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Non-cognitive factors influencing numeracy in higher education

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To Renzo

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This thesis incorporates material from previously published papers authored by me. The following publications are included:

- Lunardon, M., Cerni, T., & Rumiati, R. I. (2022). Numeracy Gender Gap in STEM Higher Education: The Role of Neuroticism and Math Anxiety. *Frontiers in Psychology, 13*, 856405. https://doi.org/10.3389/fpsyg.2022.856405
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The use of previously published content in this thesis is intended to present a cohesive narrative of my research work and to fulfil the requirements for the Ph.D. degree.

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Abstract

The promotion of numeracy across the lifespan is a key objective for many national and international institutions, given its importance at both individual and societal levels. In my dissertation, I sought to deepen our understanding of the role that non-cognitive factors, particularly math anxiety and personality, play in numeracy in higher education, taking into account gender differences the varying math content of different fields of study. I conducted four empirical studies, assessing numeracy using a large-scale cognitive test developed by the Italian National Agency for the Evaluation of University and Research (ANVUR).

In Study 1 I focused on gender differences in science, technology, engineering and mathematics (STEM) fields, where women are typically underrepresented. I investigated the contribution of math anxiety and neuroticism personality traits to numeracy. Using a sample of STEM undergraduate students balanced by gender ($N_F = N_M = 70$) and IQ, I found that women's numeracy scores were more strongly influenced by math anxiety and neuroticism than men's numeracy scores. Furthermore, for women the relationship between math anxiety and numeracy was mediated by neuroticism. These findings revealed gender-specific pathways through which non-cognitive factors influence numeracy in STEM programmes.

In Study 2 I extended the investigation to students enrolled in humanities programmes (HUM) with a large sample ($N = 410$) that completed remotely standardized tests assessing numeracy, math anxiety, personality, intelligence, and basic numerical skills. Results showed that math anxiety was negatively associated with numeracy, independent of field of study and gender, while the effect of personality, specifically neuroticism, on numeracy interacted with field of study over and above intelligence and basic numerical skills. These findings highlight the critical role of emotional experiences, particularly for students less familiar with mathematics.

In longitudinal Study 3, I followed a subset of students from the previous study (N = 118) and reassessed them two years later. The main finding was the influence of math anxiety at T1 on numeracy at T2, which was fully mediated by numeracy at T1 and, for STEM, also by math anxiety at T1. Notably, the inverse relationship, i.e., between numeracy at T1 and math anxiety at T2, was also significant, especially for STEM students. Neuroticism at T1 also predicted numeracy at T2, but the effect was small, and no significant indirect or moderating effects were observed. These findings suggest that the mechanisms linking math anxiety and numeracy, including possible bidirectional effects, vary by field of study.

In Study 4, I investigated the physiological responses during numeracy testing, an often overlooked aspect. I examined the relationship between numeracy and three indicators of physiological arousal (salivary cortisol, skin conductance, and heart rate variability) in 130 university students, and how these associations varied with different levels of self-reported math anxiety and neuroticism. The results showed that the role of physiological arousal differed depending on the type of physiological measure, the field of study and the level of neuroticism. Distinct profiles of math anxiety, neuroticism and physiological response emerged, with different numeracy performance. These findings highlight the importance of including non-cognitive factors and students' field of study for a comprehensive interpretation of physiological arousal in relation to numeracy.

Overall, the findings of this thesis highlight the importance of considering emotional and dispositional factors in relation to numeracy in higher education. Educational contexts, and to a lesser extent gender, can shape the influence of math anxiety and personality on numeracy. This has theoretical and practical implications in terms of interventions to support numeracy in higher education and for better interpretation of numeracy test results.

CHAPTER 1

General introduction

Adapted from: Lunardon, M., Cerni, T., & Rumiati, R. I. (2022). Numeracy Gender Gap in STEM Higher Education: The Role of Neuroticism and Math Anxiety. *Frontiers in Psychology, 13*, 856405. https://doi.org/10.3389/fpsyg.2022.856405; Lunardon, M., Cerni, T., & Rumiati, R. I. (2024). Field of Study and Gender Moderation of the Association of Personality and Math Anxiety with Numeracy. *The Journal of Psychology: Interdisciplinary and Applied*, 1–29. https://doi.org/10.1080/00223980.2024.2352706; Lunardon, M., Cerni, T., Zanon, M., & Rumiati, R. I. (2024). Physiological correlates of numeracy in higher education. PsyArXiv. https://doi.org/10.31234/osf.io/adnw9.

> If we are to understand how mathematics can become the object of so much passion or hatred, we have to grant as much attention to the syntax of emotions as to the computation of reason.
>
> STANISLAS DEHAENE, *The Number Sense*

Mathematical skills play a critical role in adaptive functioning in modern society. Despite this, mathematics remains a domain characterized by significant learning challenges and declines in this skill have been reported internationally, a trend that predates the global coronavirus pandemic (OECD, 2023). Low mathematical skills have a range of consequences at both the societal level (Butterworth et al., 2011) and the individual level (Parsons & Bynner, 2005), including difficulty with everyday tasks and impact on future career choices. In the 21st century, STEM (Science, Technology, Engineering, Mathematics) competences are in high demand and well paid (National Science Foundation, 2024), but a lack of foundational skills for these areas, represented by mathematics, may prevent individuals from pursuing these careers (Holmes et al., 2018).

Assessing mathematical skills has gained pivotal importance throughout the scholastic path, up to higher education, and several national and international programs have been developed. The most popular are the OECD's Program for International Student Assessment[1] (PISA) for high school students, and the Program for the International Assessment of Adult Competencies[2] (PIAAC) for adults. The theoretical framework, from which these programs stem, define numeracy (also known as mathematical literacy) as a set of knowledge and skills that allow employing mathematics in a variety of private and public contexts, to understand social phenomena, to formulate decisions, and to participate actively in society (Geiger et al., 2015; OECD, 2018; Tout et al., 2021). This concept of numeracy refers to abilities that extend beyond basic numerical cognition and formal mathematical contents acquired at school to broader real-life situations (Gal & Tout, 2014) and its

1 Official website: https://www.oecd.org/pisa/

2 Official website: https://www.oecd.org/skills/piaac/

assessment entails logical reasoning problems and questions that assess the ability to extract and use information from graphs.

Performance in these tests correlated with cognitive factors, including domain-general (such as intelligence, e.g., Song & Su, 2022) and domain-specific numerical skills (Geary, 2011; Ludewig et al., 2020; Morsanyi et al., 2018). However, besides cognition, other characteristics seem to be involved in numeracy performance, such as emotional and personality aspects.

The studies included in this dissertation aim to contribute to advancing the understanding of how math-specific emotional traits, i.e., mathematical anxiety, and broader individual differences, i.e., personality traits, are related to numeracy performance and whether these relationships depend on other individual differences, such as the field of study in higher education and gender. The following paragraphs provide a summary of the research on the association between numeracy and these individual factors to highlight the gaps in the literature.

Numeracy and non-cognitive factors

The term "non-cognitive factors" is a comprehensive concept often used in the economic literature including socio-emotional factors, personality traits, motivations, and preferences (Kautz et al., 2014). The aforementioned personal characteristics can hardly be completely separated from cognition, as cognitive and non-cognitive factors are intertwined and influence each other, jointly affecting academic and life outcomes (e.g., Borghans et al., 2008, 2016). Therefore, in the present work, I adopted the term "non-cognitive" to refer to the personal attributes that cognitive tests are not designed to measure directly, but still contribute to test results. In particular, I focused on the association of math anxiety and personality (i.e., the specific anxious feeling towards mathematics, and the stable pattern of personal characteristics, respectively) with numeracy, which is usually identified as a cognitive competence, but which also relies on personal, social, and learning skills (European Commission, 2006, 2018).

Math anxiety and numeracy

Probably the most extensively studied non-cognitive factor in relation to numeracy is mathematics anxiety, which is a feeling of tension that interferes with number manipulation, calculation and problem solving across daily and academic situations (Cipora et al., 2022; Richardson & Suinn, 1972) and interests the academic population at all ages (Ramirez et al., 2018). Math anxiety is commonly assessed by means of self-report questionnaires, in which individuals are asked to rate on a Likert scale how anxious they feel or have felt in situations involving mathematics (e.g., the Math Anxiety Rating Scale -MARS- Richardson & Suinn, 1972; the Abbreviated Math Anxiety Scale -AMAS-, Hopko et al., 2003; for a review, Cipora et al., 2019).

Higher levels of math anxiety have been consistently associated with lower performance in math-related tasks (e.g., Barroso et al., 2021). Results from the 2012 PISA, which involved about 85.000 15-year-old students, showed that performance in mathematics significantly declines as math anxiety increases and that math anxiety accounts for 14 percent of the variance in the math achievement scores (OECD, 2013). One of the possible explanations for this negative association is the fact that math anxiety leads to avoidance of mathematics-related situations or behaviours (e.g., Ahmed, 2018; Jenifer et al., 2022), which also affects brain plasticity in adolescents (Zacharopoulos et al., 2021).

Two recent meta-analyses estimated a small to moderate correlation between math anxiety and performance in numerical tasks. The effect size is -0.28 when considering studies from 1992 and 2018 (Barroso et al., 2021), and -0.32 for studies from 2000 to 2019 (Zhang et al., 2019). Notably, both meta-analyses have underscored the heterogeneity in the magnitude of this association across studies and have identified several moderating factors, including age, gender, geographical region/ethnicity, and type of math proficiency measures (i.e., basic numerical skills or higher-level math proficiency).

These findings highlight the need to explore individual differences that can account for the variability in the association between math anxiety and math performance. Considering the multifaceted mechanisms that may underlie this association, both task-related factors, such as math motivation (Wang et al., 2015), and broader characteristics, like test and general anxiety (e.g., Carey et al., 2017), should be taken into account. Indeed, moderate to strong correlations have been reported between math anxiety and general trait anxiety (r = .35 - .44) and between math anxiety and test anxiety (r = .52 – .64) (Betz, 1978; Hart & Ganley, 2019; Hembree, 1988, 1990). It has also been shown that development of general anxiety and math anxiety is predicted by common genetic and individual-specific environmental risk factors (Wang et al., 2014). Both types of anxiety share common cognitive biases, such as the tendency to shift attention to emotionally negative stimuli (i.e. numbers; Rubinsten et al., 2015). However, math anxiety and general anxiety are considered as distinct constructs, with stronger correlations between the scores on different math anxiety scales than between math anxiety and general anxiety (Demedts et al., 2022; Dowker et al., 2016).

Personality and numeracy

Stable interindividual differences can be explained in terms of personality (McCrae & Costa, 1999). A well-established taxonomy of human personality is the Five-Factor Model, according to which variability among individuals can be captured by five distinct dimensions (the so called “Big five”): agreeableness, conscientiousness, extraversion, neuroticism (or emotional stability) and openness to experience (Costa & McCrae, 1992; Goldberg, 1990; John et al., 2008). These traits represent enduring individual tendencies to exhibit behavioural, cognitive and affective responses, albeit within specific contexts or in response to particular stimuli (Corr et al., 2013; DeYoung, 2010). Agreeableness concerns the inclination to trust, altruism, kindness, affection, and other prosocial behaviours. Extraversion is characterized by excitability, sociability, talkativeness, assertiveness, and emotional expressiveness. Conscientiousness is associated with the ability to

exert self-control, organize and plan activities, demonstrate good impulse control, and engage in goal-directed behaviours. Neuroticism is characterized by a tendency toward negative affect, including emotions such as fear, anger, worry, and frustration. Openness to experience reflects an interest in art, imagination, and intellectual activities. These five personality traits are typically assessed through self-report questionnaires (e.g., the NEO Personality Inventory, Costa et al., 1991; Costa & McCrae, 1985; the Big Five Inventory, John et al., 1991) and are represented on scales with a positive and a negative pole, where higher levels of the traits correspond to the presence of the described characteristics and lower levels indicate a disposition towards opposite feelings and behaviours.

Differences in the Big Five levels were found to predict individual differences in various cognitive measures, such as visuospatial skills (Carbone et al., 2019), verbal reasoning (Cerni et al., 2021; Chamorro-Premuzic et al., 2006), memory and speed of processing (Simon et al., 2020) and achievement test scores (Borghans et al., 2016). However, in the domain of numeracy, the findings to date exhibit some degree of inconsistency. In studies where numerical ability was assessed in terms of math test scores and school grades, better outcomes were associated with higher levels of conscientiousness and lower levels of neuroticism among eighth, ninth and thirteenth graders (Brandt et al., 2019; Meyer et al., 2019; Spinath et al., 2010). This aligns with the notion that conscientiousness is linked to more effective learning behaviours and lower neuroticism is linked to greater emotional stability, both of which contribute to improved scholastic performance. However, when numeracy was assessed in adults using standardized large-scale assessment tests, outcomes were negatively correlated with conscientiousness, and still negatively with neuroticism (Rammstedt et al., 2016). This finding has been interpreted in light of the “intelligence compensation hypothesis, which suggests that, in the workplace, higher conscientiousness may compensate for lower cognitive ability, whereas individuals with higher cognitive abilities may reach their goals with lower levels of conscientiousness. For students in higher education, Cerni et

al. (2021) observed that, compared with literacy, numeracy was more strongly influenced by Intelligent Quotient (IQ) than by personality traits. However, a moderate association emerged with personality in addition to IQ depending on the level of education. Interestingly, this association was somewhat altered when field of study was simultaneously included as predictor in the model, suggesting that the effect of personality on numeracy is influenced by the specific career path chosen by a student.

The idea that the association between personality and cognition is not fixed has garnered theoretical support from perspectives that emphasize the central role of context. According to the trait activation theory (for a review, Tett et al., 2021), the influence of a personality trait on behaviour and performance depends on situational cues, whether task-related, emanating from the social environment, or arising from the broader organizational context. Within this framework, it is reasonable to predict that personality traits may exhibit distinct associations with numeracy in different fields of study; this is particularly the case when considering fields characterised by different roles and values attached to numeracy, such as the humanities (HUM) on the one hand and STEM on the other. Specifically, given that HUM students are likely less experienced with numerical problem-solving and may hold more negative attitudes toward mathematics than STEM students, certain personality traits that typically support academic success, such as high conscientiousness, which is linked to persistence and planning, and low neuroticism, associated with reduced stress and anxiety, may play a compensatory role in HUM students' numeracy performance. Thus, among HUM students, these traits could be positively associated with numeracy as they help bridge gaps in skills or confidence. In contrast, STEM students are generally more trained in mathematical thinking and may view numerical tasks more positively, potentially minimizing the reliance on personality traits to support performance. As such, we would expect weaker or negligible associations between personality traits and numeracy among STEM students, as their numeracy skills are more directly shaped by their training and interest in mathematics. In

addition, gender may also act as a moderating factor, as men and women students may perceive their academic environment differently, particularly considering their often disproportionate representation in HUM and STEM programs. Traits such as high conscientiousness and low neuroticism may be more strongly associated to numeracy in women than men and this difference may be particularly pronounced among STEM students, where women may feel more pressure to perform highly in numeracy, given its significance in a field where they are outnumbered by men.

Neuroticism in focus

Among the five factors, neuroticism holds particular relevance. Unlike other traits, neuroticism appears across nearly all major personality frameworks. Initially introduced by Eysenck (1947) as a core personality trait, alongside extraversion and psychoticism (Eysenck & Eysenck, 1977), neuroticism is included also in Cattell's (1970) 16-trait model with the name of "Emotional Stability".

Furthermore, traits akin to neuroticism are conceptualized in temperament theories. Temperament indicates stable individual differences present since early childhood with respect to energetic and temporal aspects of behaviour (Strelau, 1993). In this framework, "Emotional Reactivity" is a temperament trait characterized by strong emotional responses to external stimuli, a tendency to react easily to minor triggers, and low tolerance for stimuli that provoke intense emotions.

Several studies focused on the biological basis of neuroticism. Its heritability is high, estimated at 39–48%, independent of theoretical framework (Vukasović & Bratko, 2015). Moreover, neurobiological evidence supports the idea of neuroticism as a trait associated with reduced emotion-regulation abilities. Studies highlight reduced connectivity between the amygdala and the prefrontal cortex in individuals with high neuroticism, which can impair the prefrontal

cortex ability to effectively modulate the anxiety and fear responses in the amygdala (Ormel et al., 2013).

These findings underscore the unique and pervasive role of neuroticism, making it a critical factor in understanding individual differences in emotional stability and reactivity.

The moderating role of field of study

The pursuit of a specific field of study in higher education depends on a multitude of personal and affective factors. It has been observed that math anxiety, for example, deters individuals from entering careers with dense math content (Ahmed, 2018; Beilock & Maloney, 2015; Cuder et al., 2024; Luttenberger et al., 2018; Schmitz et al., 2023). Indeed, in higher education, math anxiety has been found to affect about one-third of the students who seek assistance from university counselling services (Suinn, 1970). Math anxiety even extends to students with good mathematical backgrounds, who are more likely to pursue STEM disciplines (Betz, 1978). Moreover, the longitudinal trajectory of math anxiety from middle school to high school predicted the probability of undertaking STEM majors: consistently low or decreasing math anxiety during schooling was related to later students' choice of scientific studies (Ahmed, 2018). Math anxiety was shown to have an impact on STEM outcomes, too: higher levels of math anxiety predicted lower STEM grades and a lower number of STEM courses taken, independent of individual math ability (Daker et al., 2021).

