appropriate age for our study. From the 94 students who volunteered to participate, the school staff selected 20 randomly to complete the study. Those students and their parents completed written consent to participate in the study. Students used an anonymous code from their school when completing the tasks. There were no exclusions from the data analysis as all participants completed all elements of the study.

Design and Procedures

To increase the reliability and reproducibility of our findings, we used tasks commonly used to measure executive function, physics problem solving, mathematical, and matrix reasoning skills. All tasks were administered online in Greek (see https://osf.io/gycq5/ for additional information).

The selected tasks are language sparse, allowing them to be more easily adapted to the Greek language setting. The instructions for the executive function and the matrix reasoning skills tasks were written in Greek by one of the researchers (a native Greek speaker). Two native Greek speakers completing their doctoral studies at the University of Cambridge reviewed the translations before we ran the study. More detailed translations were needed for the physics problem solving and the mathematical skills tasks. As those translations are task-specific, those details are included with the task descriptions below.

Due to needing to administer many tasks, we divided them into three sessions administered across three days to reduce participant screen usage and fatigue. The first session lasted 1 hour and included the executive function and matrix reasoning skills tasks and a short demographic questionnaire. The second session lasted 2 hours (with multiple breaks) and included the physics problem solving skills tasks. The third session lasted 1 hour and included the mathematical skills tasks.

Materials

Executive Function Skills. We used PsychoPy™ (Peirce et al., 2019; Peirce & MacAskill, 2018) to programme and administer the executive function skills tasks. The tasks included inhibition (Fish Flanker task; Rueda et al., 2004; Ellefson et al., 2021), switching (Figure Matching task; Ellefson et al., 2006), working memory (Spatial Span task; Corsi, 1972; Ellefson et al., 2017), and planning (Tower of London task; Shallice, 1982) (see Table 2 for more details). These experimental tasks have been used extensively in previous executive function skills research and are well-accepted measurements (e.g., Ellefson et al., 2017; Kwon & Lawson, 2000). Participants were instructed to make their answers as quickly as possible while still being accurate. Accuracy and response time were recorded for each trial in every task and, together with efficiency, were used in the analysis, following the method mentioned by Ellefson et al. (2017, 2021; see Table 3).

Matrix Reasoning Skills. We used the Matrix Reasoning Item Bank (MaRs-IB; Chierchia et al., 2019) to measure matrix reasoning skills. This task is analogous to Raven's Progressive Matrices (Raven & Raven, 2003), a well-established measure of matrix reasoning and non-verbal intelligence. The MaRs-IB is faster and easier to administer online, with all items and instructions openly available online (https://osf.io/g96f4/). Each item includes a 3 x 3 matrix, with abstract shapes/images in eight of the nine cells. The last cell is empty (and positioned at the bottom right-hand corner). We instructed participants to choose from four available options, a shape/image that best fits into the empty cell. Again, accuracy and response time were collected for each trial, and we used computed accuracy, response time, and efficiency scores (see Table 3).

Physics Problem Solving Skills. We used three different tasks to measure physics problem solving (see Table 4): Force Concept Inventory (Hestenes et al., 1992), Test of Understanding Graphs in Kinematics (Zavala et al., 2017), and Determining and Interpreting Resistive Electric Circuit Concepts Test (Engelhardt & Beichner, 2004). These tasks have been reviewed by physics experts as including appropriate physics concepts and problems and have been used extensively in other studies of physics and are reliable measures (e.g., Beichner, 1994; Hake, 1998; Zavala et al., 2017). These tasks were developed by PhysPort™ and are administered through their website (https://www.physport.org). We used all three tasks with no adaptations to the items. The Force Concept Inventory, and the Determining and Interpreting Resistive Electric Circuit Concepts Test have already been translated and used in Greek settings (Greek translations available on https://www.physport.org). We submitted a Greek translation of the Test of Understanding Graphs in Kinematics to PhysPort™. They reviewed and approved the translation to be used in our study. The total number of correct answers was computed for each task and used in the analyses.

