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2D:4D values are associated with mathematics performance in business and economics students

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ABSTRACT

Prenatal testosterone has organizational effects on adult cognition. The second-to-fourth digit length ratio, which is a proxy of prenatal testosterone exposure, has been linked to a wide variety of sexually differentiated behaviors. We analyze the association between academic performance and the second-to-fourth digit ratio among students at the Faculty of Business and Economics of the University of Granada (Spain). In a sample of 516 freshmen (304 women), we find an inverted U-shaped relationship between digit ratio and *mathematics grades*. Males and females show the same pattern. Participants with both high and low digit ratios earn lower grades in mathematics, while participants which have intermediate digit ratios achieve the highest grades in mathematics. We also find that there is no statistically significant relationship between the digit ratio and the average grades earned by students in other courses except mathematics taken in the first semester at the Faculty of Business and Economics.

1. Introduction

The relation between prenatal hormonal exposure and fetal neural organization and adult cognition has been recognized in theoretical and empirical studies (Alexander, O'Boyle, & Benbow, 1996; Anderson & Harvey, 1996; Auyeung, Lombardo, & Baron-Cohen, 2013; Collaer & Hines, 1995; Geschwind & Galaburda, 1987). Exposure to androgens such as testosterone early in life permanently masculinizes the brain, as well as behavioral and cognitive aspects associated with human sex differences in later postnatal life (Cohen-Bendahan, van de Beek, & Berenbaum, 2005). For research progress it is essential to use non-invasive somatic markers of prenatal testosterone that solve laborious tasks and other difficulties (see Cohen-Bendahan et al., 2005; Collaer & Hines, 1995).

In this context, the ratio between the index (2D) and the ring (4D) fingers (2D:4D) has been widely confirmed as a proxy of prenatal exposure to testosterone (Breedlove, 2010; Manning, 2002). A high prenatal androgen load induced either by enhanced hormone levels or more sensitive androgen signal transduction pathways results in a longer ring finger (4D) relative to the index finger (2D) in the adult human hand (Zheng & Cohn, 2011). The sex difference in 2D:4D is determined by the actions of testosterone in utero and the individual variation in the size of the ratio may be a proxy for individual differences in the level of fetal androgen exposure (Manning, Bundred, Newton, & Flanagan, 2003; Manning, Scutt, Wilson, & Lewis-Jones, 1998). A low 2D:4D (male typical ratio) is indicative of higher prenatal testosterone levels (Lutchmaya, Baron-Cohen, Raggatt, Knickmeyer, & Manning, 2004; Manning, 2011; Manning et al., 1998).

In general, significant relationships between behavioral traits and 2D:4D have been found more frequently for the right hand, which is also considered to be more affected by androgenization than the left hand (Brañas-Garza & Rustichini, 2011; Brosnan, 2008; Coates, Gurnell, & Rustichini, 2009; Hönekopp, Bartholdt, Beier, & Liebert, 2007; Hönekopp & Watson, 2010; Hopp, Pucci de Moraes, & Jorge, 2012; Manning et al., 1998; Romano, Leoni, & Saino, 2006). However, relationships with the 2D:4D of the left hand have also been found (Brosnan, 2008; Bull & Benson, 2006; Fink, Brookes, Neave, Manning, & Geary, 2006; Weis, Firker, & Henning, 2007) or with the average of both (Brookes, Neave, Hamilton, & Fink, 2007; Brosnan, 2008; Brosnan, Gallop, Iftikhar, & Keogh, 2011; Nye, Androuschak, Desierto, Jones, & Yudkevich, 2012; Sapienza, Zingales, & Maestripieri, 2009; Voracek, Pietschnig, Nader, & Stieger, 2011). Similar to 2D:4D, left hand 2D:4D minus right hand 2D:4D has also been suggested to be a negative correlate of prenatal androgenization in humans (Manning, 2002; Manning et al., 2003).

Several studies have reported an association between 2D:4D and performance on a range of measures to assess cognitive abilities. Individuals with lower 2D:4D perform better on spatial and mathematical tasks (Brookes et al., 2007; Bull & Benson, 2006; Castho et al., 2003; Fink et al., 2006; Kempel et al., 2005; Luxen & Buunk, 2005). The 2D:4D is negatively correlated to numeracy for males and positively correlated to literacy for females at the age of seven (Brosnan, 2008). In addition, low 2D:4D in men is associated with higher risk taking

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and higher scores in abstract reasoning ability (Brañas-Garza & Rustichini, 2011). Considering that capabilities in mathematics require spatial tasks, and numeric and abstract reasoning abilities (Nyborg, 1983; Spelke, 2005; Wai, Lubinski, & Benbow, 2009), our study analyzes the possibility that 2D:4D, as a putative marker for prenatal testosterone, is associated with mathematics academic performance.