Additionally, personality is interwoven with interests and motivation, exerting a significant influence on individuals' choice of undergraduate programs (Pozzebon et al., 2014). This results in personality differences across fields of study. In comparison to other majors, including STEM, students in arts and humanities tend to report higher levels of neuroticism and openness to experience, along with lower levels of conscientiousness (for a review, see Vedel, 2016). Similar findings are observed among prospective college students (Balsamo et al., 2012; Verbree et al.,

2021), suggesting that these personality differences predate the choice of the field of study. Indeed, different personality traits may be advantageous in different academic contexts, contributing to success in one field but not in a different one (e.g., Vedel et al., 2015).

In summary, both math anxiety and personality traits are associated with behavioural tendencies that influence academic choices and outcomes. However, whether these non-cognitive factors play different roles towards non-curricular transversal skills, such as numeracy, is yet to be clarified. While there is some evidence indicating that the effect of personality on numeracy is not independent of the career chosen by a student (Cerni et al., 2021), the question of whether personality traits differently contribute to numeracy in different fields of study remains open.

The moderating role of gender

Gender[3] is intertwined with the choice of field of study. It is widely acknowledged that certain fields exhibit pronounced gender imbalances, with women being overrepresented in HUM and underrepresented in STEM (e.g., Eurostat, 2022). This imbalance has been attributed to a persistent gender gap in mathematical skills. Indeed, international assessment programs showed from their first rounds that women's and girls' achievement in numeracy is lower than men's and boys' (Stoet et al., 2016). This gap shows up earlier in education (Mullis et al., 2020), and grows later on through adolescence (INVALSI, 2019; OECD, 2019) up to adulthood (Borgonovi et al., 2021). However, the gender disparity is not consistent across countries (Else-Quest et al., 2010), with more egalitarian countries, with equal educational opportunities for women and men, displaying a smaller or non-existent gender gap (Cook, 2018; Guiso et al., 2008; Spelke, 2005). Recent research failed to find empirical support for gender differences in basic numerical skills and early mathematical cognition (e.g., number and dot comparison, dot estimation and arithmetic, Hutchison et al., 2019; numerosity perception, counting and elementary school-based math concepts, Kersey et al., 2018),

[3] Gender can be described as the set of roles, behaviours and identities that society ascribes to men and women (see Heidari et al., 2016). I am aware that gender entails a spectrum of identities. However, for the purpose of this research, I decided to consider gender as a binary factor (i.e., men vs. women), in line with the reviewed studies.

suggesting that girls and boys enter formal education with the same level of mathematical knowledge. Thus, the numeracy disparity between genders, which is still observed in standardized numeracy tests in various countries, is unlikely to be exclusively associated with pure cognitive factors, such as basic numerical skills. Other non-cognitive factors seem to contribute to its existence. Consequently, it is plausible that gender differences in attitudes toward mathematics, rather than differences in cognitive abilities, contribute to the observed gender imbalance in the chosen fields of study.

Previous research consistently indicates higher levels of math anxiety in women compared to men (Betz, 1978; Ferguson et al., 2015; Hill et al., 2016; Rubinsten et al., 2012; Stoet et al., 2016), potentially making women more susceptible to the adverse effects of elevated math anxiety. A recent study found that the effect of gender on mathematical performance was indeed mediated by math anxiety, in both a simple and a complex arithmetic task (Vos et al., 2023). However, it remains unclear whether numeracy performance is correlated differently with math anxiety in men and women. While some evidence suggests that math performance is more affected by math anxiety in female students (Devine et al., 2012; Van Mier et al., 2019), meta-analytic results found a similar correlation across genders (Barroso et al., 2021; Hembree, 1990; Ma, 1999; Zhang et al., 2019).

Different reasons have been discussed for the higher math anxiety level in women, involving cognitive and non-cognitive factors (for review, see, e.g., Suárez-Pellicioni et al., 2016). As to the non-cognitive factors, several studies showed differences in the way men and women experience mathematics. Attitudes and emotions towards mathematics are more negative in girls and women than boys and men (Cohen et al., 2021; Else-Quest et al., 2010; Muzzatti & Agnoli, 2007; Pipere & Mieriņa, 2017; Rodríguez et al., 2020). For instance, girls and women develop lower levels of mathematical self-concept (i.e., one's own beliefs about being competent in math; Goetz et al., 2007; Mejía-Rodríguez et al., 2021), self-efficacy (i.e., the belief that personal action and effort can lead to success in mathematics; Louis & Mistele, 2012), and math motivation (i.e., the personal

investment and success in solving math problems, Milovanović, 2020), and they are more affected by math-related gender stereotypes, as women often are the disadvantaged group in these stereotypes (Appel et al., 2011; Spencer et al., 1999). All these personal dispositions towards math may contribute to increasing math anxiety and, as a consequence, to impact numeracy performance (Suárez-Pellicioni et al., 2016). On the other hand, gender differences in math anxiety may also be related to a greater personal inclination to feel anxious. Importantly, compared to men, women report higher levels of general anxiety (Núñez-Peña et al., 2019; Szczygie, 2020) as well as higher rates of clinical anxiety (for a review, McLean et al., 2011). However, some studies showed a discrepancy between trait math anxiety and state math anxiety in women, but not in men, suggesting that the higher math anxiety reported by women may depend on them being more open to report anxiety rather than on actual differences in experienced distress during a numerical task (Bieg et al., 2015; Goetz et al., 2013; for general anxiety related variables, see Porter et al., 2000).

Notably, beyond general anxiety, gender differences also extend into broader personality traits, with women generally reporting higher levels of agreeableness, conscientiousness, extraversion and neuroticism compared to men (Chapman et al., 2007; Schmitt et al., 2008; Weisberg et al., 2011). These differences may play a role in shaping distinct career preferences between genders. However, whether gender moderates the association between numeracy and personality has not yet been investigated.

Non-cognitive factors, numerical skills and IQ

In my research, I adopted OECD's (2013) definition of numeracy in terms of mathematical literacy, which includes the ability to use mathematics in a variety of contexts. This involves the ability to reason logically and to identify relationships between variables and numbers. To solve numeracy problems, one can use knowledge acquired through education or devise different strategies, such as applying arithmetic algorithms or basic geometric rules and their combinations

(ANVUR, 2018). Numeracy thus defined is therefore a high-level cognitive process, supported by lower-level domain-general skills, such as general cognitive skills and abstract reasoning (Duckworth et al., 2012; Passolunghi et al., 2014; S. Song & Su, 2022; Zhang et al., 2017), and domain-specific skills, such as basic numeracy skills like numerical estimation or arithmetic operations (Geary, 2011; Ludewig et al., 2020; Sasanguie et al., 2012; Xu et al., 2023). In other words, mastery of these low-level cognitive skills contributes positively to numeracy.

Research has shown that even these low-level cognitive skills are influenced by non-cognitive factors, such as personality and math anxiety. For example, processing speed was positively correlated with conscientiousness, while reasoning and language showed negative associations with extraversion and neuroticism. In contrast, openness was positively correlated with all the cognitive skills mentioned (Simon et al., 2020). Visuospatial skills showed positive associations with conscientiousness and negative associations with neuroticism (Carbone et al., 2019). Finally, basic numerical skills, such as magnitude representation, were found to be negatively correlated with math anxiety (Maloney et al., 2011). Consequently, when evaluating the association between higher-level numerical competence and non-cognitive factors, it is critical to test whether this association remains significant even after lower-level cognitive factors are taken into account. This approach allows us to assess the robustness of the relationships examined. However, studies inquiring about the influence of non-cognitive factors on numeracy in addition to lower-level skills are limited and often produce divergent results depending on differences in the skills considered and the tasks used (e.g., Douglas & LeFevre, 2017; but see also Maldonado Moscoso et al., 2020). For instance, Daker et al. (2021) confirmed the robustness of the association between math anxiety and STEM outcomes (such as STEM course attendance and STEM grades) by considering arithmetic skills as a covariate. This ensures that the effect of math anxiety on higher-level performance is not explained by its shared association with basic numerical skills.

To the best of our knowledge, studies investigating the association between personality and numeracy only assessed mathematics school achievement or mathematical literacy (Brandt et al., 2019; Cerni et al., 2021; Meyer et al., 2019; Rammstedt et al., 2016; Spinath et al., 2010). In these studies, lower-level numerical skills have been neglected. However, personality correlates with several cognitive processes, including visuospatial abilities (Carbone et al., 2019), which are known to contribute to a range of numerical abilities (for a review, Cui & Guo, 2022). Therefore, it is appropriate to hypothesize a potential shared variance between personality and several basic numerical processes to explain the personality-numeracy association.

Finally, general cognitive ability, in terms of IQ, is also a determining factor when considering the association between personality and numeracy. Correlations between personality and intelligence have been reported frequently (for a meta-analysis, Anglim et al., 2022), as both are key sources of individual differences in behaviour and cognitive performance. Therefore, intelligence is a key variable when studying independent associations between personality traits and mathematical achievement or numeracy (Borghans et al., 2016; Brandt et al., 2019; Cerni et al., 2021).

Numeracy and physiological responses

As mentioned in the previous paragraphs. the most common way to measure non-cognitive factors, both in terms of math anxiety and personality, is to use self-report scales. This technique has several advantages, such as the speed and ease of administration. However, such measures represent an a posteriori evaluation of experiences and psychological states, which may be biased by individuals' level of self-awareness or by the image they wish to present of themselves ("social desirability bias"). Therefore, self-report scales should be integrated with online measures of emotional and psychological reactions during the performance of an anxiety-provoking mathematical task (Cipora et al., 2022).

Changes in physiological activity can be used to track changes in psychological states. The activity of peripheral organs is influenced by central regulatory systems, such as the hypothalamic-pituitary-adrenal (HPA) axis and the autonomic nervous system (ANS), which work to maintain internal homeostasis in response to external demands. The HPA axis, a hormonal system, initiates a cascade of events over several minutes, culminating in the release of cortisol from the adrenal cortex (Rotenberg & McGrath, 2016). The ANS, through its sympathetic and parasympathetic branches, innervates and rapidly modulates the activity of various peripheral organs, such as the heart and sweat glands. The HPA axis and the ANS work together to ensure an appropriate behavioural response (Kreibig & Gendolla, 2014). Consequently, physiological measures representing the activation of these systems are used as indicators of arousal to understand individual differences in behaviour.

The most common physiological measures of arousal include salivary cortisol, skin conductance level (SCL) and heart rate variability (HRV). Salivary cortisol concentrations reflect the response of the HPA axis to external or internal events aimed at restoring homeostasis (Russell & Lightman, 2019). SCL represents the tonic electrodermal response caused by the activation of the sweat glands, which are innervated by the sympathetic branch of the ANS (Boucsein, 2012). HRV indicates the variation in time between successive heartbeats and represents vagal withdrawal, i.e., the inhibition of the parasympathetic branch of the ANS. This inhibition results in the activation of the cardiac system to induce rapid adaptation and prepare the body for external demands (Berntson et al., 1997; Laborde et al., 2017). Therefore, increased salivary cortisol, increased SCL and decreased HRV can be considered as signs of physiological arousal.

Changes in these physiological measures are traditionally linked to changes in affective states, including those in the mathematical domain (Cipora et al., 2019). In a seminal study, Faust (1992) administered a mental arithmetic task to undergraduate psychology students while recording multiple physiological indicators, including skin conductance. Results showed that students with

high math anxiety exhibited significantly greater global physiological reactivity during the task than those with low math anxiety. This heightened reactivity was observed across both easy and difficult items and was specific to the mathematical task. In primary school children, Mammarella and colleagues (2023) administered a mental arithmetic task to primary school children and manipulated stress levels by providing either positive ('no stress condition') or negative ('high stress condition') feedback to children's responses on a trial-by-trial basis. In children in the high-stress condition, they observed a significant increase in SCL and decrease in HRV, suggesting that negative math-related experiences can increase arousal. Higher physiological arousal, representing negative affective states such as math anxiety, may have an impact on math performance. For example, Tang and colleagues (2021) measured HRV during a mathematical task in middle school students and found that it mediated the relationship between self-reported math anxiety and math performance, with higher self-reported math-anxiety being associated with lower HRV and in turn with longer response times in the arithmetic task. Along the same lines, Daker and colleagues (2023) suggested that, among young adults with low HRV, the negative effect of self-report math anxiety on performance was due to the feelings of anxiety experienced during the task. In other studies, with university students, increased skin conductance has been associated with poorer mental arithmetic performance (Pizzie & Kraemer, 2021; Salvia et al., 2013), particularly in participants with high self-reported math anxiety (Pizzie & Kraemer, 2021). These individuals are likely to be more sensitive to physiological arousal and may tend to focus their attention on these reactions, reducing the cognitive resources available for the task (e.g., Jamieson et al., 2021). Indeed, when participants with higher math anxiety are instructed to reappraise the situation and interpret the test and their bodily responses in a more positive light (an emotion regulation strategy known as cognitive reappraisal), the negative association between physiological arousal and performance is reduced (Pizzie & Kraemer, 2021).

It should be noted, however, that studies investigating associations between physiological measures and scores on self-report math anxiety questionnaires are inconclusive and sometimes conflicting. For example, Demedts and colleagues (2023) found a significant positive association of self-reported math anxiety with skin conductance, recorded in university students while they performed a fraction comparison task. On the contrary, Qu and colleagues (2020), who measured the SCL of high school students taking a math exam, reported a negative correlation between scores on a math anxiety questionnaire and SCL before starting the exam. On the other hand, other studies found no correlations between self-reported math anxiety and SCL or HRV (Daker et al., 2023). Therefore, physiological responses should be interpreted with caution as indicators of math anxiety (Demedts et al., 2023; Dew et al., 1984).

There is also evidence that increased physiological response is associated with better performance, and self-reported math anxiety appears to moderate this association. Mattarella-Micke et al. (2011) found that higher salivary cortisol following the completion of challenging math problems was associated with better performance in individuals with low math anxiety. Conversely, higher salivary cortisol was negatively correlated with performance in individuals with high math anxiety. These findings challenge the view that increased physiological arousal only represents negative affect experienced during the task. Physiological arousal may also indicate mental effort, which supports test performance (Mendes & Park, 2014). In this case, physiological arousal cannot be identified as a proxy for self-reported math anxiety. Instead, individual differences in self-reported math anxiety may account for the differential impact of physiological responses.

Accounting for variability in physiological correlates: The biopsychosocial model

The biopsychosocial model accounts for individual differences in arousal regulation processes and their relationship to motivation and behaviour. Activation of the ANS and HPA systems is not uniquely representative of a particular psychological state, as physiological responses interact with

intrapersonal and interpersonal variables in a context-specific manner. In particular, individual differences in the context and task appraisals play a crucial role (Blascovich & Mendes, 2010; Mendes & Park, 2014). When individuals are confronted with a goal-relevant situation, their appraisal of this situation as a challenge (i.e., when individual resources are perceived as adequate for the demands) or as a threat (i.e., when demands are perceived as exceeding the individual resources) leads to different interpretations of physiological arousal, with different consequences for behaviour. Feeling challenged may lead to approach behaviour, actively responding to the situation or stimulus to achieve a goal, whereas feeling threatened may lead to avoidance behaviour, moving away from or ignoring the situation or stimulus.

Whether an individual evaluates a situation as challenging or threatening can be influenced by dispositional and affective factors, either across contexts or specifically in the domain of math. Being more prone to experience low optimism, lack of control and low resilience may lead individuals to evaluate situations more negatively in general (Tomaka & Magoc, 2021), including the situation of a numeracy test. These individual characteristics are captured by the personality trait neuroticism, which has been shown to be negatively associated with numeracy performance (e.g., Rammstedt et al., 2016; but see also Cerni et al., 2021). However, to date, no study has investigated whether different levels of neuroticism influence physiological arousal and behaviour, particularly in the mathematical domain. Moreover, it has been argued that math anxiety and its negative impact on performance is due to students' negative interpretation of their math-related experiences (Ramirez et al., 2018). Experiencing sweaty palms or an accelerated heartbeat is commonly understood as a sign of likely failure. Interpreting these reactions as indicative of a challenging situation could improve performance, whereas interpreting them as math-related distress could instead lead to worrying thoughts and impair performance. The findings of Mattarella-Micke and colleagues (2011) are consistent with this account, where different interpretations of physiological

cues are captured by different levels of self-reported math anxiety. Whether this also is true for other measures of physiological arousal remains to be investigated.

Dissertation overview

Numeracy is a complex skill influenced by various factors. Understanding the underpinnings of successful numeracy mastery requires considering the role of affective and dispositional factors, especially in young adults pursuing university-level education. University education prepares individuals for specific careers and to work life in general, with different careers favouring different individual characteristics. Gender is also a key variable, as socio-cultural influences may differently encourage men and women to pursue specific careers. Understanding whether and how these individual characteristics differ in their association with numeracy is crucial, given the universal importance of numeracy.

The aim of this thesis is to deepen our understanding of the multifaceted mechanisms through which non-cognitive factors are associated with numeracy performance among higher education students. Specifically, my work aims to answer the following questions:

a) How does numeracy relate to math anxiety and personality traits in higher education?

b) b) Do these associations differ between fields of study (specifically, whether it is in the HUM or STEM domain) and gender? Note that field of study and gender represent different types of categorizations. Gender is attributed at birth and predates formal mathematical learning. Field of study is a choice made considering individual characteristics, both in terms of personality and in terms of attitudes and preferences for specific subjects, including mathematics. Investigating differences between fields of study does not imply that these differences are due to the different field of study, because it cannot be excluded that other variables at the basis of the field choice may be responsible for these differences."

c) Do these variables modulate the association between physiological responses and numeracy performance?