Mathematical Skills. We used the PSAT™10 (Preliminary Scholastic Aptitude Test, College Board™, 2015; see: https://collegereadiness.collegeboard.org/psat-nmsqt-psat-10/practice/full-length-practice-tests) to measure mathematical skills. These tasks were developed as formal academic

Table 2

Tasks for Executive Function and Matrix Reasoning Skills

Skill	Task	Items	Duration (minutes)	Participant Responses
Executive Function Skills				
Inhibition	Fish Flanker	72	7	Accuracy: Hits/misses/false rejects (including buttons pressed) Response Time
Switching	Figure Matching	128	9	Accuracy: Number correct trials (including buttons pressed) Response Time
Working Memory	Spatial Span	32	5-10	Accuracy: Number correct trials (including which boxes are clicked) Response Time: (for each click and for completing the full sequence)
Planning	Tower of London	12	10	Accuracy: Number correct trials (including number of moves in each trial) Response Time
Matrix Reasoning Skills				
Matrix Reasoning	MaRs-IB	80	15-40	Accuracy: Number correct trials (including buttons pressed) Response Time

Notes. Fish Flanker (Rueda et al., 2004; Ellefson et al., 2021), Figure Matching (Ellefson et al., 2006), Spatial Span (Corsi, 1972; Ellefson et al., 2017), Tower of London (Shallice, 1982), MaRs-IB (Chierchia et al., 2019).

Table 3

Metrics for Executive Function and Matrix Reasoning Skills

Metric	Formula
Accuracy	Correct trials/overall number of trials
Response Time	Response time for correct trials
Efficiency	Accuracy/response time in correct trials

assessments for high school students (ages 15 to 17 years) in the United States by College Board® (https://www.collegeboard.org). It includes three standardised tasks (see Table 4) that are used in many countries outside of the United States, including Greece. We used all three tasks with no adaptations to the items. We asked three mathematics teachers from Greece, who are all teaching mathematics both in Greek and in English for British examination systems (e.g., A-Levels) to translate the instructions from English to Greek. The total number of correct answers was computed for each task and used in the analyses.

Table 4

Tasks for Physics Problem Solving and Mathematical Skills

Skill	Measure	Items	Duration (minutes)	Content
Physics Problem Solving Skills				
Forces	Force Concept Inventory	30	30	Newtonian mechanics and kinematics
Kinematics	Test of Understanding Graphs in Kinematics	26	45	Kinematics
Electricity	Determining and Interpreting Resistive Electric Circuit Concepts Test	29	30	Electricity and electrical circuits
Mathematical Skills				
Algebra	Heart of Algebra	16	20	Linear equations and systems
Data Analysis	Problem Solving and Data Analysis	16	20	Complex problems, interpreting and synthesising data
Advanced Maths	Passport to Advanced Mathematics	14	20	Complex equations, interpreting and building functions

Notes. Force Concept Inventory (Hestenes et al., 1992), Test of Understanding Graphs in Kinematics (Zavala et al., 2017), Determining and Interpreting Resistive Electric Circuit Concepts Test (Engelhardt & Beichner, 2004), Heart of Algebra (College Board®, 2015), Problem Solving and Data Analysis (College Board®, 2015), Passport to Advanced Mathematics (College Board®, 2015). All the physics tasks were developed by the American Association of Physics Teachers, in collaboration with Kansas State University, and funding from the United States National Science Foundation. All items for these tasks are in multiple choice format.

Results

The small sample size and the nature of some of the measures produced non-normal data distributions (see Table 5 for descriptive statistics). As such, we ran Spearman's non-parametric correlations (r_s; Field, 2018) and created histograms and scatter plots among the observed variables using the *corrplot* (Wei & Simko, 2021) package within the R statistical computing and graphics software (R core team, 2019). For simplicity, the results are reported using the skill names from Tables 2 and 4.

Cognitive Skills Are Intercorrelated

Most intercorrelations among the cognitive skills metrics were medium effect sized or larger. However, many were not statistically significant. For accuracy, correlations between inhibition and working memory ($r_s(19) = .45, p = .05$) and between working memory and matrix reasoning ($r_s(19) = .49, p = .03$) were statistically significant. For response times, correlations between switching and planning ($r_s(19) = .54, p = .01$), between inhibition and planning ($r_s(19) = .47, p = .04$), and between switching and matrix reasoning ($r_s(19) = .47, p = .04$) were statistically significant. For efficiency scores, correlations between switching and planning ($r_s(19) = .46, p = .04$) and between switching and matrix reasoning ($r_s(19) = .47, p = .05$) were statistically significant.