In addition, we are interested to study if the relationship between 2D:4D and mathematics performance differs in males and females. The difference in mathematical ability between men and women is one of the oldest established sex differences. Some scholars have attempted to explain the biological (Geary, 1996), socio-cultural (Furnham, Reeves, & Budhani, 2002; Herbert & Stipek, 2005; Spencer, Steele, & Quinn, 1999) and psychological (Chen, Chen, Lee, Chen, & Keith, 2013) causes of the sex difference in mathematics performance, while others have argued that these differences are correlated with the implementation of gender-equality measures in countries (Baker & Perkins Jones, 1993; Else-Quest, Hyde, & Linn, 2010; Guiso, Monte, Sapienza, & Zingales, 2008). However, this remains controversial (see Kimura, 1999; Lindberg, Hyde, Petersen, & Linn, 2010; Mullis et al., 2008).

The relationship between the 2D:4D and academic performance has only been studied in very recent years. With a sample of 73 university students (60 males), Brosnan et al. (2011) found a negative and significant correlation between 2D:4D and academic assessments in Java Programming, regardless of gender. In a sample of Brazilian dental students (40 males and 40 females), Hopp et al. (2012) concluded that theoretical and practical grades were significantly negatively correlated to 2D:4D in males controlled by age and hours of study, but not in females. Nye et al. (2012) provided evidence from several samples of undergraduate students on different participants in Moscow and Manila (277 math students in Moscow —125 males, and 123 students in Manila — 49 males). They found that 2D:4D had a nonlinear effect on different measures of academic achievement. Their results suggest that this relationship might be dependent on several factors such as culture, field of study or sex. The results for men and women show similar nonlinear effects, but are generally insignificant for men in the Moscow samples and significant for the Manila samples. Coco et al. (2011) evaluated a group of 48 male students, and found a significant negative correlation between 2D:4D and success in admissions tests for a medical school in Italy. They concluded that prenatal androgens increase performance in situations that require prompt decision making and the ability to take risks, but do not influence performance when a more analytical and planned approach is called for.

However, it should be noted that due to the small number of studies and sample sizes, the empirical results on the relationship between 2D:4D and academic performance are not conclusive. This paper provides more evidence on the association between 2D:4D and academic performance with a large sample of 516 students (304 females) enrolled in their first academic year at the Faculty of Business and Economics of the University of Granada (Spain). We analyze the possibility that 2D:4D has an influence on mathematics academic performance and other first-year participants. As the 2D:4D is determined early in life, the potential link between academic performance and exposure to testosterone cannot be reversed (Coates et al., 2009), that is, the 2D:4D could predict academic performance, but not vice versa. In addition, we analyze if the relation between 2D:4D and *mathematics grade* is the same for both sexes. A better understanding of the relationship between 2D:4D and mathematics performance will permit more informed educational choices. For example, in the future, school counselors, students' families and the students themselves could also take this information into account when making decisions about the most appropriate educational paths.

Academic performance is measured using a standardized measurement with an identical value scoring for all students throughout the course. Unlike most papers that use a test as a measurement of performance and where nothing is known about participants' motivations, we use the scores of real examinations for math and other subjects. That is, we compare participants with a similar motivation (to get the maximum score).

2. Materials and methods

2.1. Participants

In October 2011, 927 first-year students at the Faculty of Business and Economics of the University of Granada (Spain) were asked to participate voluntarily in a research study at the EGEO Experimental Economics Laboratory. The final number of participants was 659. Three non-Caucasian participants were excluded from our data set to ensure ethnic homogeneity. Thus, 656 ethnically homogeneous participants (378 females) enrolled in the first year of the BA in Economics, Finance, Management and Marketing at the University of Granada participated in the experiment.

Since one of our goals was to analyze whether biological factors (2D:4D) influence mathematics performance, participants that had not been evaluated, and hence had not been assigned a math grade, were eliminated from the initial sample of 656 students. The final data set therefore consisted of 516 participants (304 women). The average age of the participants was 18.74 ± 1.50 (range: 17 to 27 years of age); 19 ± 1.68 (range: 18 to 27 years of age) for males and 18.55 ± 1.34 (range: 17 to 26 years of age) for females. Our sample represents 55.66% of the population (927 freshmen at the Faculty of Business and Economics of the University of Granada).