The thesis is organised into four studies. In Study 1 (Lunardon et al., 2022), I investigated gender differences in a group of STEM undergraduates. Using moderated mediation analysis, I tested whether the association between math anxiety and numeracy could be explained by differences in the personality trait neuroticism and whether the effect of neuroticism differed between men and women. Study 2 (Lunardon et al., 2024) included also HUM students and focused on the moderation of both field of study and gender on numeracy association with math anxiety and the five personality traits. Importantly, I additionally tested whether these moderation effects were influenced by the inclusion of cognitive skills, i.e., basic numerical skills and IQ, in the statistical models. After two years, I reassessed the students from Study 2 to investigate the longitudinal associations between numeracy, math anxiety and personality (Study 3). Finally, in Study 4 I recorded multiple physiological responses of university students while they performed the numeracy test. The goal was to test whether the association between numeracy performance and physiological response was modulated by math anxiety and neuroticism and to unveil field- and gender-related differences in these associations.

In all studies, numeracy was assessed by means of an ad-hoc copy of the large-scale test designed by ANVUR (Agenzia Nazionale per la Valutazione del sistema Universitario e della Ricerca, Italian National Agency for the Evaluation of University and Research) to evaluate students' transversal cognitive competencies throughout university (Rumiati et al., 2018). In line with international frameworks for the lifelong assessment of cognitive competencies (Geiger et al., 2015; Tout et al., 2021), this numeracy test evaluates logical and quantitative thinking skills, independent of curricular teaching. The test included 15 multiple choice questions, each consisting of a word problem and four response options. The questions were grouped into three modules: "Graphs and Tables", "Logical reasoning" and "Infographics" (for administration details, see

Materials and Methods sections of Chapters 2-5). An English translation of the test is provided in the Appendix. Therefore, the results of these studies may not only advance our knowledge of the underpinnings of good numeracy performance but also provide policymakers and stakeholders, particularly in Italy, with evidence of the importance of considering non-cognitive factors when addressing numeracy.

CHAPTER 2

Study 1. Numeracy Gender Gap in STEM Higher Education: The Role of Neuroticism and Math Anxiety

Adapted from Lunardon, M., Cerni, T., & Rumiati, R. I. (2022). Numeracy Gender Gap in STEM Higher Education: The Role of Neuroticism and Math Anxiety. *Frontiers in Psychology*, *13*, 856405. https://doi.org/10.3389/fpsyg.2022.856405

Abstract

The under-representation of women in science, technology, engineering and mathematics (STEM) is ubiquitous and understanding the roots of this phenomenon is mandatory to guarantee social equality and economic growth. In the present study, we investigated the contribution of non-cognitive factors that usually show higher levels in women, such as math anxiety and neuroticism personality trait, to numeracy competence, a core component in STEM studies. A sample of STEM undergraduate students, balanced for gender (N_F = N_M = 70) and Intelligent Quotient (IQ), completed online self-report questionnaires and a numeracy cognitive assessment test. Results show that women scored lower in the numeracy test, and higher in the non-cognitive measures. Moreover, compared to men's, women's numeracy scores were more strongly influenced by math anxiety and neuroticism. We also tested whether math anxiety association to numeracy is mediated by neuroticism, and whether this mediation is characterized by gender differences. While we failed to detect a significant mediation of neuroticism in the association between math anxiety and numeracy overall, when gender was added as a moderator in this association, neuroticism turned out to be significant for women only. Our findings revealed that non-cognitive factors differently supported numeracy in women and men in STEM programs.

Introduction

The gender gap in science, technology, engineering and mathematics (STEM) careers, which almost always penalizes women, is at the core of current educational and economic debates. In Italy, for instance, in 2019 only 37% of the students enrolled in a scientific undergraduate course were women, and the rate of women full professors in STEM was even lower (21%, Morana & Sagramora, 2021). Overcoming the gender gap in STEM is required to achieve gender equality and promote socio-economic development. In fact, reaching gender equality is estimated to increase

total European jobs from 850.000 to 1.200.000 units by 2050 (European Institute of Gender Equality, 2017).

In the present study, we focused on the gender gap observed for numeracy competence, as its mastery is predictive of success and retention in STEM careers (Holmes et al., 2018; Watt et al., 2016). Here, we investigated whether such competence is differently supported by two non-cognitive factors – math anxiety and neuroticism – in men and women students at the beginning of a STEM career. Understanding gender differences in numeracy among STEM students may add further details on the reasons why women are penalized in STEM education and career path.

Neuroticism, numeracy and gender gap. A possible connection?

As described in Chapter 1, in addition to gender differences in numeracy and math anxiety, women and men are also found to differ in other aspects of emotional functioning. For instance, women report higher levels of general anxiety (Núñez-Peña et al., 2019; Szczygie, 2020) and correspondingly higher levels of neuroticism (Chapman et al., 2007; Costa et al., 2001; Schmitt et al., 2008; Weisberg et al., 2011). Higher-order trait neuroticism is associated with stable personal dispositions to anxiety, and to emotional instability in general (e.g., Soto & John, 2017). Neuroticism is characterized by sadness, fear, and emotional instability (Marengo et al., 2021). Individuals who are high in this trait tend to fail in coping with frustration, irritability, and stress, and are more reactive and more sensitive to criticism and hostility; in contrast, those who are low tend to be more emotionally stable and resilient (Costa & McCrae, 1992). Higher levels of neuroticism were associated with higher likelihood of manifesting anxiety symptoms (Kotov et al., 2010; Lyon et al., 2021; Sexton et al., 2003), thus making plausible an association of this trait also with math anxiety. To date, however, the relationship between math anxiety and neuroticism has not been fully investigated (but see Cipora et al., 2024). Studies has reported findings indicating a

moderate association between math anxiety and neuroticism (Rossi et al., 2023) and between math anxiety and emotion reactivity, a temperament trait akin to neuroticism (Cipora et al., 2015).

There is evidence supporting the predictive role of personality in accounting for individual differences in performance on large-scale competence assessment tests (Borghans et al., 2016; Cerni et al., 2021). Neuroticism, in particular, was found to negatively correlate with performance on various cognitive tasks. Higher levels of neuroticism correlated with lower scores on verbal reasoning (Cerni et al., 2021; Chamorro-Premuzic et al., 2006) and intelligence (Graham & Lachman, 2014; Moutafi et al., 2006), as well as with slower reaction times in response inhibition (Graham & Lachman, 2012). Considering numeracy, neuroticism seems to negatively affect numeracy test performance (Brandt et al., 2019; Rammstedt et al., 2016; Spinath et al., 2010), even if findings are not consistent; indeed, in some studies, no association between numerical skills and neuroticism was documented (Cerni et al., 2021; Chamorro-Premuzic et al., 2006; Meyer et al., 2019).

To sum up, neuroticism was found to have an impact on numeracy, but results were mixed. In our opinion, considering jointly neuroticism and math anxiety, where men and women tend to consistently show differences, should promote a better understanding of the mechanisms underlying gender differences in numeracy competence.

The present study

The aim of this study was to investigate the relationship between math anxiety, neuroticism and numeracy, and related gender differences. We advance the proposal that neuroticism level should correlate with math anxiety (as general anxiety does), and so a gender gap in math anxiety may be linked to a gender gap in neuroticism. With an exploratory approach, we proposed that these correlations may differently interact with numeracy performance in men and women.

We tested our hypotheses in a sample of undergraduate STEM students. In this field, women are dramatically underrepresented (Morana & Sagramora, 2021) and therefore gender differences in numeracy and math-related affects have been largely overlooked.

Although common sense would suggest that math anxiety does not trouble STEM students, there are findings implying the contrary. Even among students that planned careers or majors with extensive mathematical teaching, feelings of uneasiness about math teaching and testing are common (Betz, 1978; Kaleva et al., 2019).

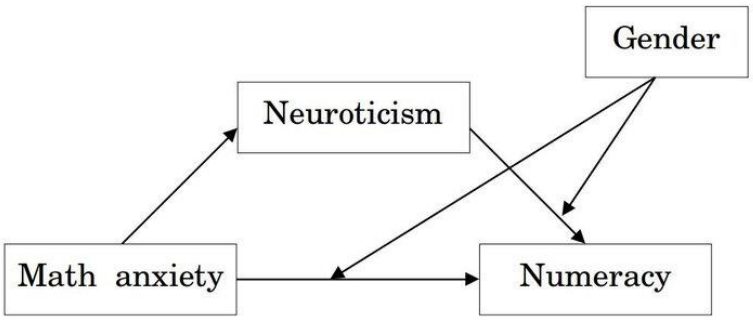
We thus recruited a sample of men and women STEM undergraduates, with equal levels of Intelligent Quotient (IQ), a variable that strongly affects numeracy (e.g., Cerni et al., 2021). We collected measures of math anxiety and neuroticism using self-report questionnaires. Additionally, to measure numeracy, we administered a competence assessment test based on the one developed by the Italian National Agency for the Evaluation of Universities and Research Institutes (Agenzia Nazionale per la Valutazione del Sistema Universitario e della Ricerca, ANVUR).

We tested whether in this sample gender differences would emerge in numeracy, math anxiety and neuroticism scores and whether the non-cognitive factors would be differently related to numeracy in men and women. Based on previous findings, we expected (1) a gender disparity in numeracy scores, even if the whole sample was familiar with mathematical and numerical contents, (2) higher levels of math anxiety and neuroticism in women than in men. (3) a stronger association of the non-cognitive variables with numeracy in women than in men. Moreover, we explored a possible pattern of relationships among these variables through a mediation analysis. We examined whether the direct association between math anxiety and numeracy may be partially mediated by neuroticism. In our view, a domain-specific effect, such that of math anxiety on numeracy, may be partly driven by more general personal predisposition, in this case the tendency to be emotional instable. Subsequently, we investigated whether differences between men and women may emerge

in this pattern of relationships, by adding gender as a moderator of the influence of the non-cognitive factors on numeracy (see Figure 1 for a graphical representation of the paths).

We believe that investigating these patterns will provide a better understanding about the extent to which non-cognitive skills contribute to numeracy performance among STEM students, who are expected to be more proficient in this competence, and about the possible gender differences in a field where women need to be encouraged.

Figure 1. The moderated mediation model tested in the present study. Arrows showed the direction of the predicted effects. Neuroticism is the mediator, while gender moderates the path from math anxiety to numeracy e from neuroticism to numeracy.



Materials and methods

Participants

Participants volunteered in the context of an ongoing research project involving freshmen and senior students from Italian universities. Recruitment was restricted to university students aged between 18 and 30 with no history of developmental and/or learning disorders. In the present study, we included students enrolled in STEM undergraduate courses[4] (N = 146, women = 76). Then, we selected a subgroup of women matched to men for IQ (see Materials for details on IQ measure). This matching procedure led to a final sample of 140 participants divided into two groups (70 women and 70 men). Moreover, we controlled for group differences in personal characteristics, in

[4] The identification of undergraduate courses as STEM was based on the official classification made by the Italian Ministry of University and Research (Decree Law 942/2020, Attachment A).

particular, age, education (i.e., total years of formal education), math knowledge at university entry (i.e., the final high school grade in mathematics), average grade[5], European Transfer and Accumulation System (ECTS) credit points[6] at the time of the test (as a measure of the learning achievements they accomplished), ECTS points specifically for math and socio-economic status[7]. Table 1 shows descriptive statistics for each group and corresponding *t*-tests. All the control variables did not statistically differ between the two groups.

The majority of students were registered at mathematics (N_W = 12; N_M = 16), information engineering (N_W = 9; N_M = 11), and industrial engineering (N_W = 7; N_M = 9). The courses with the highest women ratio were biotechnologies (N_W = 8; N_M = 1), food science and technologies (N_W = 3; N_M = 1), statistics (N_W = 8; N_M = 4) and biology (N_W = 7; N_M = 3). The courses with the highest men ratio were chemistry and environmental sciences (N_W = 1; N_M = 2) and physics (N_w = 6; N_M = 11). Details about the specific degree courses attended by participants divided by gender can be found in the Supplementary Table 1.

Participants gave written informed consent before study participation. After completing the tasks, they received 12 euros as reimbursement for the time they spent regardless of the results obtained. The study was approved by the SISSA Ethics Committee and was conducted according to the guidelines of the Declaration of Helsinki.

Statistical power for the mean differences between two groups was estimated with the G*Power statistical software (Faul et al., 2009). With an alpha level of .05, a medium effect size can be detected with 140 participants with a power of .90. For the mediation analysis, statistical power was estimated with Monte Carlo power analysis for indirect effects through the online software designed by Schoemann et al. (2017). With an alpha level of .05 and assuming a correlation of .55

[5] In the Italian university system, the exam grades range from a minimum of 18/30 to a maximum of 30/30 (with or without laude).

[6] 60 ECTS are equivalent to a full year of study. A bachelor's degree consists of 180 ECTS (European Commission, 2015).

[7] This corresponds to the parents' highest level of completed education, based on the International Standard Classification of Education (ISCED).

between math anxiety and neuroticism (e.g., correlation between math anxiety and general test anxiety, Ganley et al., 2021), of .40 between math anxiety and numeracy (e.g., approximate correlation between math anxiety and multiplication problem accuracy in undergraduate students, Hoffman, 2010) and of .03 between neuroticism and numeracy (e.g., Cerni et al., 2021), in simple mediation analysis a power of .85 can be reached with 140 participants.

Table 1. Descriptive statistics of women and men participants

	Women					Men					*t*	*p*
	N	Mean	*SD*	Min	Max	*N*	Mean	*SD*	Min	Max		
Age	70	21.4	1.89	19	30	70	21.19	1.64	19	27	0.72	.475
IQ	70	123.34	8.63	78	128	70	123.66	8.86	76	128	-0.21	.832
Level of education	70	15.34	0.95	14	16	70	15.23	0.98	14	16	0.70	.484
Math grade in high school	69[a]	8.41	1.24	6	10	70	8.36	1.26	6	10	0.20	.845
Average grade at university	66[a]	25.4	2.43	21	30	69[a]	25.65	2.37	20	30	-0.59	.557
Total ECTS	70	85.46	52.34	0	171	70	91.47	61.07	0	180	-0.63	.533
ECTS in math	70	33.21	35.76	0	157	70	39.83	42.65	0	159	-0.99	.322
Socio-economic status	70	4.54	2.05	0	8	70	4.66	1.94	2	8	-0.34	.736

Procedure

The study was carried out online from March to July 2021 and was advertised through online channels (Facebook, Sona). Participants received the instructions and the links to the tasks via e-mail. The tasks were administered in two separate sections, no more than two weeks apart, to prevent participants' fatigue. The first section included personal information questions (as detailed in the Participant section), the Raven's Progressive Matrices, the Abbreviated Math Anxiety Questionnaire (AMAS) and the Big Five Inventory (BFI). This section ended with a set of cognitive tasks, which are not part of the present study. The second section included a numeracy test. The order of the tasks was the same for all participants. All the tasks and questionnaires employed in the present work were administered through Google Forms. Details are provided in the below sections.

Materials

Raven's Progressive Matrices. A reduced nine-item form of the Raven's Standard Progressive Matrices was used (Bilker et al., 2012). The individual score on the nine-item scale was transformed in the prediction of the total score on the 60-item scale applying the formula reported by Bilker et al. (2012). The predicted total score was converted into an IQ score according to age-appropriate standardization (Raven, 1938; Valseschini, & Del Ton, 1973).

Big Five Inventory (BFI). Neuroticism was assessed with the relative items of the BFI (John et al., 1991; Italian version: Ubbiali et al., 2013; English version available online https://www.ocf.berkeley.edu/~johnlab/bfi.htm). This questionnaire consists of 44 items evaluating the traits of the Five Factor model (agreeableness, conscientiousness, extraversion, neuroticism and openness to experience). Eight of these items assess neuroticism. Each item corresponds to a statement and participants have to rate their agreement on a five-point Likert scale, with 1 indicating "Strongly disagree" and 5 "Strongly agree". The mean score for trait neuroticism was calculated. In our sample, Chronbach's alpha for the Neuroticism items was 0.85.

Abbreviated Math Anxiety Scale (AMAS). The AMAS[8] (Hopko et al., 2003; Italian version: Primi et al., 2014) consists of nine items, each representing a situation regarding mathematical learning or testing, and participants had to indicate on a five-point Likert scale the level of anxiety experienced in that situation (1 = Low anxiety; 5 = High anxiety). The AMAS total score was calculated for each participant as the sum of the 9 items. Higher scores correspond to high math anxiety levels. Cronbach's alpha for our sample was of 0.85.

Numeracy test. To measure numeracy competence, we built a reproduction of the TECO-T (TEst of COmpetence), developed by ANVUR (Agenzia Nazionale per la Valutazione del sitema Universitario e della Ricerca), the Italian National Agency for the Evaluation of Universities and

[8] AMAS was provided by the Italian standardization authors after request

Research Institutes, to evaluate students' generic literacy and numeracy competencies acquired during the university course (Rumiati et al., 2018). The items of the present numeracy test entailed the same structure and the same difficulty level as the TECO-T: an ANVUR member, expert in achievement test development, reviewed the design and the contents of the present test. The numeracy test assessed logical and quantitative thinking skills, and its content was not related to curricular teaching. The test included 15 multiple-choice questions, each consisting of a word problem and four response options. The questions are grouped into three modules of five questions each. In the "Graphs and Tables module", participants had to extract information from a graph (3 items) or a table (2 items) to infer relations between variables. In the "Logical reasoning" items, conclusions had to be drawn based on some numerical or verbal premises. To answer the questions of the "Infographics" module, participants had to infer information from visually represented data concerning the elderly population in Italy. Participants had 40 minutes to complete the test[9]. Item score was 1 (right) and 0 (wrong). The sum of correct answers was converted into an accuracy rate as a measure of numeracy competence. The TECO-T was standardized on a representative sample of 827 Italian undergraduate students (ANVUR, 2016, 2021).

Data analysis

All analyses were performed using the free software R v.4.1.1 (R Core Team, 2020).