Physics Problem Solving and Mathematical Skills Are Strongly Intercorrelated

There were strong positive intercorrelations among the physics problems solving and mathematical tasks (Figures 1, 2, and 3 show the same finding for these skills). More specifically, correlations ranged from $r_s(19) = .64$ to .92 ($p < .001$).

Some Cognitive Skills and Physics Problem Solving Are Intercorrelated

Again, the effect size measures of many intercorrelations between the cognitive skills and the physics problem solving skills were medium effect sized, but most were not statistically significant. For accuracy, matrix reasoning was significantly correlated with forces ($r_s(19) = .52$, $p = .02$), kinematics ($r_s(19) = .45$, $p = .05$), and electricity ($r_s(19) = .59$, $p = .01$). For response time, matrix reasoning was significantly correlated with forces ($r_s(19) = .60$, $p = .01$), kinematics ($r_s(19) = .56$, $p = .01$), and electricity ($r_s(19) = .64$, $p = .001$). Switching was significantly correlated with forces for both response time ($r_s(19) = .50$, $p = .02$) and efficiency ($r_s(19) = .52$, $p = .02$).

Some Cognitive Skills and Mathematical Skills Are Intercorrelated

Again, the effect size measures of many intercorrelations between the cognitive skills and the mathematical skills were medium effect sized, but most were not statistically significant. For accuracy, matrix reasoning was significantly correlated with algebra ($r_s(19) = .52$, $p = .02$), data analysis ($r_s(19) = .50$, $p = .03$), and advanced maths ($r_s(19) = .63$, $p = .001$). For response time, matrix reasoning was significantly correlated with algebra ($r_s(19) = .59$, $p = .01$), data analysis ($r_s(19) = .50$, $p = .02$), and advanced maths ($r_s(19) = .60$, $p = .001$). Switching was significantly correlated with algebra for both response time ($r_s(19) = .51$, $p = .02$) and efficiency ($r_s(19) = .50$, $p = .02$).

