Electronic Journal of Research in Educational Psychology · ejrep
EDUCATION & PSYCHOLOGY I+D+i Research, Innovation and Solutions on-line®
Ilustre Colegio Oficial de Psicología de Andalucía Oriental

Pre-University Tuition in Science and Technology can Influence Executive Functions

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Abstract

Introduction. Scientific and technological areas include tuition based on highly visuo-spatial specialization and problem solving. Spatial skills and problem solving are embedded in a curriculum that promotes understanding of Science and technical subjects. These abilities are related to the development of executive functions (EFs). We aim to assess whether students who have studied Science and Technology branches in the High School present improved EFs involved in spatial reasoning and problem solving.

Method. We assessed six different EFs in two groups of students: Science and Technology students (ST group) and students enrolled in the first course of Psychology whose pre-university studies were not oriented towards science and technology (No-ST group). The EFs tests that we applied in the ST and No-ST groups assessed spatial working memory, planning, inhibition, mental flexibility, verbal and abstract reasoning.

Results. The study revealed that spatial working memory and planning were significantly better in the ST group comparing with the No-ST group. The No-ST group presented more impulsivity. There were no differences between the groups in the rest of EFs assessed.

Conclusion: Pre-university studies that include Science and Technology subjects can influence EFs by improving planning and spatial working memory, as well as leading to less impulsivity.

Keywords: Engineering; Spatial working memory; Planning; Inhibition; Mental Flexibility.

Received: 04/11/14 *Initial Acceptance: 05/08/14* *Final Acceptance: 11/05/14*

La Enseñanza pre-Universitaria en Ciencia y Tecnología Puede Influir en las Funciones Ejecutivas

Resumen

Introducción. Las áreas científicas y tecnológicas incluyen una enseñanza basada en una alta especialización viso-espacial y de resolución de problemas. Estas capacidades espaciales y de resolución de problemas están integradas en un plan de estudios que promueve la comprensión de asignaturas científicas y técnicas y están relacionadas con el desarrollo de las funciones ejecutivas (FE). Nuestro objetivo es evaluar si los estudiantes que han estudiado las ramas de Ciencia y Tecnología en los estudios pre-universitarios presentan mejores FE implicadas en el razonamiento espacial y la resolución de problemas.

Método. Se evaluaron seis FE diferentes en dos grupos de estudiantes: estudiantes de Ciencia y Tecnología (grupo ST) y estudiantes matriculados en el primer curso de Psicología con estudios pre-universitario no orientados hacia la ciencia y la tecnología (grupo No-ST). Evaluamos la memoria de trabajo espacial, la planificación, la inhibición, la flexibilidad mental y el razonamiento verbal y abstracto en ambos grupos.

Resultados. El estudio reveló que la memoria espacial y la planificación fueron significativamente mejores en el grupo ST en comparación con el grupo No-ST. El grupo No- ST presenta más impulsividad. No hubo diferencias entre los grupos en el resto de los FE evaluadas.

Conclusión. Los estudios pre-universitarios de ciencia y tecnología pueden influir en las FE mediante la mejora de la planificación y la memoria de trabajo espacial, así como en una menor impulsividad.

Palabras Clave: ingeniería; memoria de trabajo espacial; planificación; inhibición ; flexibilidad mental.

Recepción: 11/04/14 *Aceptación inicial: 08/05/14* *Aceptación final: 05/11/14*

Introduction

Scientific and technological areas, such as mathematics, engineering or physics, include tuition based on highly visuo-spatial specialization and problem solving. In fact, spatial skills and problem solving are embedded in a curriculum that promotes a holistic understanding of scientific and technical subjects (Marunic & Glazar, 2012). Researchers from science indicate that spatial ability is necessary to succeed in specific domains, such as mathematics, as well as in architecture, cartography, chemistry, physics and engineering (Diezmann & Lowrie, 2012; Coleman & Gotch, 1998). Therefore, a great deal of the research on science and mathematics focuses on how spatial skills can predict students' success in comprehending particular concepts (Sorby, 2001). Together with spatial ability, problem solving is a skill required for success in science and mathematics. This ability includes planning the design, construction, evaluation and redesign of a solution for a given problem in any topic of the disciplines (Stamovlasis & Tsaparlis, 2005; Lawson, 2004). These processes that enable the planning, control and monitoring of complex, goal-directed behavior and thoughts are often referred to as executive functions (EFs) (Seiferth, Thienel, & Kirchner, 2007).