As a first step, we carried out a set of *t*-tests to investigate gender differences between the variables of interest: neuroticism, math anxiety and numeracy. Moreover, to test whether numeracy is differently related to math anxiety and neuroticism according to gender, we ran Pearson correlation analyses on the whole sample and separately for women and men. We then conducted path analysis-based mediation to explore whether the effect of math anxiety on numeracy is mediated by neuroticism regardless of gender. Subsequently, we performed a moderated mediation

[9] We used the Apps Script tool in Google Form to build a function that forces the form to close after 40 minutes.

analysis (Holland et al., 2017; Preacher et al., 2007), where gender was entered as a moderator in the previous mediation model. The mediation and the moderated mediation analyses were conducted with the PROCESS tool for R (Hayes, 2021). An index of moderated mediation was used to test the significance of the moderated mediation, i.e., the difference of the indirect effects between men and women (Hayes, 2015). The continuous variables were standardized before estimating the models in PROCESS to obtain standardized regression coefficients (β) and standardized indirect effect indexes. Indirect mediating effects and the index of moderated mediation were evaluated with 95% confidence intervals (CIs) estimated using bootstrapping with 10000 samples. If the CI did not contain zero, the indirect effect and the index of moderated mediation were considered statistically significant (Hayes, 2017).

Results

Descriptive statistics are reported in Table 2. First, men outperformed women in the numeracy test ($t(138) = 2.49$, $p = .014$, Cohen's $d = -0.42$). Second, women scored higher in the math anxiety and neuroticism scales compared to men. The difference between the two groups was statistically significant both for math anxiety ($t(138) = 3.26$, $p = .001$, Cohen's $d = 0.55$) and neuroticism ($t(138) = 4.62$, $p < .001$, Cohen's $d = 0.78$).

We inspected relationships between math anxiety, neuroticism, and numeracy scores in the total sample and separately for both genders through zero-order Pearson correlation (Table 2). When the whole sample was considered, math anxiety was positively associated with neuroticism and negatively with numeracy. When the two groups were considered separately, math anxiety was significantly and positively associated with neuroticism only in men, and significantly and negatively associated with numeracy only in women. However, these correlations between men and women did not significantly differ (correlation between math anxiety and neuroticism: $z = 0.43$, $p = .666$; correlation between math anxiety and numeracy: $z = -1.19$, $p = .235$; Soper, 2024).

Additionally, in women, the numeracy score was positively correlated with neuroticism (test on correlation difference: $z = 2.06$, $p = .039$).

Table 2. Descriptive statistics and correlations (Pearson's *r*) between math anxiety, neuroticism and numeracy scores – correlation coefficients, sig. (**p<.05; **p<.01; ***p<.001*).

	M	*SD*	range	skewness	kurtosis	1	2	3
Whole sample (*N* = 140)								
1. Math anxiety	19.71	6.56	9.00-43.00	0.69	0.35	1.00		
2. Neuroticism	3.19	0.81	1.50-4.75	-0.12	-0.77	.32***	1.00	
3. Numeracy	0.69	0.16	0.20-1.00	-0.42	-0.17	-.30***	-.02	1.00
Women (*N* = 70)								
1. Math anxiety	21.46	6.13	11.00-35.00	0.48	-0.64	1.00		
2. Neuroticism	3.49	0.71	2.00-4.75	0.01	-0.99	.21	1.00	
3. Numeracy	0.65	0.15	0.27-0.93	-0.38	-0.49	-.36**	.25*	1.00
Men (*N* = 70)								
1. Math anxiety	17.96	6.56	9.00-43.00	1.09	1.88	1.00		
2. Neuroticism	2.9	0.79	1.50-4.25	-0.05	-1.11	.28*	1.00	
3. Numeracy	0.72	0.17	0.20-1.00	-0.48	0.16	-.17	-.10	1.00

Note. *M* = mean: *SD* = standard deviation.

To explore whether neuroticism mediates the relationship between math anxiety and numeracy, the indirect and direct effects were calculated. Table 3 reports detailed results. The total effect (*c*) and the direct effect (path *c'*) of math anxiety on numeracy were significant and moderate, as well as the association of math anxiety with neuroticism (path *a*). The association of neuroticism to numeracy (path *b*) and the indirect effect of math anxiety on numeracy (*ab*) were not significant, indicating that neuroticism did not mediate the effect of math anxiety on numeracy. We further investigated gender differences by adding gender as a moderator of the effects of math anxiety and neuroticism on numeracy (paths *b* and *c'*, see Figure 1 for schematic representation). The interaction between gender and math anxiety was not statistically significant: for both men and

women the association between math anxiety and numeracy (conditional path *c'*) was negative. So, gender cannot be identified as a moderator of the relationship between math anxiety and numeracy.

On the other hand, the interaction between gender and neuroticism was significant. Accordingly, women' standardized regression coefficient for path *b* indicate a significant moderate positive association between neuroticism and numeracy, while for men this association had the opposite sign and was not significant. These results identify gender as a moderator of the relationship between neuroticism and numeracy. The test of the indirect effect (conditional *ab*) showed that neuroticism mediated the effect of math anxiety on numeracy in women but not in men. The index of moderated mediation supported the significance of the moderated mediation.

We repeated the mediation and moderated mediation analyses adding the control variables as covariates and we found that the results are fully aligned with those described above. Details are reported in Supplementary Table 2.

Table 3. Results of simple mediation and moderated mediation.

	β	*p*	CI	R^2
Mediation				
Outcome: Neuroticism (mediator)				0.10
Math anxiety (*a*)	0.32	<.001	0.16 - 0.48	
Outcome: numeracy (dependent variable)				0.09
Math anxiety (*c'*)	-0.32	<.001	-0.49 - -0.15	
Neuroticism (*b*)	0.08	.364	-0.09 – 0.25	
Total effect (*c*)	-0.30	<.001	-0.45 - -0.13	
Indirect effect (*ab*)	0.03		-0.02 – 0.08	
Moderated mediation				
Outcome: Neuroticism (mediator)				0.10
Math anxiety (*a*)	0.32	<.001	0.16 - 0.48	
Outcome: numeracy (dependent variable)				0.16
Math anxiety	-0.15	.196	-0.38 – 0.08	
Neuroticism	-0.07	.580	-0.30 – 0.17	
Gender (women = 1)	-0.37	.034	-0.71 - -0.03	
Math anxiety x gender (moderation of *c'*)	-0.28	.103	-0.61 – 0.06	
Neuroticism x gender (moderation of *b*)	0.43	.015	0.08 – 0.77	
Conditional effect of mediator (*b*)				
Men	-0.07	.580	-0.30 – 0.17	
Women	0.36	.006	0.10 – 0.62	
Conditional direct effect (*c'*)				
Men	-0.15	0.196	-0.38 – 0.08	
Women	-0.43	<.001	-0.67 - -0.19	
Conditional indirect effect (*ab*)				
Men	-0.02		-0.10 – 0.06	
Women	0.12		0.04 – 0.21	
Index of moderated mediation	0.14		0.03 – 0.27	

Note. Letters in italics refer to the traditional representation of mediation as a path diagram (Baron & Kenny, 1986): *a* = path from the predictor (i.e., math anxiety) to the mediator (i.e., neuroticism); *b* = path from the mediator to the dependent variable (i.e., numeracy); *c'* = direct path from the predictor to the dependent variable, when the effect of the mediator is accounted for; *ab* = indirect

path of the predictor on the dependent variable through the mediator; *c* = total effect of the predictor on the dependent variable (*c* = *ab* + *c'*).

Discussion

In the present study, we investigated the extent to which math anxiety and neuroticism are associated with numeracy and whether there are gender differences in these relationships in STEM undergraduate students. In our sample, men and women were matched for IQ, a factor that strongly predicts numeracy competence (e.g., Cerni et al., 2021). Furthermore, the two groups were balanced for other relevant variables, such as age, education, mathematical knowledge, average grade, general and math learning achievement and socioeconomic status.

Consistently with previous studies, *t*-test statistics confirmed that women scored worse than men on numeracy and showed higher levels of math anxiety and neuroticism. These findings are consistent with previous studies highlighting gaps in numeracy, math anxiety, and neuroticism. In addition, only women' numeracy scores significantly correlated with math anxiety (r = -.36) and neuroticism (r = .25). Second, we explored a mediation model, in which neuroticism mediated the negative path from math anxiety to numeracy. In line with recent meta-analyses (Barroso et al., 2021; Zhang et al., 2019), higher levels of math anxiety were consistently associated with lower numeracy scores in the whole sample, with one standard deviation increase in math anxiety associated with a 0.32 standard deviation decrease in numeracy, but no mediating effect of neuroticism emerged. However, when we added the moderating effect of gender to the model, neuroticism emerged as a significant mediator for women only. Notably, in women math anxiety was positively associated with neuroticism, which in turn had a positive and moderate association with numeracy: the increase of one standard deviation in math anxiety was associated with a numeracy increase of 0.12 standard deviations through the indirect effect of neuroticism. In men, no mediation effect of neuroticism was found, while the relationship between math anxiety and numeracy was not significant.

Even though the general view is that neuroticism has a negative impact on performance, (Brandt et al., 2019; Cerni et al., 2021; Chamorro-Premuzic et al., 2006; Graham & Lachman, 2012, 2014; Moutafi et al., 2006; Rammstedt et al., 2016; Spinath et al., 2010), there is also evidence that higher levels of this trait can have positive effects. In one study, participants higher in neuroticism were more accurate than those lower in neuroticism on a conflict recognition task (Smillie et al., 2006). In another study, participants higher in the withdrawal facet of neuroticism - a sub-component more related to anxiety - improved their performance on a visual search task as it became more demanding, whereas the opposite was observed in participants with higher volatility facet levels, - a sub-component more related to the expression of negative affect (Van Doorn & Lang, 2010).

Similar evidence was observed in more ecological contexts. Research in organizational psychology showed that higher levels of neuroticism favoured higher performance in terms of job productivity during busy workdays (Study 2, Smillie et al., 2006). The relationship between neuroticism level and job performance appeared to be curvilinear rather than linear, suggesting that the positive influence of neuroticism on performance holds up to a certain level of the trait, beyond which such association flattens (Uppal, 2017). Importantly, in higher education neuroticism was also found to have a positive effect on performance. McKanzie and collaborators (McKenzie, 1989; McKenzie et al., 2000) selected students with a specific coping factor, i.e., the Cattell's independence trait (Cattell et al., 1970), which entails aspects of dominance, independent mind and innovation. They found that, among these students, neuroticism positively correlated with achievement, and that this positive association was more likely to be observed in more advanced stages of higher education and in study programs with more rigorous assessment procedures.

Taken together, these findings suggest that higher levels of neuroticism positively boost performance, especially when task demands are high and hence individuals likely experience distress. Adjusting the affective state to stable personality characteristics can be an effective

emotional regulation strategy (Hemenover & Harbke, 2020; Tamir & Gutentag, 2017). In this vein, when individuals with higher levels of neuroticism experience unpleasant feelings, they are in the condition of consistency between a transient affective state and what they typically feel according to their personality: this condition prevents the emotional state from disrupting cognitive resources, leading to improved task performance (Tamir, 2005; Tamir & Robinson, 2004).

According to the definition of math anxiety, individuals with higher levels of math anxiety are more likely to experience negative emotions than individuals with lower levels when they perform a numeracy test. It is possible that women reporting higher levels of math anxiety and higher levels of neuroticism activate emotional regulation strategies to tune their momentary affective state (i.e., the negative emotions towards the numeracy test) to their personality, thus enhancing their numeracy performance. To reveal the presence of these regulation strategies, future studies should be targeted to measure state anxiety and affective states during numeracy tasks.

Despite the presence of this positive mediation of neuroticism on the association between math anxiety and numeracy, in our study women's numeracy competence was still lower than men's. Probably, the small positive indirect effect of math anxiety through neuroticism, even if statistically significant, was not enough for women to overcome the numeracy gap. The regression model with the moderation of gender on math anxiety and neuroticism explained only 16% of the variance in numeracy scores, suggesting that likely other factors are involved. Understanding why women in STEM are still affected by trait math anxiety differently from men should be a future direction of targeted studies to disclose possible causes of the numeracy gender gap.

As for the association between math anxiety and neuroticism, based on previous studies assessing the association between math anxiety and general anxiety (Betz, 1978; Hart & Ganley, 2019; Hembree, 1988, 1990), one would expect that higher levels of math anxiety correspond to higher levels in trait neuroticism, and this is what we observed. Despite this association, math anxiety and neuroticism differ conceptually, as the former refers to a specific situation or activity,

and the latter to a general pattern of feelings. Here we provided some evidence in favour of the conceptual independence of math anxiety. First, the magnitude of the correlation between math anxiety and neuroticism was weak-to-moderate (r = .32). Second, math anxiety and neuroticism correlations with women' numeracy scores had opposite signs: the correlation was negative for math anxiety and positive in the case of neuroticism. Third, while in the whole sample the effect of math anxiety on numeracy was not mediated by neuroticism, in the women subgroup, where the partial mediation of neuroticism was significant, the effect of math anxiety on numeracy was still strong. This suggests that math anxiety is a domain-specific anxiety trait, which can negatively influence numerical performance beyond general sensitivity to stress.

This study presents some limitations. First, the sample included in the present study is relatively small. Our findings showed significant correlations of numeracy with neuroticism and math anxiety, and a significant indirect effect, for women only. However, we cannot exclude the possibility that with a larger sample significant effects may have emerged for men as well. Moreover, our sample was composed of STEM undergraduate students. These students may differ from other groups of students on the one hand for the more intensive mathematical and scientific training in their study program, and on the other hand for more positive attitudes towards mathematics that led them to choose this specific field of study (i.e., selection bias). This prevents the generalization of our conclusions to the other student groups. Further research including students from arts and humanities is needed to understand whether what we observed here could be applied to the whole population or only to the students that are more predisposed towards mathematics and science. Future studies should also include specific measures of general anxiety, such as trait and test anxiety, to identify the extent of the contribution of this specific factor compared to the broader neuroticism trait.

To conclude, understanding the relationship between cognitive and non-cognitive factors can help in planning effective strategies to sustain students in their studies, especially women enrolled

in STEM programs. Women students survived the “bottleneck” represented by the university choice, which deprives the scientific field of young women (Ceci et al., 2014). Further in the pipeline, women are even less represented, suggesting that they face more obstacles than men in their careers. We encourage policymakers and educators to consider the role of math anxiety and neuroticism in the context of STEM education. Although students enrolled in this field are supposedly better at mastering numeracy, performance on numeracy tests can still correlate with math anxiety, especially among women, with neuroticism playing a mediating role.

CHAPTER 3

Study 2. Field of study and gender moderation of the association of personality and math anxiety with numeracy

Adapted from Lunardon, M., Cerni, T., & Rumiati, R. I. (2024). Field of Study and Gender Moderation of the Association of Personality and Math Anxiety with Numeracy. *The Journal of Psychology: Interdisciplinary and Applied*, *0*(0), 1–29. https://doi.org/10.1080/00223980.2024.2352706

Abstract

Math anxiety and personality influence numeracy, although the nature of their contribution has been overlooked. In the present study, we investigated whether their association with numeracy depended on field of study and gender in higher education. Participants were Italian undergraduate in either the humanities (N = 201) or science, technology, engineering and mathematics (STEM; N = 209) fields of study. These participants remotely completed standardized tests assessing numeracy, math anxiety, personality, intelligence, and basic numerical skills. We tested whether math anxiety and personality interacted with field of study and gender in predicting numeracy. Results showed that math anxiety was negatively associated with numeracy independently of field of study and gender, while the effect of personality, especially neuroticism, on numeracy interacted with field of study over and above intelligence and basic numerical skills. Specifically, humanities undergraduates with higher neuroticism levels scored lower in numeracy than STEM undergraduates. These findings underscore the importance of emotional experience for a good performance in mathematics, beyond math anxiety and the other personality traits, in the students that are less familiar with mathematics. Finally, no robust gender moderation emerged, suggesting that its role may be overridden by differences associated with career choice.

Introduction

As reviewed in Chapter 1, personality influences individual motivation and preferences for specific academic environments and tasks, while negative feelings towards math make it less likely for individuals, especially women, to enrol in careers with math as core knowledge. This system of individual characteristics is likely to impact the individual numeracy competence of young students. However, it still remains to be clarified whether this impact is consistent across individuals, or if it may be modulated by other sources of individual differences, such as the chosen field of study and

gender.

In the previous study (Chapter 2), we investigated the role of gender in moderating the association between numeracy and personality, focusing specifically on the neuroticism trait in a group of undergraduate STEM students. The results showed that only in women neuroticism was positively correlated with numeracy, and the strength of this correlation intensified with increasing levels of math anxiety. In contrast, among men, numeracy was negatively correlated with math anxiety, but no significant association with neuroticism emerged. This suggests that the nature of the association between personality and numeracy in STEM students may be gender specific. However, this study leaves the question open regarding its generalizability to non-STEM, particularly those in humanities (HUM) fields, who are likely to differ from their STEM peers in their attitudes towards mathematics (Watt et al., 2016), as well as in their mathematics knowledge (Holmes et al., 2018) and numerical skills (Sella et al., 2016). Moreover, this study did not investigate the role of the other personality traits, which may potentially have an association with numeracy performance (e.g., Cerni et al., 2021; Rammstedt et al., 2016). The study presented in this chapter aims to fill these gaps.

The present study

In this study, we investigated whether the influence of math anxiety and personality on numeracy varied by the field of study and gender (Supplementary Figure 1). Specifically, we asked whether the association of math anxiety and personality with numeracy is moderated by field of study (research question 1a - RQ1.a-), gender (research question 1b - RQ1.b-) or both (research question 1c - RQ1.c-). To answer these questions, we assessed numeracy in a large sample of Italian-speaking undergraduate students. We recruited men and women students enrolled in STEM or HUM degree programs.