2.2. Procedure

During the research study, we gathered information about the participants' academic performance, demographic characteristics, socioeconomic status, and measured their finger lengths. The survey-experiment was run in 27 sessions with about 24 students per session. An identical protocol was followed in all the sessions. Upon arriving at the laboratory, each participant was assigned to a computer and given an identification number prior to scanning their 2D:4D. The students were not allowed to communicate with the other participants. All the participants received the same instructions and signed an informed consent form.

The research was conducted in accordance with the Code of Ethics of the University of Granada. In accordance with the Spanish Law 15/1999 on Personal Data Protection, the anonymity of the participants was ensured throughout the survey by randomly assigning them a username to identify them in the system. No association was ever made between their real names and the results, thus preserving the anonymity of participants. The procedure was checked and approved by the Vice Provost for Research at the University of Granada, the institution hosting the experiment.

2.3. Measures

2.3.1. 2D:4D *digit ratio*

During the experiment, the participants were asked to go one by one to the main desk to have both of their hands scanned. The participants were asked to straighten their fingers and gently press their hand on the scanner. We used a high-resolution scanner (Canon Slide 90), because computer-assisted measurements of 2D:4D from scanned pictures have been found to be more precise and reliable than measurements using other methods (Allaway, Bloski, Pierson, & Lujan, 2009; Kemper & Schwerdtfeger, 2009). Two marks were made at the crease of the base of the finger proximal to the palm and tip of the finger, and the length of the two fingers was measured with a ruler. The research assistant in charge of recording the finger length measurements did not know the responses given by the participants on the questionnaire and was not involved in the present study.

To ensure the most accurate measurements, we measured the ratio obtained from the scanned pictures twice. The lengths of the index (2D) and ring (4D) fingers were measured by the same rater with a time span of one month. As expected, both measurements were highly correlated (correlation coefficient right hand: $r = 0.94$, $p < 0.001$; left hand: $r = 0.92$, $p < 0.001$). The variables of interest were the 2D:4D of the right hand (*Right* 2D:4D), the 2D:4D of the left hand (*Left* 2D:4D), the arithmetic mean between the average of the two measurements of the left hand and the average of the two measurements of the right hand (*Average* 2D:4D), and the difference between the Right 2D:4D and Left 2D:4D (*Dr-l*).

2.3.2. Performance in mathematics

We used the final grade earned by students in a first-semester mathematics course. The students' grades were obtained from the university database. The mathematics course syllabus consists of differential and integral calculus, algebra and geometry of economic functions. The evaluation system is the same for all the groups taking this course at the Faculty of Business and Economics. Specifically, the final grade is obtained as the weighted sum of two mid-term exams (theoretical and practical) given during the course. The graded examinations were scored on a continuous scale of 0-10 (fail-excellent). The exams are given on the same day and at the same time to all the students. Hence, all the students enrolled in the course must fulfill the same academic requirements.

2.3.3. Grade point average of other courses

The grade point average of other courses (*GPA-other*) is the average grade obtained by first-year students in all courses except mathematics on a scale of 0-10. In the first semester of the first year, the students take the following courses: Economics, Foundations of Business Organization, Introduction to Financial Management, Introduction to Marketing, and Mathematics. This information was obtained from the university database.

3. Results

In this section, we test if there is an association between 2D:4D and academic performance and, if so, we estimate the type of functional relationship. Firstly, we present the preliminary results: the descriptive statistics of the main variables, the differences between sexes using ANOVA and non-parametric tests; and Pearson's correlations between 2D:4D and *Mathematics grade*, and between 2D:4D and *GPA-other* in males, females and in the whole sample. Secondly, we conduct a regression analysis. We have estimateds several OLS regression models to analyze the association between digit ratio and *Mathematics grade* and the *GPA-other*. We only control for the effect of gender (the variable *Gender* is included as a dummy with male $= 1$), since our sample is relatively homogeneous in terms of age (range: 17 to 27 years of age), cultural and educational background (all of the participants were freshmen), and socioeconomic status, thereby minimizing the effects of many potential confounds on the variables of interest.