EFs are of relevance because they mediate learning processes (St. Clair-Thompson, Stevens, Hung, & Bolder, 2010; Rabin, Fogel, & Nutter-Upham, 2010). Therefore, these EFs consist of many specific cognitive abilities that are higher order skills that influence performance on other cognitive tasks. These higher cognitive abilities include, but are not limited to, mental flexibility (the ability to maintain and shift set), planning (the ability to manage current task demand in an organized sequence of events), response inhibition (the ability to stop one's own behavior at the appropriate time), working memory (the ability to hold and manipulate information in mind), organizational skills, reasoning, problem-solving, and abstract thinking (the ability of reaching conclusions through the use of symbols or generalizations) (Alvarez & Emory, 2006).

Although the frontal cortex was initially seen as a discrete module where different EFs were thought to reside in isolation (Luria, 2002). Nowadays, it is becoming increasingly clear that EFs are supported by several brain areas forming complex functional networks (Enriquez-Geppert, Huster, & Herrmann, 2013).

Some of these EFs can be influenced by the type of instruction we are exposed to. It has been shown that spatial-related experience, common in engineering and science, has a great impact on the development of spatial working memory. In fact, several experiments have shown that applications designed to improve basic spatial ability have the effect of increasing spatial working memory in engineering and science students and general population (Carbonell, Saorín, de la Torre, & Marrero, 2011). Regarding pre-university studies, researchers point out that it is possible to improve spatial skills and problem solving through science, mathematics and drawing classes (Fantz, Siller, & DeMiranda, 2011). These types of learning experiences help students to become familiar with new information through problem solving in order to easily remember the new concept to construct mental images and, therefore, could contribute to the development of planning, flexibility and spatial working memory.

Aims and hypothesis

We aim to assess whether students who have studied Science and Technology branches in the High School and are enrolled in the first course of their university studies present improved EF that are related to spatial reasoning and problem solving with respect to students that did not received this specific technological tuition. For this purpose, we assess six different EFs in Science and Technology students and students enrolled in the first course of Psychology whose pre-university studies were not oriented towards science and technology. The EFs that we assess are spatial working memory, planning, inhibition, mental flexibility, verbal reasoning and abstract reasoning. Based on the previous knowledge, we hypothesize that students of Science and Technology would present better spatial working memory and planning ability.

Method

Participants

One hundred forty students (86 female and 54 male, age mean=19.10 years STD=1.25), all undergraduate students in the first year of their studies at the University of Oviedo (Spain), participated in the study in return for course credit. All participants had normal or corrected-to-normal vision.

http://dx.doi.org/10.14204/ejrep.34.14016

The study was conducted with 57 students that studied Science and Technology branches in the High School (ST Group) and 83 students that study Psychology, whose pre-university studies were not oriented towards science and technology (No-ST Group). All procedures and measures were approved by the Ethics Committee of the Faculty of Psychology (University of Oviedo).

Measures

Spatial working memory

To test the role of spatial working memory, we used the *Figures' Mental Rotation (FMR) test* (Yela, 1968), the Spanish adaptation of the Rotation of Solid Figures (Thurstone & Thurstone, 1949), in which the ability to rotate solid figures mentally was assessed. It consists of 21 items, each one presenting a complex three-dimensional solid figure and five choice figures. For each item, the participant has to choose which one of the choice figures represents a form matching the mentally rotated target. There was a time limit of 5 min for solving this test. We recorded the number of correct responses.

Mental Flexibility

Wisconsin Card Sorting test (WCST) (Heaton, Chelune, Talley, Kay, & Curtiss, 1993) was used to assess mental flexibility, the ability to display flexibility in the face of changing schedules of reinforcement. We used a computerized version of the task. Initially, a number of stimulus cards were presented to the participant. The participants were told to match the cards, but not how to match; however, they were told whether a particular match is right or wrong. The test included 64 trials. The number of correct matches was recorded.

Planning

We used a computerized version of the *Tower of Hanoi test* (TOH) (Welsh, 1991). We assess the execution of the subjects in the five disks version of the task. The task consists of three rods and five discs of subsequently smaller size. The objective of the task is to move the entire stack to another rod, obeying the following rules: only one disk can be moved at a time, each move consists of taking the upper disk from one of the rods and sliding it onto another rod and on the top of the other disks that may already be on the rod and no disk can be placed on top of a smaller disk. Planning is a key component of the problem solving skills necessary to achieve this objective. The number of disks movements made by the participants and the total time spent in the task were registered.