These two fields are expected to differ in the mathematical content covered during curricular

training. STEM students are likely to be more accustomed to numerical problem-solving compared to HUM students. While we expect a negative association between math anxiety and numeracy in both groups, differences in the associations between personality traits and numeracy may emerge. For instance, since HUM students show lower levels of conscientiousness and higher levels of neuroticism in comparison to other majors (Vedel, 2016), we can expect these traits to be particularly related to numeracy in this group. Indeed, higher conscientiousness (indicating greater self-discipline and goal-directed behaviour) and lower neuroticism (indicating lower susceptibility to negative emotions that may hinder task execution) may be more advantageous for performing well in a numeracy test among HUM students.

On the other hand, gender may play a different role. Culturally, mathematics is claimed to be for men (Eccles & Jacobs, 1986), and our participants, as young adults, may have been exposed to this stereotype over the years. This could potentially lead to a stronger association between math anxiety and numeracy in women students compared to men (Aiken, 1970). We also expect a gender moderation of personality traits, particularly in relation to neuroticism. The previous research has found a positive correlation between neuroticism and numeracy in women STEM students (Chapter 2). This effect may be particularly pronounced for STEM rather than HUM students: the former may be more driven to perform well in a numeracy test, given its significance in a field where they are outnumbered by men. This motivation might push them to overcome negative feelings when performing the task.

Our second objective was to determine whether the moderation effects explored in research question 1 explain the variance in numeracy beyond cognitive factors, such as IQ and basic numerical skills (research question 2 - RQ2-). To our knowledge, this is the first study directly assessing the contribution of personality to numeracy also considering basic numerical abilities. Specifically, we chose to measure numerical estimation, number ordering, and calculation, which are recognized as not only influencing mathematical achievement (Geary, 2011), but also

numeracy-related abilities, such as graph reading (Ludewig et al., 2020) and logical reasoning (Morsanyi et al., 2018).

Investigating whether the unique contribution of math anxiety and personality to numeracy differs by field of study and gender will provide further insights into the role played by individual differences in these associations.

Materials and Methods

Participants

Four hundred seventeen undergraduate students took part in the study. Recruitment was restricted to students enrolled to an Italian university, attending a bachelor's degree course in humanities (HUM) or STEM[10], aged between 18 and 30 years, with no history of developmental and/or learning disorders. Before the analyses, we removed 7 participants (6 women, 5 from HUM), whose IQ was below 80[11], resulting in a final sample of 410.

Demographic and academic characteristics of the students in HUM (N = 201, women = 94) and STEM (N = 209, women = 106), divided by gender, are reported in Table 4. The level of education was comparable in the two groups, as indexed by the actual years of education and accomplished general learning outcomes (as indexed by total ECTS[12] credits). As could be expected, STEM students reported a significantly higher workload in mathematics. HUM and STEM students differed also in age, math knowledge at university entry (i.e., the final high school grade in mathematics, and average university grade; moreover, men and women differed in total ECTS credits (see Results). Supplementary Table 4 reports the degree courses attended by participants.

[10] HUM or STEM were categorized according to the official classification made by the Italian Ministry of University and Research (Decree Law 942/2020, Attachment A)

[11] We excluded participants with an IQ below 80, as this threshold marks the boundary between average and borderline intellectual performance (e.g., Flanagan & Kaufman, 2009). The latter may indicate clinically relevant impairments (e.g., Ninivaggi, 2009), potentially suggesting the presence of developmental disorders, which is one of our exclusion criteria

[12] European Transfer and Accumulation System university credit

Participants gave written informed consent before study participation. After completing the tasks, they received 12 euros as reimbursement. The study was approved by the SISSA Ethics Committee (approval number Ib/2021/1). It was conducted according to the guidelines of the Declaration of Helsinki and of the Italian law about copyright for the reproduction of material online.

Power analysis was conducted with the G*Power statistical software (Faul et al., 2009). Assuming a power of .80 and an alpha level of .05, this sample was suitable to detect correlation effect sizes as small as Pearson's r values of .12 and to find Cohen's f^2 effect sizes for multiple regression with 35 predictors (the most complex model we fitted) as small as 0.07.

Procedure

The study was held online from March to December 2021. Participants were recruited through online channels (Facebook, Sona) and through university institutional channels. All participants received instructions and links to the tasks via email. The tasks were grouped into two separate sessions, administered no more than two weeks apart, to prevent participants' fatigue. The first session included personal information questions and all the questionnaires, and the cognitive tasks listed in the next section, excluding the numeracy test. The numeracy test was included in the second session.

The non-cognitive measures, the Raven's Matrices, and the numeracy test were administered through Google Forms. The basic numerical cognitive tasks were administered through the Pavlovia platform (https://pavlovia.org/).

Materials

More details about the questionnaires and the tasks described below can be found in the Supplementary Material.

Non-cognitive factors

Personality. Personality traits were measured with the Italian version of the Big Five Inventory (BFI) (John et al., 1991; Ubbiali et al., 2013). The scale assesses the big five personality dimensions through 44 items, including eight for extraversion and nine for each of the remaining traits (openness, conscientiousness, agreeableness, neuroticism). Each item corresponds to a statement to which participants expressed agreement on a five-point Likert scale. The mean score for each trait was calculated. Chronbach's alpha values for our sample were 0.75 for agreeableness, 0.84 for conscientiousness, 0.87 for extraversion and 0.81 for neuroticism and openness to experience.

Math anxiety. Math anxiety was measured with The Abbreviated Math Anxiety Scale (AMAS) (Hopko et al., 2003; Primi et al., 2014). Each item represents a mathematical learning or testing situation. Participants had to select on a five-point Likert scale the level of anxiety experienced in that situation. The individual total score was calculated as the sum of item scores, with higher scores corresponding to higher math anxiety levels. In our sample we observed a Cronbach's alpha of 0.90.

Cognitive tasks

Intelligence quotient. A reduced nine-item form of the Raven's Standard Progressive Matrices (Bilker et al., 2012) was used to estimate participants' IQ. The authors reported satisfying internal consistency (Chronbach's alpha: 0.80; Bilker et al., 2012). In our sample, Chronbach's alpha was 0.69. The lower reliability observed in our sample may stem from two factors: (1) our participants were young adults, unlike the sample in the original study aged between 16 and 77, and (2) the test administration differed, with our study conducted remotely, whereas the original study employed a paper-and-pencil version of the test administered face-to-face.

Basic numerical skills.

- *Arithmetic skills*. They were assessed using three tests from a standardized battery designed to diagnose learning disorders in university students and adults (Montesano et al., 2020). The *Mental calculation task* evaluates the strategic aspects of calculation, and the *Arithmetic facts retrieval task* the automaticity of solution retrieval. In both tasks, participants had to solve as accurately and fast as possible a set of operations, auditorily presented one at the time, and to type their answer within 30 seconds in the former task, and 5 seconds in the latter. The *Approximate calculation task* evaluates the ability to reason with numerical magnitude by requiring participants to choose the correct result, among three options, for 16 trials within 1 minute. For all the three tests, 1 point was assigned for correct answers, and 0 for incorrect or blank answers. The sum of correct responses was converted into an accuracy rate for each test. These subtests displayed a good test-retest reliability, as reported in the standardization manual (Montesano et al., 2020): 0.82 for mental calculation, 0.85 for arithmetic facts and 0.72 for approximate calculation.
- *Number line estimation*. To examine numerical estimation abilities, we administered the number-to-position task (Siegler & Opfer, 2003). In such a task, participants were presented with a horizontal line at the centre of the computer screen, labelled with 0 on the left and 1000 on the right. Participants had to mark the correct position of a target number on the line by moving the mouse cursor and clicking on the selected position. The target numbers were shown above the line, on the centre of the screen, for one second, in random order. We calculated the percentage of absolute error (PAE, i.e., (|Estimate-Target Number|)/Numerical Interval) * 100) as a measure of accuracy. Cronbach's alpha for our sample was 0.86.
- *Number ordering*. In the number ordering task, participants decided whether the presented number triads (e.g., 2, 4, 1) were in increasing order or not, by pressing Z and M keys on the keyboard respectively. All numbers were between 1 and 9. We computed a composite score from the accuracy (in terms of error rate, ER) and reaction time (RT) according to the formula: P = RT(1

+ 2ER), with a higher value indicating a worse performance (for a further discussion of this formula, see Morsanyi et al., 2017). We observed a Cronbach's alpha of 0.79 in our sample.

Numeracy test

To measure numeracy, we built an ad-hoc test reproducing the items of the TECO-T (TEst of COmpetence) developed by ANVUR (Agenzia Nazionale per la Valutazione del sistema Universitario e della Ricerca, Italian National Agency for the Evaluation of University and Research) to evaluate students' generic literacy and numeracy competencies acquired during higher education degrees (Rumiati et al., 2018). The numeracy test assessed logical and quantitative thinking skills, not related to curricular teaching. The test included 15 multiple choice questions, each consisting of a word problem and four response options. The questions were grouped into three modules of five questions each: "Graphs and Tables", "Logical reasoning" and "Infographics". Participants had 40 minutes to complete the test. Item score was 1 (correct) and 0 (wrong). The TECO-T was standardized on a representative sample of 827 Italian undergraduate students (ANVUR, 2016, 2021) and a Chronbach's alpha of 0.83 was reported (ANVUR, 2016). In our sample, Chronbach's alpha was 0.61. The lower reliability could be due to the characteristics of the sample -the original study included social sciences and health sciences students in addition to HUM and STEM- and the administration type -our study was conducted remotely without direct assistance, whereas the original study had participants complete the test in groups with a tutor present-.

Data analysis

Differences in the cognitive and non-cognitive variables between groups (field of study [HUM vs. STEM] and gender [women vs. men]) were tested with a series of two-way ANOVAs.

We employed multiple linear regressions, with the proportion of correct answers in the

numeracy test as the dependent variable, to answer each point of research question 1. In model 1, we included math anxiety, personality traits and their interactions with field of study to test whether the latter moderates the effect of the non-cognitive variables (RQ1.a). In model 2, we similarly investigated the moderator effect of gender on the non-cognitive variables (RQ1.b). In model 3, we simultaneously included field of study and gender to test whether they jointly moderate the effect of non-cognitive factors (RQ1.c).

Finally, we investigated the degree to which the non-cognitive factors, moderated by field of study and gender, explained numeracy variance over and beyond the cognitive factors (RQ2). To this end, we included the cognitive variables (i.e., IQ and the scores in the basic numerical tasks) as additional regressors to the previous models, resulting in three new models (models from 4 to 6).

In all models, we included math knowledge and ECTS as control variables, since they showed significant group differences (see Participants). We did not include average grade at university because of the high number of missing values (61 participants were at the beginning of the university course and had not taken exams yet, and 24 participants provided an invalid answer) and age because of its correlation with both math knowledge ($r_{Pearson}$ = -.20, C.I. [-.29; -.10], p < .001) and ECTS ($r_{Pearson}$ = .35, C.I. [.26; .43], p < .001).

We evaluated the contribution of the variables to numeracy and the moderation of field of study and gender in terms of regression coefficients. We also reported variance explained as a measure of model performance. Continuous regressors were standardized before being entered in the models. The six missing values for the basic numerical skill tasks (two in the number ordering, three in the number line and one in the fact retrieval task) and the missing value for math knowledge (see Supplementary Table 3) were replaced by their average within field of study and gender. Beside *p*-values, for regression coefficients we also reported confidence intervals (CIs), in line with current recommendations (Cumming, 2014). All statistical analyses were performed using R v.4.1.1 (R Core Team, 2020).

Results

Descriptive statistics

Descriptive statistics are reported in Table 4 and in Supplementary Table 3, and visually presented in Supplementary Figure 2 for the main variables. Their correlations are reported in Supplementary Table 5. Complete ANOVA results are reported in Supplementary Table 3.

As far as the demographic information is concerned, HUM and STEM students reported different amounts of math workload ($F(1, 406) = 31.09$, $p < .001$, $\eta^2_p = 0.07$), age ($F(1, 406) = 6.16$, $p = .013$, $\eta^2_p = 0.01$), math knowledge at university entry (i.e., the final high school grade in mathematics, $F(1, 405) = 28.48$, $p < .001$, $\eta^2_p = 0.07$) and average university grade ($F(1, 321) = 4.74$, $p = .030$, $\eta^2_p = 0.01$). STEM students reported a significantly higher workload in mathematics ($d = -0.81$), higher math knowledge at university entry ($d = -0.74$), lower average university grade ($d = 0.23$), and were younger ($d = 0.26$). There was a significant gender difference on total ECTS credits ($F(1, 406) = 5.45$, $p = .020$, $\eta^2_p = 0.01$), which were lower in men ($d = 0.15$).

We found significant field of study ($F(1, 406) = 25.26$, $p < .001$, $\eta^2_p = 0.06$) and gender ($F(1, 406) = 8.47$, $p = .004$, $\eta^2_p = 0.02$) differences in numeracy, but no significant interaction. Higher scores in numeracy were obtained by STEM ($d = 0.73$) and men ($d = 0.41$) students. Similarly, we found significant differences in math anxiety between fields of study ($F(1, 406) = 25.40$, $p < .001$, $\eta^2_p = 0.08$) and genders ($F(1, 406) = 8.35$, $p = .004$, $\eta^2_p = 0.02$) without interaction. HUM ($d = -0.81$) and women ($d = -0.34$) students reported higher math anxiety. Students in the two fields of study showed differences in trait openness to experience ($F(1, 406) = 11.90$, $p = .001$, $\eta^2_p = 0.03$), with HUM students reporting higher scores ($d = -0.45$). Gender was significantly associated with conscientiousness ($F(1, 406) = 4.04$, $p = .045$, $\eta^2_p = 0.01$), neuroticism ($F(1, 406) = 3.96$, $p = .047$, $\eta^2_p = 0.01$) and extraversion ($F(1, 406) = 4.56$, $p = .033$, $\eta^2_p = 0.01$), where women scored higher (Conscientiousness: $d = -0.26$; Neuroticism: $d = -0.47$; Extraversion: $d = -0.18$).

As far as the cognitive factors are concerned, ANOVAs yielded significant associations of the field of study with IQ ($F(1, 406) = 22.30$, $p < .001$, $\eta^2_p = 0.05$) and the numerical tasks excluded approximate calculation (mental calculation: $F(1, 406) = 25.81$, $p < .001$, $\eta^2_p = 0.06$; fact retrieval: $F(1, 405) = 25.81$, $p < .001$, $\eta^2_p = 0.04$; number line estimation: $F(1, 403) = 5.62$, $p = .018$, $\eta^2_p = 0.01$; number ordering: $F(1, 404) = 7.26$, $p = .007$, $\eta^2_p = 0.02$). In general, STEM students exhibited a better performance (IQ: $d = 0.53$; mental calculation: $d = 0.69$; fact retrieval: $d = 0.61$; number line: $d = -0.15$; number ordering: $d = -0.40$). A significant gender difference was observed for mental calculation ($F(1, 406) = 4.17$, $p = .042$, $\eta^2_p = 0.01$), approximate calculation ($F(1, 406) = 6.67$, $p = .010$, $\eta^2_p = 0.02$) and number line estimation ($F(1, 403) = 10.44$, $p = .001$, $\eta^2_p = 0.03$), with a better performance of men (number line estimation: $d = -0.28$; mental calculation: $d = 0.24$; approximate calculation: $d = 0.45$). No field by gender interaction was significant.

Table 4. Descriptive statistics for the study variables divided by field of study and gender.