3.1. Summary statistics, gender differences and correlation analysis

Tables 1 and 2 show a summary description of the main variables of interest. Given that *Right* 2D:4D, *Left* 2D:4D and *Average* 2D:4D show a normal distribution (skewness and kurtosis test for normality: *Right* 2D:4D, $X^2 = 4.14$, $p = 0.126$; *Left* 2D:4D, $X^2 = 3.93$, $p = 0.140$; and *Average* 2D:4D, $X^2 = 0.84$, $p = 0.658$), the differences between sexes were analyzed using ANOVA. Because the rest of the variables did not show a normal distribution (skewness and kurtosis test for normality: *Dr-l*, $X^2 = 12.34$, $p = 0.002$; *Mathematics grade*, $p = 0.000$; and *GPA-other*, $X^2 = 9.05$, $p = 0.011$), the Kruskal-Wallis equality-of-populations rank test and the Wilcoxon rank-sum (Mann-Whitney) test were used to analyze sex differences.

In the variables *Right* 2D:4D, *Left* 2D:4D and *Average* 2D:4D the ratio is significantly lower for men than for women, in line with previous literature (e.g., Brañas-Garza & Rustichini, 2011; Bull & Benson, 2006; Hönekopp & Watson, 2010; Manning et al., 1998; Stenstrom, Saad, Nepomuceno, & Mendenhall, 2011; Weis et al., 2007). To calculate the extent of these differences in averages and assess their relevance, the effect size (Cohen's d) was calculated for the differences between females and males in the *Right* 2D:4D, *Left* 2D:4D and *Average* 2D:4D. In all cases, the effect size is lower than 0.5, thus indicating a small effect size (Cohen, 1988), but it is within the expected range for 2D:4D (Hopp et al., 2012; Manning, 2002). Since the three variables are normally distributed, the practical relevance of Cohen's d can also be assessed using the table of the normal distribution. Specifically, in the case of Average 2D:4D, in which Cohen's d takes the value of 0.360, it would appear that the average female in Average 2D:4D has a greater digit ratio than about 64% of males.

In line with other works (Brosnan et al., 2011; Hönekopp et al., 2007), *Dr-l* did not differ significantly between sexes. With regard to sex differences in the grades earned in the mathematics course, no significant differences were found between the males and females in our study. Moreover, no significant differences were observed between men and women as regards the average grades obtained in the other courses (*GPA-other*) (Table 2). To facilitate comparison of the results with those obtained in other studies, we calculated the effect size or Cohen's d (the mean for females minus that for males divided by the pooled standard deviation) of the variables *Dr-l*, *Mathematics grade* and *GPA-other* (last column, Table 2).

Table 3 shows Pearson's correlations between 2D:4D and *Mathematics grade*, and between 2D:4D and *GPA-other* in males, females and in the whole sample. A significant correlation was not found between *Mathematics grade* and any of the three digit ratio variables in males and females in the whole sample or between *GPA-other* and 2D:4D.

3.2. Regression analysis

Table 4 presents the results of eight OLS regression models (columns 1-8). In all regressions, the explanatory variables are *Average* 2D:4D and *Gender*. We show the regression analysis with *Average* 2D:4D, since it is the 2D:4D measurement that provided more robust results. Specifically, in the model 1 (column 1) we analyze the existence of a linear relationship between *Average* 2D:4D and *Mathematics grade* controlling by

Table 1
Sex differences in digit ratios.

	Females[a]		Males[b]		ANOVA	
	Mean (SD)	Min-max	Mean (SD)	Min-max	F (1, 514), (p-value)	Cohen's d
Right 2D:4D	0.971 (0.034)	0.886-1.087	0.959 (0.034)	0.870-1.051	16.45 (0.000)	0.346
Left 2D:4D	0.976 (0.031)	0.887-1.059	0.965 (0.032)	0.895-1.046	13.28 (0.000)	0.309
Average 2D:4D	0.973 (0.030)	0.893-1.063	0.962 (0.030)	0.899-1.031	17.74 (0.000)	0.360

[a] $n = 304$.
[b] $n = 212$.

Table 2
Sex differences in *Dr-l* and academic performance.

	Females[a]		Males[b]		Kruskal-Wallis equality-of-populations rank test	Wilcoxon rank-sum (Mann-Whitney) test	Cohen's d
	Mean (SD)	Min-max	Mean (SD)	Min-max	X^2 (p-value)	Z (p-value)	
Dr-l	-0.004 (0.025)	-0.081-0.056	-0.006 (0.028)	-0.114-0.081	0.623 (0.430)	0.789 (0.430)	0.073
Mathematics grade	5.146 (2.590)	1-10	4.872 (2.762)	1-10	0.994 (0.319)	0.997 (0.319)	0.103
GPA-other	5.718 (1.612)	1.475-9.475	5.681 (1.795)	0.8-9.45	0.008 (0.931)	0.086 (0.931)	0.009

[a] n = 304.
[b] n = 212.