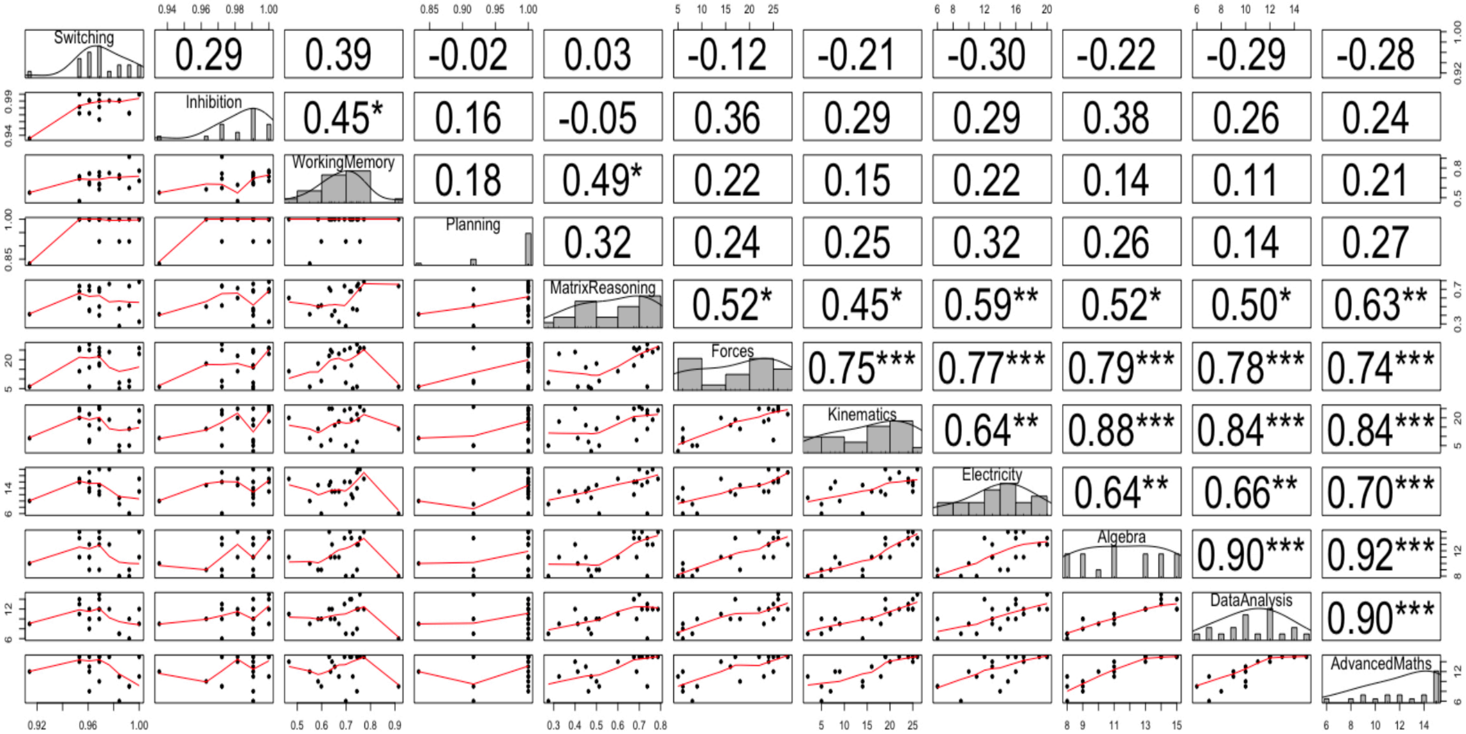
Table 5

Descriptive Statistics for All Measures (N = 20)

Task	Mean	SD	Median	Min	Max
Cognitive Tasks: Accuracy					
Switching	0.97	0.02	0.96	0.91	1.00
Inhibition	0.98	0.02	0.99	0.93	1.00
Working Memory	0.68	0.09	0.69	0.46	0.91
Planning	0.98	0.04	1.00	0.83	1.00
Matrix Reasoning	0.58	0.16	0.63	275	0.78
Cognitive Tasks: Response Time (seconds)					
Switching	1.29	1.37	0.95	0.63	7.05
Inhibition	0.50	0.09	0.48	0.39	0.79
Working Memory	0.78	0.48	0.61	0.39	2.55
Planning	1.47	0.45	1.33	0.94	2.55
Matrix Reasoning	10.74	4.70	11.51	1.35	17.39
Cognitive Tasks: Efficiency					
Switching	1.33	1.44	0.98	0.63	7.40
Inhibition	0.50	0.09	0.49	0.39	0.79
Working Memory	0.22	0.15	0.15	0.07	0.77
Planning	1.50	0.47	1.36	0.94	2.55
Matrix Reasoning	17.87	5.97	17.36	4.91	28.52
Physics Problem Solving Tasks					
Forces	17.70	8.28	20.00	5.00	28.00
Kinematics	16.35	7.89	18.50	2.00	26.00
Electricity	13.90	4.06	14.5	6.00	20.00
Mathematical Tasks					
Algebra	11.55	2.52	11.00	8.00	15.00
Data Analysis	10.65	2.50	10.50	6.00	15.00
Advanced Maths	12.45	2.84	13.50	6.00	15.00