		HUM				STEM			
		Women		Men		Women		Men	
	N	*M* (SD)	Range	*M* (SD)	range	*M* (SD)	range	*M* (SD)	range
Demographic and academic variables									
Age	410	21.51 (2.40)	18-30	21.08 (2.25)	18-29	20.77 (1.95)	18-30	20.72 (1.75)	18-27
SES[a]	389[a]	4.01 (1.82)	2-8	4.24 (1.92)	1-8	4.52 (1.93)	2-8	4.58 (1.95)	2-8
Level of education	410	14.98 (1.01)	14-16	14.99 (1.00)	14-16	14.98 (1.00)	14-16	14.95 (1.00)	14-16
Math grade in high school	409[b]	7.40 (1.30)	3-10	7.21 (1.31)	4-10	8.37 (1.20)	6-10	8.13 (1.29)	4-10
Average grade in university	349[c]	26.57 (2.58)	18-30	26.35 (2.47)	20-30	25.74 (2.50)	21-30	26.08 (2.43)	20-30
Total ECTS	410	71.90 (59.33)	0-180	51.97 (59.27)	0-180	70.58 (60.47)	0-172	72.56 (62.38)	0-180
ECTS in math	410	0.11 (1.03)	0-10	4.16 (13.63)	0-96	21.31 (31.43)	0-157	26.85 (40.71)	0-159
Numeracy									
Proportion of correct answers	410	0.53 (0.16)	0.20-0.87	0.59 (0.18)	0.20-1.00	0.64 (0.16)	0.27-0.93	0.73 (0.15)	0.20-1.00
Non-cognitive factors									
Math anxiety	410	27.43 (8.48)	12-45	24.48 (7.91)	9-42	21.34 (6.24)	9-35	18.44 (6.08)	9-34
Agreeableness	410	3.57 (0.63)	2.00-4.78	3.55 (0.64)	1.78-4.78	3.55 (0.69)	1.67-4.78	3.59 (0.60)	2.00-4.67
Conscientiousness	410	3.56 (0.77)	1.78-4.89	3.36 (0.71)	1.56-4.78	3.58 (0.67)	1.56-4.78	3.42 (0.68)	1.56-4.67
Extraversion	410	3.14 (0.80)	1.25-4.75	2.90 (0.89)	1.12-5.00	2.99 (0.72)	1.00-4.75	2.94 (0.84)	1.12-5.00
Neuroticism	410	3.35 (0.72)	1.50-4.75	3.14 (0.70)	1.25-4.75	3.37 (0.76)	1.75-4.75	2.88 (0.77)	1.12-4.50
Openness to	410	3.93	2.50-	3.87	2.10-	3.62	1.80-	3.61	2.30-

experience		(0.61)	5.00	(0.69)	5.00	(0.61)	4.90	(0.59)	5.00
Cognitive factors									
IQ	410	117.23 (11.73)	80-128	119.54 (10.08)	87-128	123.49 (7.00)	100-128	123.31 (8.15)	94-128
Number ordering (P score)	408[d]	1.77 (0.37)	0.83-2.86	1.69 (0.49)	0.73-3.84	1.62 (0.33)	0.96-2.50	1.52 (0.36)	0.70-2.74
Number line (PAE)	407[d]	5.54 (6.35)	1.22-29.94	3.47 (1.99)	0.65-13.56	4.02 (4.55)	1.18-29.89	3.48 (4.27)	1.02-34.61
Mental calculation (accuracy rate)	410	0.62 (0.2)	0.00-1.00	0.68 (0.23)	0.00-1.00	0.76 (0.18)	0.20-1.00	0.81 (0.16)	0.30-1.00
Fact retrieval (accuracy rate)	409[d]	0.79 (0.13)	0.37-1.00	0.83 (0.13)	0.40-1.00	0.87 (0.10)	0.37-1.00	0.91 (0.11)	0.24-1.00
Approximate calculation (accuracy rate)	410	0.50 (0.18)	0.19-1.00	0.56 (0.19)	0.12-1.00	0.52 (0.16)	0.19-0.88	0.62 (0.17)	0.12-1.00

Notes. [a] SES corresponds to the parents' highest level of completed education, based on the International Standard Classification of Education (ISCED). Twenty-one answers were discarded because overly generic to establish the corresponding ISCED level. [b] One datapoint was missing because a participant provided an invalid answer. [c] Sixty-one participants were at the beginning of the university course and had not taken exams yet, while 24 participants provided an invalid answer. They were not included in this analysis. [d] Because of errors in online data saving, two results in the number ordering, three in the number line and one in the fact retrieval tasks were missing.

The association between non-cognitive factors and numeracy

Tables from 5 to 7 display the results of the models assessing the contribution of math anxiety and personality to numeracy and their interactions with field of study and gender. Figure 2 shows the interactions that resulted statistically significant. Plots showing the other differential associations between the non-cognitive variables and numeracy according to field of study and gender are in Supplementary Figures 3, 4 and 5.

Field of study as a moderator (RQ1.a)

Model 1 explained 26% of total variance. There was a significant negative effect of math

anxiety (β = -0.27), extraversion (β = -0.14) and neuroticism (β = -0.23) on numeracy (Table 5). Field of study was also a significant regressor (β = 0.32) and significantly interacted only with neuroticism (β = 0.26). A simple slope analysis showed that neuroticism was negatively associated with numeracy in HUM students (trend = -0.04, CI [-0.07; -0.01], p = .001), whereas no association emerged in STEM students (trend = 0.005, CI [-0.02; 0.03], p = .677; Figure 2a).

Gender as a moderator (RQ1.b)

Model 2 accounted for 26% of the total variance. In this model, math anxiety (β = -0.29) and conscientiousness (β = -0.14) were negatively associated with numeracy, in addition to gender (β = 0.30) and its interaction with neuroticism (β = -0.19, Table 6). According to the simple slope analysis, the association between neuroticism and numeracy was negative for men (trend = -0.03, CI [-0.05; -0.003], p = .025), but positive and not significant for women (trend = 0.01, CI [-0.02; 0.03], p = .565; Figure 2b).

The joint moderation of field of study and gender (RQ1.c)

When the joint moderation of field of study and gender were entered (model 3, see Table 7), the total variance explained was 28%. However, no triple interaction between the two moderators and the non-cognitive factors reached statistical significance. On the other hand, the negative effect of math anxiety (β = -0.25) and the interaction between field of study and neuroticism (β = -0.34) were significant.

Table 5. Multiple linear regression results to evaluate the relationship between numeracy and the non-cognitive factors with the moderation of field of study (model 1).

	Model 1				
Predictors	Estimates	std. Beta	std. CI	*t*	*p*
(Intercept)	0.60	-0,14	-0.28 – -0.01	49.57	**<0.001**
Math grade in high school	0.04	0.20	0.11 – 0.30	4.20	**<0.001**
ECTS	0.01	0.05	-0.03 – 0.14	1.22	0.222
Math anxiety	-0.05	-0.27	-0.39 – -0.15	-4.40	**<0.001**
Field	0.06	0.32	0.13 – 0.52	3.32	**0.001**
Agreeableness	0.01	0.03	-0.10 – 0.16	0.46	0.646
Conscientiousness	-0.01	-0.07	-0.19 – 0.06	-1.02	0.308
Extraversion	-0.03	-0.14	-0.28 – -0.01	-2.16	**0.031**
Neuroticism	-0.04	-0.23	-0.37 – -0.09	-3.23	**0.001**
Openness	0.00	-0.02	-0.15 – 0.11	-0.33	0.745
Math anxiety * Field	0.00	0.02	-0.18 – 0.22	0.20	0.839
Field * Agreeableness	-0.01	-0.04	-0.21 – 0.14	-0.43	0.669
Field * Conscientiousness	-0.02	-0.09	-0.27 – 0.08	-1.04	0.300
Field * Extraversion	0.02	0.11	-0.08 – 0.29	1.12	0.264
Field * Neuroticism	0.05	0.26	0.07 – 0.44	2.75	**0.006**
Field * Openness	0.01	0.04	-0.14 – 0.22	0.41	0.680
Observations			410		
R2 / R2 adjusted			0.286 / 0.259		

Note. Field code: HUM = 0; STEM = 1

Table 6. Multiple linear regression results to evaluate the relationship between numeracy and the non-cognitive factors with the moderation of gender (model 2).

	Model 2				
Predictors	Estimates	std. Beta	std. CI	*t*	*p*
(Intercept)	0.59	-0.18	-0.30 – -0.05	50.84	**<0.001**
Math grade in high school	0.05	0.26	0.17 – 0.35	5.49	**<0.001**
ECTS	0.01	0.06	-0.02 – 0.15	1.43	0.153
Math anxiety	-0.05	-0.29	-0.42 – -0.16	-4.33	**<0.001**
Gender	0.05	0.30	0.12 – 0.48	3.30	**0.001**
Agreeableness	0.00	0.01	-0.11 – 0.14	0.20	0.844
Conscientiousness	-0.03	-0.14	-0.27 – -0.01	-2.13	**0.034**
Extraversion	0.00	0.01	-0.13 – 0.14	0.07	0.942
Neuroticism	0.01	0.04	-0.10 – 0.18	0.58	0.565
Openness	-0.01	-0.03	-0.16 – 0.09	-0.53	0.595
Math anxiety * Gender	0.00	-0.01	-0.19 – 0.17	-0.10	0.917
Gender * Agreeableness	0.00	0.03	-0.15 – 0.20	0.31	0.760
Gender * Conscientiousness	0.03	0.14	-0.04 – 0.33	1.53	0.126
Gender * Extraversion	-0.03	-0.17	-0.36 – 0.02	-1.75	0.082
Gender * Neuroticism	-0.03	-0.19	-0.38 – -0.00	-1.97	**0.049**
Gender * Openness	0.00	0.00	-0.18 – 0.18	0.02	0.984
Observations			410		
R2 / R2 adjusted			0.283 / 0.256		

Note. Gender code: Women = 1; Men = 0.

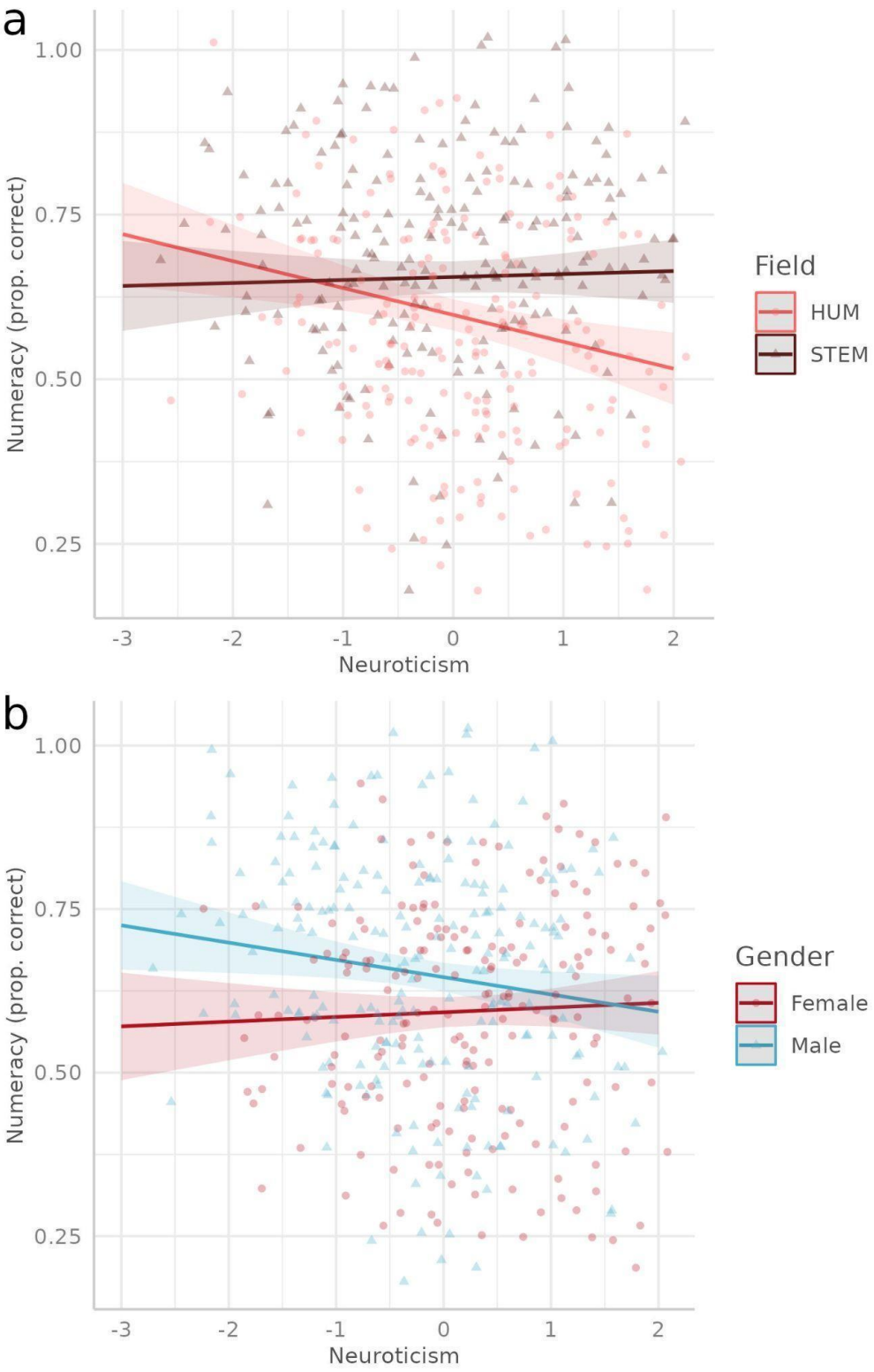
Table 7. Multiple linear regression results to evaluate the relationship between numeracy and the non-cognitive factors with the joint moderation of field and gender (model 3).

	Model 3				
Predictors	Estimates	std. Beta	std. CI	*t*	*p*
(Intercept)	0.57	-0.27	-0.49 – -0.06	29.44	**<0.001**
Math grade in high school	0.04	0.22	0.12 – 0.31	4.45	**<0.001**
ECTS	0.01	0.06	-0.03 – 0.14	1.29	0.199
Math anxiety	-0.04	-0.25	-0.42 – -0.08	-2.86	**0.004**
Field	0.04	0.22	-0.07 – 0.50	1.51	0.131
Gender	0.04	0.23	-0.05 – 0.51	1.65	0.100
Agreeableness	0.01	0.04	-0.15 – 0.24	0.43	0.667
Conscientiousness	-0.02	-0.12	-0.30 – 0.06	-1.34	0.183
Extraversion	-0.01	-0.07	-0.26 – 0.13	-0.70	0.483
Neuroticism	-0.03	-0.16	-0.36 – 0.05	-1.50	0.133
Openness	-0.01	-0.05	-0.24 – 0.14	-0.50	0.618
Math anxiety * Field	0.00	0.00	-0.27 – 0.28	0.02	0.982
Math anxiety * Gender	0.00	-0.03	-0.27 – 0.22	-0.20	0.838
Field * Gender	0.04	0.23	-0.17 – 0.62	1.13	0.259
Field * Agreeableness	-0.01	-0.08	-0.33 – 0.17	-0.61	0.543
Gender * Agreeableness	0.00	-0.02	-0.28 – 0.23	-0.19	0.849
Field * Conscientiousness	0.00	-0.03	-0.29 – 0.23	-0.21	0.833
Gender * Conscientiousness	0.03	0.16	-0.09 – 0.42	1.26	0.208
Field * Extraversion	0.02	0.13	-0.14 – 0.41	0.94	0.346
Gender * Extraversion	-0.02	-0.13	-0.40 – 0.13	-0.99	0.323
Field * Neuroticism	0.06	0.34	0.07 – 0.62	2.45	**0.015**

Gender * Neuroticism	-0.02	-0.11	-0.40 – 0.17	-0.79	0.428
Field * Openness	0.02	0.10	-0.17 – 0.36	0.73	0.465
Gender * Openness	0.01	0.04	-0.21 – 0.30	0.34	0.732
(Math anxiety * Field) * Gender	0.02	0.10	-0.29 – 0.50	0.52	0.600
(Field * Gender) * Agreeableness	0.02	0.09	-0.26 – 0.44	0.51	0.612
(Field * Gender) * Conscientiousness	-0.01	-0.06	-0.42 – 0.31	-0.31	0.753
(Field * Gender) * Extraversion	-0.01	-0.06	-0.43 – 0.32	-0.29	0.770
(Field * Gender) * Neuroticism	-0.02	-0.09	-0.47 – 0.29	-0.46	0.649
(Field * Gender) * Openness	-0.02	-0.10	-0.47 – 0.26	-0.55	0.583
Observations			410		
R2 / R2 adjusted			0.331 / 0.280		

Notes. Field code: HUM = 0; STEM = 1. Gender code: Women = 0; Men = 1

Figure 2. Significant interactions in predicting numeracy. a) Interaction between field of study and neuroticism standardized scores (model 1). b) Interaction between gender and neuroticism standardized scores (model 2). Regression lines and 95% confidence intervals for the two groups are displayed. Dots represent individual raw data.



The associations between non-cognitive factors and numeracy over and above IQ and numerical skills

To investigate whether non-cognitive factors explained additional variance over and above domain-general and domain-specific cognitive factors (RQ2), we added IQ and numerical tasks scores to the previous models, obtaining three new models (models from 4 to 6).

Overall, adding the cognitive variables increases the variance explained, which ranges from 38% to 40% (see Tables from 8 to 10). Moreover, among the cognitive variables, IQ (β = 0.33 to 0.35), fact retrieval (β = 0.13 to 0.15) and approximate calculation (β = 0.09 to 0.10) significantly and positively contributed to numeracy in all models.

Table 8 shows the regression results for model 4 (i.e., model 1 plus cognitive regressors). A significant effect still emerged for math anxiety (β = -0.13), neuroticism (β = -0.13), field of study (β = 0.22) and the interaction between field and neuroticism (β = 0.17), but not for extraversion.

In model 5 (i.e., model 2 plus cognitive regressors), math anxiety (β = -0.15) and gender (β = 0.26) significantly contributed to numeracy (see Table 9). Moreover, gender significantly interacted with conscientiousness (β = 0.18). The simple slope analysis showed an opposite trend for men (trend = 0.02, CI [-0.01; 0.03], p = .158) and women (trend = -0.02, CI [-0.03; 0.01], p = .136) in the association between numeracy and conscientiousness, although not statistically significant.

When the cognitive factors were added to the model with both field of study and gender (model 6, see Table 10), only the interaction between field of study and neuroticism reached statistical significance (β = 0.27).

Table 8. Multiple linear regression results to evaluate the relationship between numeracy and the non-cognitive factors with the cognitive factors as covariates and the moderation of field of study (model 4).