Table 3
Pearson's correlations between 2D:4D and *Mathematics grade*, and between 2D:4D and *GPA-other*.

	Mathematics grade and Right 2D:4D	*Mathematics grade* and Left 2D:4D	*Mathematics grade* and Average 2D:4D	*GPA-other* and Right 2D:4D	*GPA-other* and Left 2D:4D	*GPA-other* and Average 2D:4D
All	subjects[a]	0.042	0.035	0.042	0.070	0.018
0.049						
	(0.347)	(0.424)	(0.342)	(0.113)	(0.687)	0.270
Females[b]	-0.006	0.017	0.006	0.064	-0.033	0.019
	(0.914)	(0.761)	(0.922)	(0.266)	(0.569)	(0.742)
Males[c]	0.086	0.041	0.071	0.076	0.078	0.085
	(0.211)	(0.553)	(0.305)	(0.273)	(0.257)	0.219

p-Values in parentheses.
[a] N = 516.
[b] n = 304
[c] n = 212.

Gender. Its results show that the linear relationship is not significant. Model 2 (column 2) includes the interaction between *Average* 2D:4D and *Gender*. The results of model 2 show that the lack of a linear relationship holds true irrespective of gender (i.e., the interaction between *Average* 2D:4D and *Gender* is not significant). The linear relationship is not significant for all the participants. That is, the results of the Pearson´s correlations (Table 3) together with the results of regressions 1 and 2 permit us to conclude that there does not exist a linear functional relationship between *Mathematics grade* and *Average* 2D:4D. Namely, holding constant the other factors that may influence *Mathematics grade*, we cannot predict that a variation in *Average* 2D:4D will be associated with a constant variation (in the same direction or not) in *Mathematics grade*, regardless of whether very low or very high values of *Average* 2D:4D are considered.

This first step leads us to rule out the possibility of a linear relationship between *Mathematics grade* and *Average* 2D:4D. In observing the *Mathematics grade*, we find that students with the highest and lowest 2D:4D values have the lowest marks (students for the 5th percentile of the *Average* 2D:4D distribution obtain an average math score of 3.984 ± 2.752, N = 25; students for the 95th percentile of the *Average* 2D:4D distribution obtain an average math score of 3.852 ± 2.616, N = 25). This behavior is observed in both men and women. This finding and the lack of a linear relationship (models 1 and 2) led us to hypothesize that there may be a quadratic relationship between *Average* 2D:4D and *Mathematics grade*. That is, the non-monotonic approach could capture participants' heterogeneity in more detail. We propose model 3 (column 3) in which *Mathematics grade* depends quadratically on the digit ratio (*Average* 2D:4D and *Average* $2D:4D^2$) to capture increasing or decreasing marginal effects. The results of regression 3 showed that the relationship between *Average* 2D:4D and *Mathematics grade* is significant ($p < 0.05$ in both *Average* 2D:4D and *Average* $2D:4D^2$). In model 4 (column 4) the interaction between *Average* 2D:4D and *Gender* is added. The relationship between *Average* 2D:4D and *Mathematics grade* is significant and the control variable *Gender* and the interaction are not significant ($p > 0.05$), thus the results can be extended to the entire sample. For all participants, the regression analysis showed that the relationship between *Average* 2D:4D and *Mathematics grade* is significant ($p < 0.05$ in both *Average* 2D:4D and *Average* $2D:4D^2$). The Akaike information criterion (AIC) shows a better goodness of fit in models 3 and 4 than in the linear models (Table 4).[1]

As regards model 3, showing better results, since the coefficient of *Average* 2D:4D is positive and the coefficient of *Average* $2D:4D^2$ is negative, the quadratic function has a parabolic shape. That is, we find an inverted U-shaped relationship between *Average* 2D:4D and *Mathematics grade*. The critical value of the digit ratio value can be calculated for the highest *Mathematics grade* as the absolute value of the ratio between the estimated coefficient of *Average* 2D:4D and twice the estimated coefficient of *Average* $2D:4D^2$, such that the digit ratio =0.9763. For 59.50% of all participants (participants with a digit ratio less than 0.9763), the digit ratio – measured as *Average* 2D:4D – is positively associated with *Mathematics grade*. For the remaining 41.50% (participants with a digit ratio greater than 0.9763), the digit ratio is negatively associated with *Mathematics grade*. In any case, the lowest and highest *Average* 2D:4D values (parabola ends) are associated with a lower *Mathematics grade* (Fig. 1). Hence, participants with an intermediate *Average* 2D:4D earn better grades in mathematics.