Figure 1

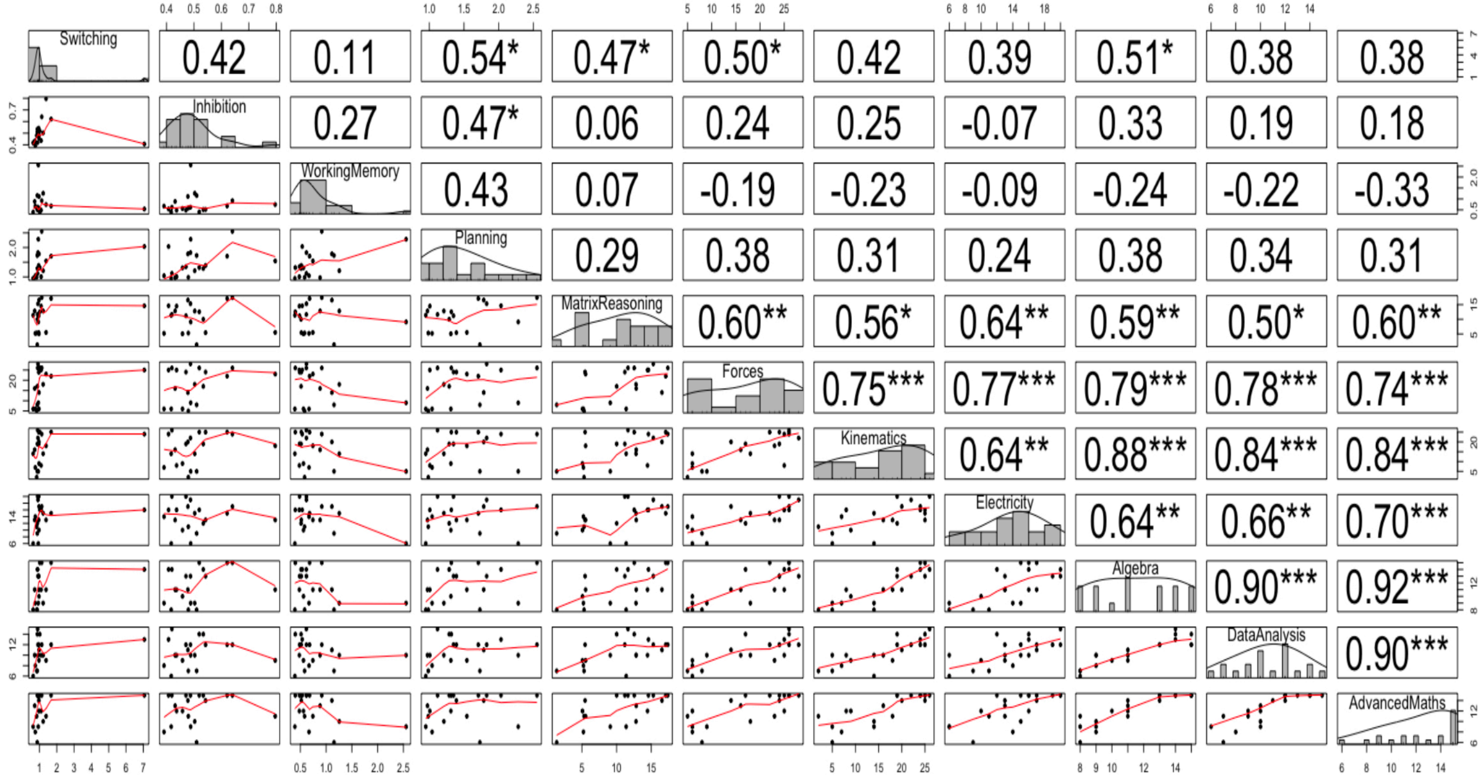
Spearman's Correlations, Histograms, and Scatterplots for the Accuracy Scores of the Executive Function and Matrix Reasoning Skills Tasks and the Scores in Physics Problem Solving and Mathematical Skills Tasks.



Notes. *$p < .05$, **$p < .01$, ***$p < .001$. Forces: Force Concept Inventory, Kinematics: Test of Understanding Graphs in Kinematics, Electricity: Determining and Interpreting Resistive Electric Circuit Concepts Test, Algebra: Heart of Algebra, Data Analysis: Problem Solving and Data Analysis, Advanced Maths: Passport to Advanced Mathematics.