Inhibition

The inhibitory control requires stopping a response when prompted. This EF was assessed by an action*/inhibition Go-No Go task* that require participants to respond (Go) to one type of stimulus with a motor action and to withhold a response (No Go) to other type of stimulus (Bruin, Wijers, & van Staveren, 2001). Therefore, participants perform a binary decision on each stimulus. After a number of trials the stimulus that needs a motor response changes to the other one. In the task we used two stimuli that appeared in the computer screen in a random order: a duck and a mouse. During the first 16 trials, we ask the participants to press the spacebar of the keyboard when the duck appeared in the computer screen, whereas in the last 16 trials they should press when the mouse was presented. The number of correct responses (motor responses to the correct stimulus) and response inhibition errors, commission errors (motor responses to the incorrect stimulus) were recorded.

Verbal reasoning

Verbal reasoning was assessed by the *Differential Aptitudes Test* (DAT-5) (Bennett, Seashore, & Wesman, 2000). The test assesses the ability to understand concepts framed in words. The participants should find commonalities among different concepts and manipulate ideas on an abstract level. The students answered 40 multiple-choice verbal analogies in a time limit of 20 min. The number of correct responses was registered.

Abstract Reasoning

The abstract reasoning was assessed using *Ravens Advanced Progressive Matrices* (Raven, Court, & Raven, 1994) Set I and Set II. Also, this test gives us a measure of the general Intelligence quotient (IQ) of the participants in the study. The number of correct responses was registered.

Procedure

Subjects were given the tests in the order described above.

Data analysis

Data were analyzed using the Statistical Package for the Social Sciences (SPSS) version 19. To examine differences between the two groups of our study, we have compared ST group and No-ST group using a t-test for independent samples that was performed for each type of EF. In this way, we can compare EF scores of those who were oriented to science and technology in their pre-university studies versus those who had no science and technology subjects.

Results

According to our hypothesis the students of Science and Technology present better spatial working memory and planning ability. This group presented higher score in the FMR test than the No-ST group (t_{138}= 4.40, p<0.001). Also, the ST group made less number of disks movements than the No-ST group (t_{138}=3.43, p<0.001). Accordingly, the ST group spent less time to finish the task (t_{138}=3.27, p=0.001). In addition, inhibition is improved in the ST group. Although there were no differences between the groups in the number of motor responses to the correct stimulus in the Go No-Go task (t_{138}=0.25, p=0.80), the No-ST group did significantly more number of commission errors, motor responses to the incorrect stimulus, than the ST group (t_{138}=2.29, p=0.02). See Table 1.

***Table 1*. Mean and SEM of the measured variables in both groups**

	ST Group		No-ST Group		
	Mean	SEM	Mean	SEM	*p*
Spatial Working Memory Correct FMR responses	10.00	0.58	7.00	0.39	<0.001*
Mental Flexibility Correct WCST matches	39.26	1.28	40.71	1.20	0.42
Planning Movements TOH	63.44	3.78	92.01	6.39	<0.001*
Planning Time (sec) TOH	153.79	12.69	225.39	15.92	0.001*
Inhibition Go-No Go task correct responses	29.82	0.81	30.07	0.58	0.80
Inhibition Go-No Go task Commission errors	0.28	0.07	0.59	0.10	0.02*
Verbal Reasoning Correct DAT responses	6.197	0.19	6.09	0.15	0.66
Abstract Reasoning Correct Raven responses	52.28	0.52	51.31	0.34	0.11

*Significant differences.

There are no differences between the groups in the rest of assessed variables. Both ST and No-ST groups presented similar level of mental flexibility, as they did not differ in the number of correct matches in the WCST (t_{138}=0.81, p=0.42). Also, they showed similar scores in verbal reasoning, the number of correct responses in the DAT-5 did not differ between the groups (t_{138}=0.44, p=0.66). In addition, the number of correct responses in the abstract reasoning test was similar between the groups ST and No-ST (t_{138}=1.63, p=0.11). Therefore, IQ did not influence the results.

Discussion

Our study has shown that pre-university tuition could influence some of the EF linked to the dorsolateral prefrontal cortex (DLPFC), a brain region that has consistently been associated with cognitive control processes when complexity or integration demands during action control increase (Hoshi, 2006). The students that were more exposed to Science and Technology subjects showed improved spatial working memory and planning, as well as less impulsivity.

The fact that there were differences between groups in spatial working memory could be caused by a specific training during High School years. The ST group coursed mandatory subjects related to mathematics, physics and technical drawing in the last courses of High School. These subjects are important for the development of cognitive control and are closely related with the EFs. The specific spatial working memory task that we used in this study is a mental rotation task, which is a component of spatial ability (McGee, 1979). The mental rotation task that we used in this study requires the ability to mentally manipulate, rotate, twist, or invert pictorially presented stimuli (Tartre, 1990). Therefore, it assessed the ability to rotate mental images of objects, reflecting spatial working memory capacity. The participants of the study, in order to derive a correct solution, should rotate two or three dimensional objects in the mind and manipulate their spatial information through several, sequential stages (Zacks, Mires, Tversky, & Hazeltine, 2000).