Finally, models 5, 6, 7 and 8 analyze the type of relationship that might exist between *Average* 2D:4D and the grade point average of freshmen in their first semester at college, except in mathematics (*GPA-other*). The results of these models show that the *Average* 2D:4D is not significantly associated with the grades in the other courses taken in the first semester. That is, the 2D:4D is important in math grades but not for the other courses.[2]

We estimated these same eight regression models using *Dr-l*, *Right 2D:4D* and *Left* 2D:4D as independent variables. We did not find any significant association between *Dr-l* and *Mathematics grade*, or between *Dr-l* and *GPA-other*. In the case of the other two 2D:4D measurements, the results show that *Right* 2D:4D and *Left* 2D:4D are associated with

[1] We also tested if there was a cubic relationship between 2D:4D and *Mathematics grade* and the results were negative (available upon request from the authors).

[2] Furthermore, a statistically significant linear and quadratic relationship was not found between digit ratio and one of the courses taken in the first semester (except mathematics).

Table 4
Regression analysis: academic performance and Average 2D:4D.

Dependent variable:	*Mathematics grade*				*GPA-other*			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Average 2D:4D	2.977	0.487	446.487	437.804	2.698	1.023	-12.841	-40.583
	(0.451)	(0.924)	(0.015)	(0.022)	(0.282)	(0.753)	(0.913)	(0.739)
Average 2D:4D^2			-228.667	-224.489			8.012	21.358
			(0.016)	(0.022)			(0.895)	(0.732)
Gender (male)	-0.241	-6.150	-0.234	-1.613	-0.007	-3.980	-0.007	-4.412
	(0.321)	(0.429)	(0.333)	(0.840)	(0.966)	(0.420)	(0.965)	(0.387)
Average 2D:4D × gender		6.112		1.426		4.110		4.556
		(0.447)		(0.863)		(0.420)		(0.387)
Constant	2.248	4.672	−212.598	−208.107	3.091	4.721	10.619	24.965
	(0.559)	(0.350)	(0.017)	(0.025)	(0.206)	(0.137)	(0.852)	(0.673)
N	516	516	516	516	516	516	516	516
p-Value (model)	(0.389)	(0.481)	(0.053)	(0.103)	(0.544)	(0.600)	(0.744)	(0.739)
AIC	4.803	4.806	4.795	4.799	3.892	3.895	3.896	3.898

Note: Ordinary least squares estimates. In the models 1, 2, 3 and 4, the dependent variable is *Mathematics grade*. In column (1), the explanatory variables are Average 2D:4D and Gender, while their interaction is added in column (2). In column (3), the explanatory variables are Average 2D:4D, Average 2D:4D^2, and Gender. Column (4) takes into account the interaction between Average 2D:4D and Gender. In models 5, 6, 7 and 8, the dependent variable is *GPA-other*; they repeat, respectively, the same regressions than (1), (2), (3) and (4).
AIC = Akaike information criterion.
p-Values in parentheses.

Mathematics grade similar to the case of *Average* 2D:4D discussed above. That is, we found an inverted U-shaped relationship between *Right* 2D:4D and *Mathematics grade*, and between *Left* 2D:4D and *Mathematics grade* for the entire sample, with higher significance levels recorded for *Left* 2D:4D ($p < 0.05$) than *Right* 2D:4D (Table 5). Like *Average* 2D:4D, *Right* 2D:4D and *Left* 2D:4D did not have a statistically significant relationship with the grades in the other courses taken in the first semester (*GPA-other*).

4. Discussion and conclusions

The objective of this paper is to provide more evidence on the association between 2D:4D and academic performance in a sample of 516 students (304 females) enrolled in their first year at the Faculty of Business and Economics of the University of Granada (Spain). Specifically, we analyze if 2D:4D is associated with mathematics performance and the other subjects of the first year, controlling by gender. Our work provides new results about the relationships between 2D:4D and academic performance with a large sample of university students. Another remarkable aspect is that the paper provides evidence of 2D:4D on a real task, since we use the scores of real math examinations and exams for other subjects rather than a test where nothing is known about participants' motivations.