Figure 2

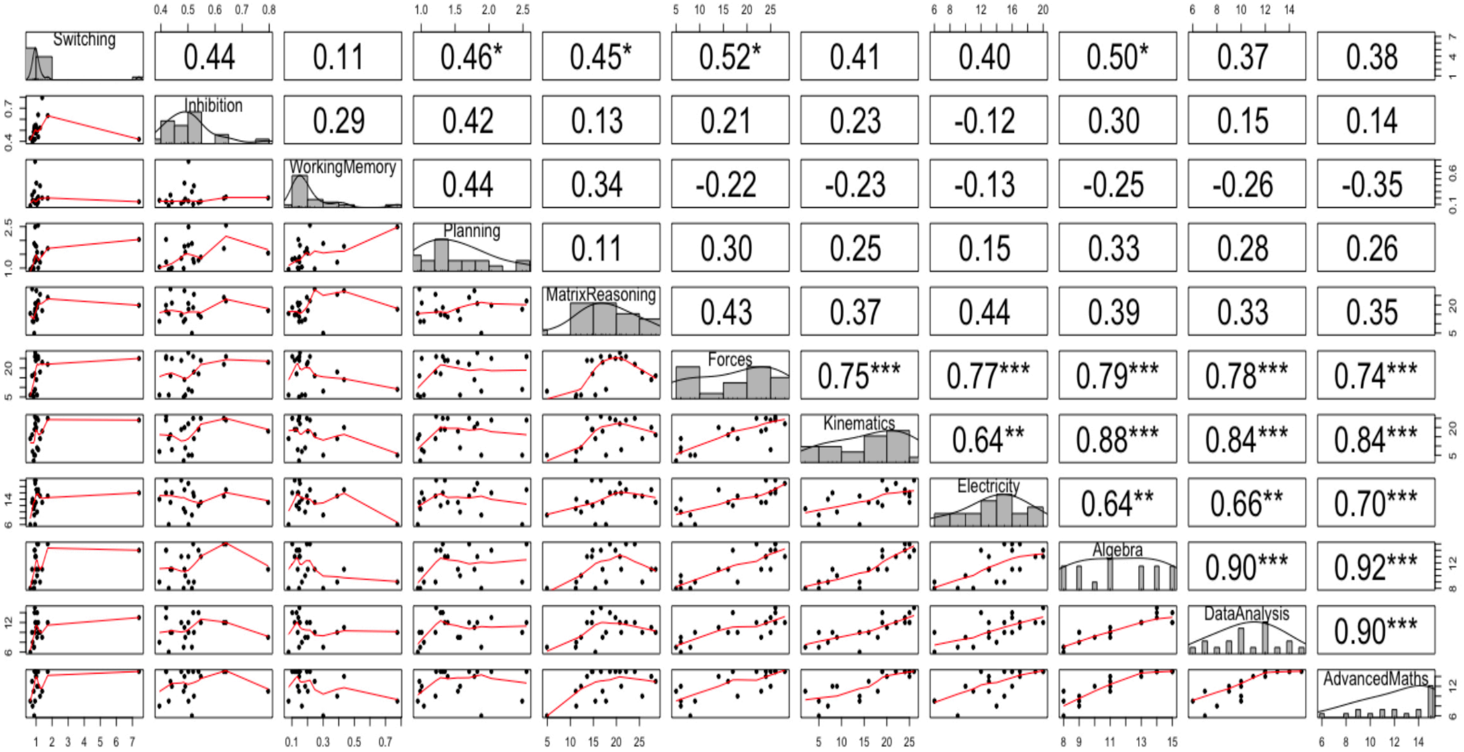
Spearman's Correlations, Histograms, and Scatterplots for the Response Time Scores of the Executive Function and Matrix Reasoning Skills Tasks and the Scores in Physics Problem Solving and Mathematical Skills Tasks.



Notes. *$p < .05$, **$p < .01$, ***$p < .001$. Forces: Force Concept Inventory, Kinematics: Test of Understanding Graphs in Kinematics, Electricity: Determining and Interpreting Resistive Electric Circuit Concepts Test, Algebra: Heart of Algebra, Data Analysis: Problem Solving and Data Analysis, Advanced Maths: Passport to Advanced Mathematics.

Figure 3

Spearman's Correlations, Histograms, and Scatterplots for the Efficiency Scores of the Executive Function and Matrix Reasoning Skills Tasks and the Scores in Physics Problem Solving and Mathematical Skills Tasks.



Notes. *$p < .05$, **$p < .01$, ***$p < .001$. Forces: Force Concept Inventory, Kinematics: Test of Understanding Graphs in Kinematics, Electricity: Determining and Interpreting Resistive Electric Circuit Concepts Test, Algebra: Heart of Algebra, Data Analysis: Problem Solving and Data Analysis, Advanced Maths: Passport to Advanced Mathematics.

Discussion

The findings indicate that there is a significant correlation among the Figure Matching task for switching, the Force Concept Inventory physics problem solving skills task, and the Heart of Algebra mathematical skills task, when testing for response time and efficiency. These findings support our central hypothesis concerning an intercorrelation among executive function, physics problem solving, and mathematical skills. All the mathematical skills tasks were significantly correlated with all the physics problem solving skills tasks, which is in line with the findings of previous studies (Docktor et al., 2015; Hake, 1998; Huffman, 1997). Matrix reasoning skills exhibited a significant correlation with mathematical and physics problem solving skills when testing for accuracy and response time, following the findings of former studies (Ellefson et al., 2021; Vosniadou et al., 2018). In addition, as reported in previously conducted studies (e.g., Blair et al., 2005; Ellefson et al., 2021), a link between matrix reasoning skills, inhibition, planning, and switching is seen through the results when testing for accuracy, response time and efficiency. These results align with our hypotheses about the intercorrelation among executive function, physics problem solving, mathematical, and matrix reasoning skills.