	Model 4				
Predictors	Estimates	std. Beta	str. CI	*t*	*p*
(Intercept)	0.60	-0.11	-0.23 – 0.01	54.23	**<0.001**
Math grade in high school	0.02	0.14	0.05 – 0.23	3.01	**0.003**
ECTS	0.01	0.05	-0.03 – 0.13	1.32	0.186
Math anxiety	-0.02	-0.13	-0.25 – -0.01	-2.19	**0.029**
Field	0.04	0.22	0.04 – 0.39	2.36	**0.019**
Agreeableness	0.00	0.01	-0.11 – 0.13	0.17	0.864
Conscientiousness	0.00	0.01	-0.10 – 0.13	0.25	0.803
Extraversion	-0.01	-0.05	-0.17 – 0.07	-0.81	0.418
Neuroticism	-0.02	-0.13	-0.26 – -0.00	-1.99	**0.048**
Openness	0.00	0.00	-0.11 – 0.12	0.08	0.934
IQ	0.06	0.33	0.24 – 0.41	7.17	**<0.001**
Number ordering	0.00	0.02	-0.07 – 0.10	0.37	0.712
Number line	-0.01	-0.06	-0.15 – 0.02	-1.50	0.136
Mental calc.	-0.01	-0.04	-0.15 – 0.06	-0.86	0.388
Fact retrieval	0.02	0.13	0.03 – 0.24	2.51	**0.013**
Approximate calc.	0.02	0.12	0.03 – 0.20	2.70	**0.007**
Math anxiety * Field	-0.01	-0.06	-0.24 – 0.13	-0.61	0.539
Field * Agreeableness	-0.01	-0.06	-0.22 – 0.10	-0.68	0.494
Field * Conscientiousness	-0.02	-0.12	-0.28 – 0.05	-1.40	0.162
Field * Extraversion	0.00	0.02	-0.15 – 0.19	0.26	0.792
Field * Neuroticism	0.03	0.17	0.00 – 0.34	1.99	**0.047**
Field * Openness	0.00	0.00	-0.16 – 0.17	0.04	0.968
Observations			410		
R2 / R2 adjusted			0.414 / 0.382		

Note. Field code: HUM = 0; STEM = 1

Table 9. Multiple linear regression results to evaluate the relationship between numeracy and the non-cognitive factors with the cognitive factors as covariates and the moderation of gender (model 5).

	Model 5				
Predictors	Estimates	std. Beta	std. CI	*t*	*p*
(Intercept)	0.60	-0.15	-0.27 – -0.03	55.72	**<0.001**
Math grade in high school	0.03	0.17	0.09 – 0.26	3.92	**<0.001**
ECTS	0.01	0.07	-0.01 – 0.14	1.66	0.098
Math anxiety	-0.03	-0.15	-0.27 – -0.02	-2.34	**0.020**
Gender	0.05	0.26	0.09 – 0.43	3.08	**0.002**
Agreeableness	0.00	-0.02	-0.13 – 0.09	-0.34	0.735
Conscientiousness	-0.02	-0.09	-0.22 – 0.03	-1.49	0.136
Extraversion	0.01	0.04	-0.09 – 0.16	0.55	0.583
Neuroticism	0.01	0.07	-0.06 – 0.20	1.08	0.280
Openness	0.00	-0.03	-0.14 – 0.09	-0.43	0.670
IQ	0.06	0.35	0.26 – 0.43	7.91	**<0.001**
Number ordering	0.00	0.02	-0.07 – 0.10	0.34	0.732
Number line	-0.01	-0.05	-0.13 – 0.04	-1.06	0.290
Mental calc.	-0.01	-0.04	-0.14 – 0.06	-0.81	0.418
Fact retrieval	0.03	0.15	0.05 – 0.25	2.89	**0.004**
Approximate calc.	0.02	0.10	0.02 – 0.19	2.31	**0.021**
Math anxiety * Gender	0.00	-0.02	-0.18 – 0.14	-0.26	0.793
Gender * Agreeableness	0.01	0.03	-0.13 – 0.19	0.35	0.727
Gender * Conscientiousness	0.03	0.18	0.01 – 0.35	2.09	**0.037**
Gender * Extraversion	-0.02	-0.13	-0.30 – 0.04	-1.48	0.139
Gender * Neuroticism	-0.03	-0.17	-0.34 – 0.00	-1.94	0.053
Gender * Openness	0.00	0.02	-0.14 – 0.18	0.24	0.811
Observations	410				
R2 / R2 adjusted	0.425 / 0.394				

Note. Gender code: Women = 0; Men = 1

Table 10. Multiple linear regression results to evaluate the relationship between numeracy and the non-cognitive factors with the cognitive factors as covariates and the joint moderation of field and gender (model 6).

	Model 6				
Predictors	Estimates	std. Beta	std. CI	*t*	*p*
(Intercept)	0.59	-0.21	-0.41 – -0.01	32.20	**<0.001**
Math grade in high school	0.03	0.15	0.06 – 0.24	3.33	**0.001**
ECTS	0.01	0.05	-0.03 – 0.13	1.29	0.197
Math anxiety	-0.02	-0.11	-0.28 – 0.05	-1.34	0.181
Field	0.02	0.10	-0.16 – 0.36	0.73	0.465
Gender	0.04	0.21	-0.05 – 0.47	1.57	0.118
Agreeableness	0.00	-0.01	-0.18 – 0.17	-0.06	0.955
Conscientiousness	-0.01	-0.07	-0.24 – 0.10	-0.77	0.442
Extraversion	0.00	-0.02	-0.20 – 0.16	-0.23	0.818
Neuroticism	-0.02	-0.09	-0.28 – 0.10	-0.89	0.373
Openness	0.00	0.01	-0.17 – 0.18	0.07	0.941
IQ	0.06	0.34	0.25 – 0.43	7.42	**<0.001**
Number ordering	0.00	0.03	-0.06 – 0.11	0.59	0.556
Number line	-0.01	-0.05	-0.14 – 0.03	-1.20	0.230
Mental calc.	-0.01	-0.05	-0.15 – 0.05	-0.96	0.339
Fact retrieval	0.03	0.14	0.04 – 0.25	2.70	**0.007**
Approximate calc.	0.02	0.09	0.01 – 0.18	2.10	**0.036**
Math anxiety * Field	-0.01	-0.06	-0.32 – 0.20	-0.44	0.661
Math anxiety * Gender	0.00	-0.03	-0.25 – 0.20	-0.22	0.824
Field * Gender	0.04	0.20	-0.16 – 0.57	1.11	0.267
Field * Agreeableness	-0.01	-0.03	-0.27 – 0.20	-0.27	0.786
Gender * Agreeableness	0.01	0.04	-0.20 – 0.27	0.33	0.739

Field * Conscientiousness	-0.01	-0.05	-0.29 – 0.19	-0.43	0.671
Gender * Conscientiousness	0.04	0.21	-0.03 – 0.44	1.74	0.082
Field * Extraversion	0.02	0.10	-0.15 – 0.35	0.78	0.433
Gender * Extraversion	-0.01	-0.04	-0.28 – 0.20	-0.32	0.752
Field * Neuroticism	0.05	0.27	0.02 – 0.53	2.14	**0.033**
Gender * Neuroticism	-0.01	-0.08	-0.34 – 0.18	-0.59	0.552
Field * Openness	0.00	-0.03	-0.27 – 0.22	-0.20	0.838
Gender * Openness	-0.01	-0.03	-0.26 – 0.21	-0.25	0.806
(Math anxiety * Field) * Gender	0.01	0.06	-0.30 – 0.42	0.32	0.747
(Field * Gender) * Agreeableness	-0.01	-0.04	-0.37 – 0.28	-0.27	0.790
(Field * Gender) * Conscientiousness	-0.01	-0.08	-0.41 – 0.26	-0.45	0.653
(Field * Gender) * Extraversion	-0.03	-0.17	-0.51 – 0.17	-0.96	0.336
(Field * Gender) * Neuroticism	-0.02	-0.12	-0.47 – 0.22	-0.70	0.482
(Field * Gender) * Openness	0.01	0.07	-0.27 – 0.41	0.40	0.692
Observations			410		
R2 / R2 adjusted			0.453 / 0.401		

Notes. Field code: HUM = 0; STEM = 1. Gender code: Women = 0; Men = 1

Discussion

The aim of our study was to deepen the understanding of the contributions of math anxiety and personality towards numeracy in higher education. We investigated whether these associations manifest differently based on students' field of study and gender, beyond cognitive factors. To achieve this, we recruited a large sample of Italian undergraduates pursuing degrees in either STEM or HUM disciplines. Our findings reveal robust differences across fields of study in the association between neuroticism trait and numeracy, providing new insights into the different role of non-cognitive factors in influencing numeracy.

The moderation of field and gender on personality

While individual personality traits did not consistently demonstrate main effects on numeracy, a significant and robust interaction emerged between the trait neuroticism and the field of study. Specifically, neuroticism was not only significantly associated with numeracy within the STEM group, whereas higher neuroticism levels were associated with lower numeracy scores among HUM students. It is noteworthy that neuroticism scores do not significantly differ between HUM and STEM students in our sample. Additionally, the interaction between field of study and neuroticism remained a significant predictor of numeracy, even when accounting for cognitive factors. In fact, the variance explained increases when IQ and basic numerical skills are added to the models, but the differential association between neuroticism and numeracy in HUM and STEM students remains significant.

These findings indicate that the relation between personality and numeracy varied according to the choice of field of study. The observed negative association between neuroticism and performance aligns with existing literature. Individuals with higher levels of neuroticism are more likely to experience negative feelings (e.g., Thompson, 2008) that impair efficient information processing, thus affecting cognitive performance (Munoz et al., 2018). This study extends previous

knowledge by revealing that this negative association is specifically observed in the context of numeracy with students enrolled in HUM undergraduate programs and not in STEM programs. This differential association may be attributed to inherent differences between students who chose to pursue math dense study programs and students who made a different choice in terms of emotion and attitudes towards math and more general individual differences (Ahmed, 2018; Cuder et al., 2024; Vedel, 2016). Moreover, HUM and STEM programs may represent distinct learning environments that provide different demands and opportunities for the expression of trait neuroticism in relation to numeracy. HUM and STEM students in our sample differed in the amount of curricular mathematical workload. They also differed in specific attitudes towards math and in basic numerical skills, with HUM students reporting higher math anxiety and lower scores in the numerical tasks. Therefore, when performing the numeracy test, HUM students may feel more under pressure or threatened by the task complexity. This heightened inclination towards negative affect, which is an expression of higher levels of neuroticism, consequently, affects numeracy performance (for a similar interpretation, see Tett et al., 2014).

In contrast, we did not observe a robust moderation of gender on the relationship between personality and numeracy scores, although women reported higher scores in conscientiousness, neuroticism, and extraversion. A significant interaction emerged with neuroticism and conscientiousness, but these interactions lost statistical significance when field of study was also in the models.

Regarding neuroticism, a weak but significant negative association with numeracy emerged in men, while in women this association was positive but approximately equal to zero. This is partly in line with the results of our previous study showing a positive correlation between neuroticism and numeracy in women, but not men, STEM students (see Chapter 2). However, we did not observe a statistically significant joint moderation of field of study and gender, as hypothesized. Although the data trended in the expected directions, with a positive association between

mathematical ability and neuroticism for women STEM students and a negative one in the other groups (see Supplementary Figure 5e), the joint moderation of field of study and gender was not statistically significant.

Conversely, conscientiousness exhibited a positive association with numeracy among men and a negative association among women. This suggests that men may benefit more from a conscientious attitude, which often entails a sense of competence (e.g., Anglim et al., 2022), while for women higher levels of conscientiousness may serve to compensate for lower numeracy ability (e.g., Rammstedt et al., 2016). However, these associations were weak and not statistically significant. Moreover, these differences are likely confounded with variations in general and domain-specific cognitive skills, as evidenced by the fact that the interaction between gender and conscientiousness only became significant when cognitive skills were included in the model. This aligns with research demonstrating an association between conscientiousness and a variety of cognitive skills (e.g., Carbone et al., 2019; Simon et al., 2020).

However, both the interactions of neuroticism and conscientiousness with gender were not significant when the field of study was included in the model. Evidently, the gender difference in the association of personality traits with students' mathematical skills was washed out by the type of field of study.

The moderation of field and gender on math anxiety

Overall, math anxiety was significantly and negatively associated with numeracy. Interestingly, even if women and HUM students experience higher levels of math anxiety than men and STEM students, respectively, neither the interaction with field of study nor the interaction with gender reached statistical significance.

The lack of interaction with field of study is consistent with recent findings suggesting that math anxiety negatively affects academic performance even in STEM students (Daker et al., 2021).

This highlights the pervasive nature of math anxiety, affecting people across multiple fields of study. In contrast, we expected gender moderation, consistent with the idea that women undergraduate students, influenced by social stereotypes (e.g., math is for men), might be more susceptible to the impacts of math anxiety (Aiken, 1970). However, our findings are in line with meta-analytic findings showing an equal correlation between math anxiety and math achievement in men and women (Barroso et al., 2021; Zhang et al., 2019).

It is crucial to note that in our study, as well as in the meta-analyses cited above, we refer to trait mathematical anxiety, which indicates a general feeling of tension towards mathematics. This concept is not necessarily in line with the momentary (state) anxiety experienced during the act of solving a math test. For example, research has shown that students who endorse the math gender stereotype reported a higher level of math anxiety than the actual anxiety experienced while performing a math task (Bieg et al., 2015). In other words, higher math anxiety does not necessarily translate into higher in-the-moment anxiety. Consistent with this perspective, Daker and colleagues (2023) found that in-the-moment anxiety predicted poorer performance on an arithmetic task only in those individuals with lower emotion regulation abilities.

These findings highlighted heterogeneity in the mechanisms contributing to the negative association between math anxiety and math performance, which may override gender-related variations.

Insights and implications

While domain-specific attitudes, i.e., math anxiety, exerted a consistent influence on numeracy regardless of gender and career choice, personality showed different associations with numeracy depending on the field of study. In particular, among the five traits, neuroticism, which is closely related to emotional experience, played a significant role. Being more prone to negative emotional responses, such as fear, anger, worry, irritability and depression, is associated with lower

numeracy scores in students pursuing a non-scientific career path.

Several possible explanations for this result deserve consideration. It is plausible that individuals with a higher level of neuroticism within HUM courses are more sensitive to stress induced by mathematics, an unfamiliar domain for them. The greater aversion to uncertainty typical of individuals with higher neuroticism might cause them to avoid numerical situations, thereby reducing their numeracy ability, similar to what is observed for math anxiety (e.g., Schmitz et al., 2023). In addition, individuals with greater neuroticism may have difficulty using effective stress management strategies, which could be particularly detrimental to HUM students, whose math background is likely to be less robust. Lack of adequate emotion regulation might be a more significant obstacle for them than for STEM students. These mechanisms may partly explain the decline in numeracy during HUM studies, which could be a natural consequence of the lack of direct numeracy training in these curricula (Rumiati et al., 2018). Further research is needed to clarify the direction of the relationship between neuroticism and numeracy, including the potential longitudinal impact of the former on the latter.

Another observation is that differences between fields that vary in mathematical load have greater explanatory power than gender differences. This does not rule out the existence of gender differences. In fact, we found that women report higher math anxiety, neuroticism, conscientiousness, and extraversion and score lower on math than men, consistent with previous literature (Borgonovi et al., 2021; Schmitt et al., 2008; Stoet et al., 2016). However, the effect sizes for gender differences in math anxiety and numeracy are smaller than the same effect sizes for field differences. Moreover, the lack of or inconsistent interactions with gender suggests that the mechanisms underlying men's and women's performance in mathematics may be influenced by other individual characteristics. For example, Rossi and colleagues (2022) found that math self-concept mediates the link between math anxiety and arithmetic performance, with complete mediation in men and only partial mediation in women. This suggests that additional factors may

help explain the link between math anxiety and arithmetic in women. Our results highlight the complexity of the issue related to gender differences in attitudes and achievement in mathematics. Future studies should go beyond the men/women dichotomy, considering that gender diversity can also be accounted for by variation related to the field of study.

Overall, our findings underscore the importance of studying numeracy in relation to emotional experience beyond math anxiety and provide insights for educators and policy makers to implement targeted actions. Because mathematics is widely taught in schools, being a core subject in all Italian high schools, attitudes developed during mathematics education, such as math anxiety, continue to negatively affect numeracy after high school, regardless of the career chosen. Therefore, programs that address math anxiety should include all students. On the other hand, for those pursuing humanities paths, the promotion of emotional stability could serve as another potential mechanism to support numeracy. Given the malleability of personality (Parker et al., 2004), institutions of higher education may consider implementing psychological programs aimed at adaptively modifying neuroticism to prevent the decline of numeracy skills.

Limitations

The results of the present study should be considered in light of some limitations. First, it is important to recognize that our sample does not fully represent the typical gender distribution within the HUM and STEM populations. In this study, the two groups are fairly balanced with regard to gender. However, these groups are typically characterized by over-representation of women in the HUM field and men in the STEM fields. The decision to balance the groups by gender was made on purpose to prevent gender imbalances from influencing the results related to the field of study. However, it is essential to recognize this lack of representativeness when interpreting the results of the study.

Second, participation in the study was voluntary, which may have introduced a self-selection

bias. Self-selection bias in this study may be particularly strong among students in the HUM field. Since mathematics is typically perceived as less appealing to students in HUM, those who chose to participate may have had more positive attitudes towards math. Consequently, the findings presented here may be biased.

Third, we cannot generalize our conclusions to the other student groups, such as health care students, or younger or older students, as we included only undergraduate students in STEM and HUM.

Fourth, we did not assess general anxiety. General anxiety is a component of trait neuroticism (e.g., Soto & John, 2017), on one hand, and it correlates with math anxiety, though representing a separate construct (Dowker et al., 2016), on the other hand. Adding general anxiety to the model as a control variable could reinforce or decrease the specific contribution of neuroticism and math anxiety.

Lastly, this study was held online remotely. Although we designed the study to prevent cheating, we cannot rule out the possibility that some participants got distracted or interrupted during the execution of the tasks.

Conclusions

Numeracy is a key competence in our society, and it is critical in choosing a STEM career (e.g., Holmes et al., 2018), which is often gender unbalanced. Understanding the factors associated with this competence is therefore crucial. Our study contributes to the existing literature by showing that the link between numeracy and personality, particularly neuroticism, is not fixed, but depends on the field of study chosen, rather than gender. Educators and policy makers should consider implementing different strategies to promote numeracy competence in higher education.