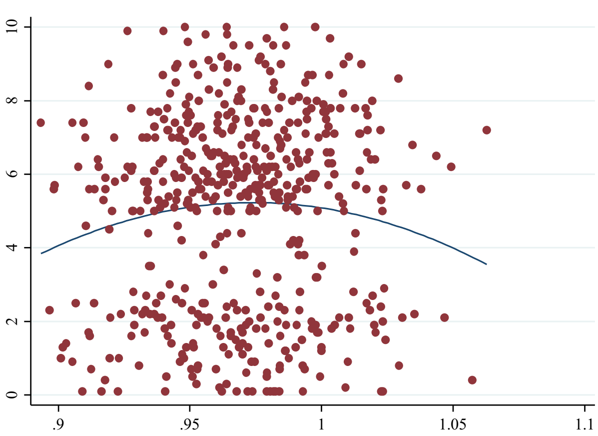

Fig. 1. Quadratic regression between Average 2D:4D and *Mathematics grade* in all participants. (*Mathematics grade* was scored on a continuous scale of 0-10 points, fail-excellent). (2D:4D is the ratio between the lengths of the index (2D) and ring (4D) fingers).

We have found that 2D:4D values – measured as *Average* 2D:4D, *Left* 2D:4D and *Right* 2D:4D – are associated with *mathematics grade*. Therefore, biological and genetic factors, in addition to other factors, could play an important role in mathematics performance. Specifically, we have found an inverted U-shaped relationship between 2D:4D and *mathematics grade* for all participants. Lower *mathematics grades* were found to be related to both relatively higher and lower 2D:4Ds, while higher *mathematics grades* were related to relatively intermediate 2D:4D values. Under the assumption that two students (one with an intermediate *Average* 2D:4D and another with a high *Average* 2D:4D) make the same effort in mathematics and in the other courses, the overall results may differ due to biological and genetic factors. A student with an intermediate digit ratio is likely to earn better grades.

Previous studies have shown that testosterone has nonlinear effects on spatial cognition such that individuals with intermediate levels of this hormone (women with high testosterone and men with low testosterone) perform better on spatial cognition tasks than individuals at the extremes of the distribution (women with low testosterone and men with high testosterone) (Kimura, 1999; Moffat & Hampson, 1996; Nyborg, 1983). In the literature on 2D:4D, Nye et al. (2012) provided evidence of a nonlinear relationship between 2D:4D and academic achievement among university students in two country samples from Moscow and Manila. Brañas-Garza, Kovářík, and Neyse (2013) found an inverted U-shaped relation between altruism in adults and the 2D:4D, which is very consistent for men and less systematic for women. Participants with both high and low digit ratios give less than

Table 5
Mathematics performance and right 2D:4D and left 2D:4D.

Dependent variable	*Mathematics grade* (1)	Dependent variable	*Mathematics grade* (2)
Right 2D:4D	259.169	Left 2D:4D	410.205
	(0.057)		(0.020)
Right 2D:4D^2	-132.255	Left 2D:4D^2	-210.104
	(0.059)		(0.020)
Gender (male)	-0.228	Gender (male)	-0.241
	(0.349)		(0.317)
Constant	-121.663	Constant	-194.871
	(0.065)		(0.022)
N	516	N	516
p-Value (model)	(0.142)	p-Value (model)	(0.069)

Note: Ordinary least squares estimates. In the two models, the dependent variable is *Mathematics grade*. In column (1), the explanatory variables are Right 2D:4D, Right 2D:4D^2, and Gender. In column (2), the explanatory variables are Left 2D:4D, Left 2D:4D^2, and Gender.
p-Values in parentheses.

individuals with intermediate digit ratios. In line with these findings, the results of our study suggest that there might be an optimal level of exposure to hormones from the academic and social perspective. Given that our dependent variable – *Mathematics grade* – reflects students' academic performance throughout the year, social influences in addition to cognitive skills are key (Voyer & Voyer, 2014). Since sharing with others is socially beneficial, selfish individuals would be socially excluded (Brañas-Garza et al., 2013) and their academic performance may be affected negatively. Moreover, some risk-taking or aggressiveness may be beneficial to achieve good academic performance, but too much might lead to destructive behavior (Nye et al., 2012).

Furthermore, we find that 2D:4D does not have a significant effect on the grade point average of the participants in the rest of the courses taken in the first semester. Moreover, if we break the sample down into two subsamples (one consisting of participants with a *GPA-other* higher than or equal to the GPA in all first-semester courses except mathematics, and another subsample comprising participants with a lower *GPA-other* in the same courses), the results are similar to those obtained for all the participants. This indicates that there is a quadratic relationship between 2D:4D and *Mathematics grade* regardless of whether the student is in the group of participants with higher academic performance or not.