Implications for Future Research

Through the results of our small-scale experiment, it seems our tasks could provide measurements for the intercorrelation among executive function, physics problem solving, mathematical, and matrix reasoning skills. The small sample size limits the generalisability of the results, yet there is an indication of a possible intercorrelation among the selected variables. Several participants commented that the spatial span task for working memory did not operate properly. Therefore, it needs to be re-programmed before any future usage.

To substantively investigate the contribution of executive function skills to physics problem solving skills, future research should include the cognitive skills involved in understanding physics concepts, along with demographic variables like age or number of science subjects being studied (e.g., Docktor et al., 2015; Heron & Meltzer, 2005; Kozhevnikov et al., 2007).

Building on these promising results, we are running a larger-scale study to investigate the link between executive function and physics problem solving skills. The study will explore three research questions with a sufficiently powered sample. First, do executive function skills predict the understanding of physics concepts and physics problem solving skills in 15- to 17-year-old adolescents after controlling for age, chosen discipline, and matrix reasoning skills? Second, to what extent do mathematical skills mediate the link between executive function skills, the understanding of physics concepts, and physics problem solving skills in 15- to 17-year-old adolescents after controlling for age, chosen discipline, and matrix reasoning skills? Third, do executive function skills affect 15- to 17-year-old adolescents' decisions to select a science discipline after controlling for age, mathematical skills, the understanding of physics concepts, physics problem solving, and matrix reasoning skills?

We plan to use structural equation modelling so that we can investigate the complex intercorrelations between these variables more effectively. We expect that such a study will allow us to thoroughly explore the contribution of executive function skills to physics problem solving skills, adding new knowledge to the ongoing investigation concerning the role of executive function skills in science achievement and students' low preference in selecting science courses.

Following open science practices, the preregistration for the larger-scale study is available online (https://doi.org/10.17605/OSF.IO/BA2HV). The site includes a complete description of the methods and statistical analysis as well as their justification. Our planned analyses were guided by the findings of this small-scale experiment.

Implications for Practice

Establishing the role of executive function skills in physics problem solving skills could contribute to the broader investigation of the links between executive function skills and science achievement. Although our research might not cause immediate changes to the physics curriculum (we did not apply any new interventions), it will offer the chance to further our understanding of the role of executive function skills in physics problem solving. The findings could be the springboard for more extensive investigations. In the long run, those more extensive investigations could lead to designing pioneer interventions based on the role executive function skills play in learning physics at the secondary school level. Such interventions could address concerns teachers have about students needing more effective physics problem solving skills.

Conclusions

Physics problem solving is one critical part of physics education and is a fundamental skill for learning physics at an advanced level (e.g., Heron & Meltzer, 2005). However, physics educators report that students lack sophisticated physics problem solving skills during the school years (Docktor et al., 2015; Reif, 1995). Although there is some evidence that executive function skills might help with science achievement (Brookman-Byrne, 2018; Mason & Zaccoletti, 2020; Potvin et al., 2014; Rhodes et al., 2016), there is a need for further research to examine the possible impact executive function, mathematical, and matrix reasoning skills all have on physics problem solving. The findings of this small-scale experiment suggest significant positive intercorrelations among executive function, physics problem solving, mathematical, and matrix reasoning skills, respectively. Further investigations are needed to better understand the exact impact among these intercorrelations. Those studies should use larger samples and statistical techniques that investigate shared and unique variance and test more complex links. In addition, other variables like students' age, chosen discipline (science vs non-science), and understanding of physics concepts will further elucidate the cognitive skills underpinning physics problem solving.

CRediT author statement

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R scripts and data for this manuscript are openly available from https://osf.io/gycq5/.

Disclosure Statement

The authors reported no potential conflict of interest. This work has been presented to the following conferences as poster presentations: Wolfson Research Event 2022, Mathematical Cognition and Learning Society 2022, Australian Science Education Research Association Conference 2002, and Kaleidoscope 2022. It is also part of the PhD work of Konstantinos Tsigaridis.

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