Spatial working memory develops over time during different stages of life as a result of exposure to several learning environments and life experiences (Pickering, 2001). Therefore, the acquisition of complex spatial skills may require training in specific domains as experienced and practiced during pre-university instruction that encourage visuo-spatial activities. It is possible that the pre-university specific training of the ST group improved mental rotation ability, and for instance spatial working memory. Moreover, it is possible that after continuous pre-university specific mathematics, physics and drawing instruction the students improved their visual information retention rates in comparison with students who did not receive this tuition. According to this view, studies demonstrate that drawing seems to be especially effective for the development of spatial skills and visual imaginary (Sorby, 1999). Similarly, O'Boyle (1998) has shown that the study of mathematics develop the part of the brain involved in visualization and spatial ability with high working memory demands and it has also been suggested that physics involves a specific training in working memory (Chen & Whitehead, 2009). Also, the effect of a specific training can be transferred to the general executive processing, as it has been demonstrated by Minear and Shah (2008). These authors provide evidence for a transfer effect of training into a specific EF domain that is not only merely based on a non-specific improvement in automaticity or motor control.

Regarding planning, this ability involves developing and executing plans. It is crucial for tackling a wide range of daily situations effectively. Planning entails a set of cognitive processes that includes creating and ordering goals, developing hypotheses how each may be tackled and checking that achieving one does not destructively affect the achievement of another and if it does revising the overall procedure. In addition, the structure of the necessary steps must then be encoded in memory. Plan execution can then follow, involving the retrieval and executing of the individual steps, checking that the plan is proceeding appropriately (Crescentini, Seyed-Allaei, Vallesi, & Shallice, 2012). It could be that the better planning ability presented by the ST group in the TOH test was a consequence of their improved working memory for visual information. These two processes seem to be strongly related (Crescentini, Seyed-Allaei, Vallesi, & Shallice, 2012). It has been found by functional imaging techniques that the activation in mid dorsolateral prefrontal cortex is attributed to the working memory components of the task (Wagner, Koch, Reichenbach, Sauer, & Schlosser, 2006). Also, an externally ordered working memory task, requiring short-term retention and reproduction of sequences of spatial moves matched to the TOH task, activates similar brain regions to those activated by planning TOH problems (Owen et al., 1996; Crescentini, Seyed-Allaei, Vallesi, & Shallice, 2012).

In fact, the dorsolateral prefrontal cortex (DLPFC) due to be well positioned to exert control via its connections with proximal and distant brain regions (Cieslik et al., 2012), has been proposed to be involved in the executive ‘top-down” control of behavior (Hoshi, 2006). Evidence from two different networks involving the DLPFC supports our data. In particular, activation in the anterior-DLPFC-anterior cingulate cortex network was more related to attentional processes and action inhibition as well as tasks requiring conflict resolution like the Go/No-Go task. In contrast, the posterior DLPFC-posterior parietal network was more related to the execution of movement as well as working memory processes (Cieslik et al., 2012). In this case the memory component of this ability consists on maintaining the veracity of the spatial and visual information over time or during a delay, that is, processing a series of spatial transformations and stores these mental representations in memory (D'Ardenne et al., 2012). Therefore, it simultaneously demands processing and storage, which depend on working memory capacity (Zimmer, 2008).

We have also found that ST students showed better inhibitory control, they made fewer commission errors, presenting lower impulsivity than the No-ST group. Related to this, improved self-regulation skills can help students to success in math (Blair & Razza, 2007; Badai, Eidelman & Stavy, 2012). The inhibitory control and attention-shifting are strongly related to math ability in children, they can predict academic outcomes independent of general intelligence (Blair & Razza, 2007), which global aspects rely on the DLPFC (Barbey et al., 2012).

Interestingly, a longitudinal study of the development of EF has found that the scores of three distinct tasks, tapping inhibitory control, working memory, and planning, are strongly related during the development and can predict academic success (Hughes, Ensor, Wilson, & Graham, 2010). It could be that the ST students of our study are just this example. These students could have developed good achievement in science subjects as the consequence of the higher ability in the three domains we have shown to be improved in this study: planning, working memory and inhibitory control. Also, as a consequence of the higher success, the specific training in planning and working memory, implicit in science subjects, could also help them to develop better EF in these domains. However, it could be nicely to explore how trainability and transferability of different training procedures could benefit the basic understanding of EFs as well as their possible enhancement.

Acknowledgements

Supported by MICINN PSI 2010-19348, TIN2011-24302 and MEC AP2009-1714 to NA.

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