A remarkable finding of our work is that, although there are significant differences between the digit ratios of men and women, the relation between 2D:4D and *Mathematics grade* is the same for both sexes. These results are in line with those of Nyborg (1983), Moffat and Hampson (1996) and Kimura (1999). In the case of mathematics performance, the debate over sex differences stretches back more than 30 years. However, there is no consensus on this matter. A recent meta-analysis found a significant female advantage in math scores, with an estimated overall Cohen's d of 0.225; this effect is reduced to $d = 0.12$ when considering the undergraduate level (Voyer & Voyer, 2014). In our study, females also perform better in mathematics with a $d = 0.103$, which is very close to that found by Voyer and Voyer (2014), but we cannot rule out that this difference is random, as it is not statistically significant. Another meta-analysis of 242 research articles on gender differences in mathematics essentially confirms that there is no difference, showing a very small effect size of 0.05 in favor of males (Lindberg et al., 2010). Mullis et al. (2008) analyzed the results of the eighth-grade Trends in Mathematics and Science Study (TIMSS) exam (2007). They found that in eight countries boys outscored girls, in 25 countries there was no statistically detectable difference, and in 17 countries girls outscored boys. Stoet and Geary (2013) analyzed one decade of data collected by the Programme for International Student Assessment (PISA), including the mathematics performance of nearly 1.5 million 15-year-olds in 75 countries. They found that girls score lower in mathematics at the high end of the mathematics performance continuum, regardless of the level of development of the country. According to the authors, this could explain the underrepresentation of women in Science, Technology, Engineering, and Mathematics (STEM).

In addition to the findings of Stoet and Geary (2013), career decisions may be influenced by cultural beliefs about gender differences. Specifically, Correll (2001) highlights self-perceptions of mathematical competence in high school students as one mechanism by which cultural beliefs about gender constrain the early career-relevant choices of men and women. For males and females, the higher they rate their mathematical competence, the greater the odds that they will continue on the path leading to careers in science, math, and engineering. Given that males tend to overestimate their mathematical competence, they are more prone to pursue quantitative degrees. The findings of Stoet and Geary (2013) and Correll (2001) help to explain why the relationship between 2D:4D and math grades is the same for both men and women in our study. First, in the university programs analyzed in our work (Faculty of Business and Economics) women are not underrepresented as the number of women (304) is higher than the number of men (212). Moreover, no significant differences were found between the math scores of males and females (Table 2). Second, in Spain, the majority of students who want to pursue a university degree must complete Bachillerato (two pre-university academic years equivalent to A Levels in the UK or grades 11 and 12 in the US) in one of three modules: Science and Technology – for those who want to pursue a degree in technology, engineering, mathematics or medicine – Humanities and Social Sciences, and Art. Of the 516 participants in our research study, 78.87% had undertaken the Humanities and Social Sciences module (164 men and 243 women), while the remaining 21.13% had done the Science and Technology module (49 men and 60 women). Therefore, the participants in our research study have already made early career decisions of the type described by Correll (2001), and it is likely that they do not belong to the high end group of the mathematics performance continuum since the mathematics content and the level of difficulty of these modules is different.[3]

In addition, the finding that 2D:4D is associated with math scores regardless of sex could be explained by the fact that Business and Economics students may have chosen to do this university degree based upon their academic strengths, which could be reflected in their 2D:4Ds (Brosnan, 2008; Romano et al., 2006). However, in addition to cognitive factors, the prenatal exposure to sex hormones could manifest their influence behaviourally via emotional aspects. That is, a male or female student for whom financial and economic decision making or the use of computers produces anxiety would not be likely to study Business and Economics. That is, given the relationship between 2D:4D and financial and economic decision making (Apicella et al., 2008; Coates et al., 2009; Sapienza et al., 2009) and the relationship between 2D:4D and the use of information and communication technologies (Brosnan et al., 2011), we could hypothesize that the 2D:4D in the female participants is lower than in other groups (females that do not like the fields of computer science, finance and economics). The analysis of this question in future research would require studying the association between 2D:4D and the choice of university degree.

Our work provides new and robust results with a large sample, although we are aware that there remain interesting questions that deserve further research. For example, it would be interesting to track the academic performance of the participants throughout the entire degree program to analyze if different forms of assessment contribute to students' final grades, for instance, written assignments versus oral examinations, or multiple choice questions versus essay questions, and to determine whether there is any association between these aspects and the 2D:4D.

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