CHAPTER 4

Study 3. The longitudinal relationship of math anxiety and personality with numeracy in higher education

Abstract

Previous research has shown that non-cognitive factors, in particular math anxiety and the personality trait neuroticism, are associated with numeracy. However, most of these studies are cross-sectional, which limits claims about the persistence of the effect of non-cognitive factors over time. This study aims to improve our understanding of the predictive role of non-cognitive factors on numeracy in young adults using longitudinal data. We assessed numeracy, math anxiety and neuroticism in students entering a bachelor's degree (N = 118) in either science, technology, engineering and mathematics (STEM) or humanities and reassessed them two years later. While numeracy and neuroticism remained stable over time, math anxiety showed a slight decrease, particularly among humanities students. In addition, early math anxiety influenced later numeracy, with this effect being fully mediated by earlier numeracy. For STEM students, the effect of earlier math anxiety was also partly mediated by later math anxiety, while for humanities students the association between the two numeracy scores was stronger than for STEM students. Notably, the relationship between earlier numeracy and later math anxiety was significant, especially in STEM students. Early neuroticism also predicted later numeracy, but the effect was small, and no significant indirect or moderating effects were observed. In conclusion, non-cognitive factors are associated with later numeracy, with math anxiety exerting a stronger influence than neuroticism. The mechanisms underlying this association, including the possible bidirectional effect, appear to vary depending on the field of study.

Introduction

The studies presented in the previous chapters have shown the links between numeracy performance and non-cognitive factors in university students. Higher math anxiety is generally associated with lower numeracy performance, while the relationship with personality traits,

particularly neuroticism, varies between fields of study with different levels of mathematical content and, to some extent, between genders.

The prevailing interpretation of these associations is that non-cognitive factors *affect* numeracy. For example, math anxiety may trigger worrying thoughts that interfere with cognitive processing, leading to a decline in performance. Similarly, neuroticism can shape the emotional experience during a test, which may be of different importance to different students. For students that chose to study humanities (HUM) subjects, who are likely to have more negative attitudes towards mathematics and may be less familiar with it, this meaning could be often negative. Conversely, for students that enrolled to science technology, engineering, and mathematics (STEM) fields, where numeracy is central, the significance could be more positive. Thus, neuroticism may hinder performance in HUM students or facilitate it among STEM women, depending on the individual's emotional state during the test.

However, interpreting these associations in terms of "one variable affecting the other" is limited because the studies in the previous chapters, like most of the literature, are cross-sectional. This approach does not allow the directionality of the effects to be determined. Therefore, in the present study we conducted a longitudinal assessment of numeracy, math anxiety and neuroticism to investigate whether non-cognitive factors are associated with later numeracy and to identify the potential mechanisms underlying this relationship over the course of a bachelor's degree.

Numeracy, math anxiety, personality and their associations over time

Numeracy (also known as mathematical literacy) has been defined as a set of knowledge and skills that allow employing mathematics in a variety of private and public contexts, to understand social phenomena, to formulate decisions, and to participate actively in society (Geiger et al., 2015; OECD, 2018; Tout et al., 2021). This concept of numeracy refers to multi-faceted abilities that can be acquired through education and experience and is expected to be stable over time in adulthood.

Indeed, studies have shown that, on average, adult cohorts show little change in numeracy skills over a period of three to six years, although individual patterns of change vary, with improvements and declines evenly distributed across individuals (Lechner et al., 2021). A key factor contributing to the stability of numeracy may be the type of study program pursued after leaving high school. For example, among Italian undergraduates, a significant decline in numeracy was observed among students enrolled in socio-humanities degree programmes, while numeracy remained stable among students in STEM and health sciences (Rumiati et al., 2018). Gender also influences patterns of numeracy change, with men being less likely than women to show a numeracy decline (Best et al., 2022).

Research on the longitudinal development of math anxiety is less conclusive. Some studies suggest that math anxiety increases during primary school (for a review, see Dowker et al., 2016), whereas it tends to remain stable (Ahmed et al., 2013; Madjar et al., 2018; Sakaki et al., 2024) or even decrease (Lichtenfeld et al., 2023; Wigfield & Eccles, 1989) in older students. Ahmed (2018) and Wang, Oh and colleagues (2020) identified multiple developmental trajectories of math anxiety in adolescents: one characterised by increasing math anxiety, one by decreasing math anxiety, one by consistently low math anxiety and one by consistently high math anxiety. Although the gender distribution was similar across the trajectories (Ahmed, 2018; Wang, Oh, et al., 2020), students with consistently low math anxiety were more likely to pursue STEM careers than those with increasing or consistently high math anxiety (Ahmed, 2018).

Beyond career choices, longitudinal studies have shown that math anxiety can predict later numeracy. For example, higher math anxiety in first and second grade has been found to predict lower performance on third-grade calculation and problem-solving tasks (Ching, 2017), word problem solving (Pantoja et al., 2020), and tasks involving algebra and probability (Vukovic et al., 2013). Some studies have investigated both directions of causality - whether early math anxiety predicts later numeracy or vice versa. Studies by Cargnelutti and colleagues (2017) and Sorvo and

colleagues (2022) with second and sixth graders, respectively, found that math anxiety had a negative effect on math performance measured one year later, supporting the view that math anxiety plays a role in the development of numeracy (but see also Ma & Xu, 2004; C. S. Song et al., 2021; Sorvo et al., 2019; Wang, Rimfeld, et al., 2020). However, to the best of our knowledge, no studies have tested these longitudinal relationships in adults, particularly university students, leaving open the question of the lifelong impact of math anxiety on numeracy.

Unlike math anxiety, which can change over time for some individuals, personality traits tend to remain relatively stable over the years, with changes occurring gradually and often being small (for a meta-analysis, see Bühler et al., 2024). Studies of the longitudinal relationship between numeracy and personality are scarce and have focused mainly on adolescents. While higher neuroticism was associated with lower concurrent math achievement (Israel et al., 2019), this trait did not predict later math achievement (Bardach et al., 2023; Israel et al., 2019; Spengler et al., 2016). However, neuroticism was found to negatively predict later fluid intelligence (Bardach et al., 2023). It should be noted that math achievement in high school and numeracy in university students are different constructs. In high school, mathematics is a compulsory subject that is taught directly, making diligence and organizational skills more important for success (Israel et al., 2019; Spengler et al., 2016). In contrast, numeracy is a cognitive skill that is strongly correlated with intelligence (Cerni et al., 2021). The significant associations previously observed between numeracy and neuroticism (Chapters 2 and 3) can be interpreted within this framework. Thus, given the identified longitudinal relationship between neuroticism and intelligence in high school students (Bardach et al., 2023), a similar relationship might be expected in university students.

The present study

While the longitudinal relationship between non-cognitive factors and numeracy has been investigated in primary and secondary school students, there is a significant lack of evidence

concerning adults, particularly university students. This study aims to address this gap by assessing numeracy, math anxiety, and neuroticism in university students at two points in time: when they were in the first year of a bachelor's programme (T1) and two years later, when they were expected to be at the end of the programme (T2). We selected students enrolled in either STEM or HUM programmes.

The first aim of this study was to examine changes in these variables over time. We expected numeracy to change according to the participants' field of study. Specifically, we expected numeracy to decrease for HUM students and to remain stable or increase in STEM, in line with previous cross-sectional findings (ANVUR, 2017; Rumiati et al., 2018) Hypotheses regarding changes in math anxiety were more difficult to formulate due to the variability in developmental trajectories observed among high school students (Ahmed, 2018; Wang, Oh, et al., 2020). However, based on the findings of Ahmed (2018), it was expected that math anxiety would decrease or remain stable among STEM students. Finally, given the relative stability of personality (McCrae & Costa, 1999), we did not expect significant changes in neuroticism over the two-year period of the study.

The second aim of this study was to examine the longitudinal relationship between non-cognitive factors and numeracy. We examined whether math anxiety and neuroticism, measured at the beginning of a bachelor's programme, were associated with numeracy at the end of the programme. To do this, we used path analysis to account for concurrent associations between non-cognitive factors and numeracy, thereby shedding light on possible pathways. We considered the possibility that the effect of non-cognitive factors on later numeracy might be mediated by their influence on earlier numeracy, given the high stability of numeracy and math achievement reported in previous studies (Lechner et al., 2021; Sorvo et al., 2022). Another potential pathway could be the association between earlier non-cognitive factors and their later counterparts: higher math anxiety or neuroticism at the start of university could be associated with higher levels of these factors two years later, which could then influence numeracy at T2. Finally, it is possible that all

variables contribute to a single pathway: numeracy at entry (T1), influenced by concurrent non-cognitive factors, could influence subsequent non-cognitive factors, which in turn would influence numeracy at T2. In addition, we investigated whether these pathways differed by field of study and gender. Our previous findings indicated that both field of study and gender moderated the relationship between non-cognitive factors and numeracy, particularly in the case of neuroticism. With these analyses, we aimed to disentangle these moderating effects in order to better understand whether the differential effects of the non-cognitive factors are driven by distinct underlying mechanisms.

Materials and Methods

Participants

Two hundred and ten undergraduate students participated in the study. At the time of recruitment (T1), they were enrolled in the first year of a bachelor's degree in humanities (HUM) or STEM[13] at an Italian university. Inclusion criteria included an age between 18 and 30 years and no history of developmental or learning disabilities. Two years later, these students were contacted for the follow-up assessment (T2), and 121 students completed this phase. Three students were excluded from the sample due to insufficient effort in completing the tasks (see uality checks). The final sample consisted of 118 students.

Between T1 and T2, 17 participants changed degree programmes, with the majority choosing a new programme within the same field (HUM or STEM). Two students originally enrolled in a STEM programme at T1 switched to a HUM programme by T2 and were included in the HUM group for analysis. Four students enrolled in a STEM programme at T1 switched to a health sciences programme by T2 and were included in the STEM group for analysis. In addition,

[13] HUM or STEM were categorized according to the official classification made by the Italian Ministry of University and Research (Decree Law 942/2020, Attachment A)

five participants left the university (four in the second year and one in the first year) to pursue employment; they were included in the analysis within their original T1 group (all were in HUM).

The demographic and academic characteristics of the students divided by field and by gender (HUM: N = 57, women = 29; STEM: N = 61, women = 36) are presented in Table 11. The level of general learning outcomes achieved, as indicated by total ECTS[14] credits, was similar between the groups. As expected, STEM students reported a significantly higher workload in mathematics, which increased over time, and had higher math skills at entry (i.e., the final high school grade in mathematics). The groups were homogeneous in terms of socio-economic status but differed in age: women in HUM were older than men in HUM and women in STEM (see Results). Therefore, main analyses were repeated including age as a covariate to check whether it influenced the results.

At each assessment point, participants gave written informed consent before participating in the study and were paid €12 after completing the tasks. The study was approved by the SISSA Ethics Committee (approval number Ib/2021/1) and was conducted in accordance with the guidelines of the Declaration of Helsinki and Italian copyright law regarding the reproduction of material online.

Sensitivity power analysis was conducted to determine the effect sizes that could be detected with 118 participants using the G*Power statistical software (Faul et al., 2009). With an alpha level of .05 and a power of .80, an effect size f = 0.15 (small effect, Cohen, 1992) can be reached in a mixed ANOVA with four groups (field of study [HUM vs. STEM] x gender [Women vs. Men]) and two measurements. In a linear regression model with 7 predictors (the most complex model in the path analyses), an alpha level of .05 and a power of .80, the effect size that can be reached is f^2 = 0.13 (medium effect, Cohen, 1992).

[14] European Transfer and Accumulation System university credit

Procedure

The study was conducted online from March to December 2021 (T1) and from March to December 2023 (T2). Participants were recruited in T1 through online channels (Facebook, Sona) and through university institutional channels. At T2, they were invited by email to participate in the follow-up. If they did not respond, a reminder email was sent, with up to four reminders sent in total.

Participants received instructions and links to the tasks via email. To minimize fatigue, the tasks at both assessment times were divided into two separate sessions. The first session included the personal information questions, and all the questionnaires listed in the next section, except for the numeracy test, which was administered in the second session. The non-cognitive measures were administered via Google Forms. The numeracy test was administered via Google Form with a customised script for time limits at T1, whereas it was administered via the Pavlovia platform at T2 (https://pavlovia.org/).

Materials

Numeracy test

To measure numeracy, we constructed an ad hoc test reproducing the items of the TECO-T (TEst of COmpetence), developed by ANVUR (Agenzia Nazionale per la Valutazione del sistema Universitario e della Ricerca, Italian National Agency for the Evaluation of University and Research) to assess students' generic literacy and numeracy competences acquired during higher education degrees (Rumiati et al., 2018). The numeracy test assessed logical and quantitative thinking skills, not related to curricular teaching. The test consisted of 15 multiple-choice questions, each consisting of a word problem and four response options. The questions were grouped into three modules of five questions each: "Graphs and Tables", "Logical Reasoning" and "Infographics". Participants were given 40 minutes to complete the test. Item scores were 1

(correct) and 0 (incorrect). The TECO-T has been standardized on a representative sample of 827 Italian undergraduate students (see ANVUR, 2016, 2021) and a Chronbach's alpha of 0.83 has been reported (ANVUR, 2016). In the present sample, the Chronbach's alpha was 0.66 at T1 and 0.56 at T2.

Math anxiety

Math anxiety was measured using the Abbreviated Math Anxiety Scale (AMAS) (Hopko et al., 2003; Primi et al., 2014). Each item represents a mathematical learning or testing situation. Participants had to select the level of anxiety they experienced in this situation on a five-point Likert scale. The individual total score was calculated as the sum of the item scores, with higher scores corresponding to higher math anxiety. In our sample we observed a Chronbach's alpha of 0.90 at T1 and 0.88 at T2.

Neuroticism

Neuroticism was assessed with the relative items of the Big Five Inventory (BFI) (John et al., 1991; Italian version: Ubbiali et al., 2013; English version available online https://www.ocf.berkeley.edu/~johnlab/bfi.htm). This questionnaire consists of 44 items that assess the traits of the Five Factor model (agreeableness, conscientiousness, extraversion, neuroticism and openness to experience). Eight of the items assess neuroticism. Each item corresponds to a statement and participants must rate their agreement on a five-point Likert scale, with 1 indicating "strongly disagree" and 5 "strongly agree". The mean score for trait neuroticism was calculated. In our sample, the Chronbach's alpha for the neuroticism items was 0.80 at T1 and 0.84 at T2.

Quality control questions

At the end of the numeracy test at T2, some quality control items were included to assess the reliability of the data. Participants were asked whether the questions in the numeracy test were familiar to them (response options: “Yes” or “No”). If they answered “Yes”, they were prompted to indicated how many questions they recognized (response options: “Less than 5”, “From 6 to 10”, or “More than 10”) and whether they remembered the answers (response options: “Yes”, “No”, or “Partially”). Participants were then asked whether they were distracted during the tasks (response options: “Yes” or “No”). If they answered “Yes”, they were further asked to specify whether the distraction occurred during the questionnaires, the numeracy test, or both. Finally, they were asked to rate their overall effort on a 10-point Likert scale (1 = “No effort at all, I answered at random”; 10 = “Maximum effort, as if it were a very important exam”).

Data analysis

Data analyses were performed using R software (version 4.2.2, R Core Team, 2020). First, we performed preliminary data quality checks. We examined the responses to the quality control questions and tested whether familiarity with the numeracy test questions affected performance using a one-way ANOVA with the proportion of correct answers in the numeracy test as the dependent variable and the familiarity with the questions and answers as the factor. A similar ANOVA was used to test the effect of distractions on numeracy test performance. In addition, we tested for significant differences in the variables at T1 between participants who completed the follow-up and those who dropped out. We ran a series of 2x2x2 ANOVAs with the proportion of correct answers in numeracy, the math anxiety and neuroticism scores as dependent variables, and drop-out status [yes vs. no], gender [Women vs. Men] and field of study [HUM vs. STEM] as factors.

Next, we examined group differences in demographic and academic variables. For variables measured only at T1 (i.e., age, socioeconomic status, and high school math grade), we conducted a

2x2 ANOVA with gender and field of study as factors. Significant interactions were further explored with four *t*-tests to compare women and men within HUM, women and men within STEM, HUM and STEM women, and HUM and STEM men. Alphas lower 0.0125 (Bonferroni correction: .05/4[15]) were considered as significant.

To examine changes over time in numeracy, math anxiety, neuroticism, and demographics assessed at both time points (i.e., ECTS and ECTS in math), we conducted mixed ANOVAs with time as the within-subject factor and field and gender as the between-subject factors. Significant two-way interactions with time were further tested comparing the scores at T1 and T2 within gender or field at the two time points, using a Bonferroni-corrected alpha of 0.025 (.05/2). We also computed Spearman correlations between numeracy, math anxiety and neuroticism at T1 and T2 to determine whether their relationships remained stable over time.

Finally, to address our primary research question about the longitudinal association between non-cognitive factors and numeracy, we conducted path analyses using the PROCESS macro for R (Hayes, 2021). We set math anxiety/neuroticism at T1 as the predictor, numeracy at T1 and math anxiety/neuroticism at T2 as the mediators and numeracy at T2 as the outcome (PROCESS model 6, Hayes, 2017). This approach allowed us to test the cross-sectional associations between non-cognitive factors and numeracy, as well as their cross-lagged associations, while controlling for their respective values at T1. We estimated the total and indirect effects of math anxiety/neuroticism at T1 on numeracy at T2 through numeracy at T1, through math anxiety/neuroticism at T2 and through numeracy at T1 and math anxiety/neuroticism at T2. We then repeated these path analyses, adding field of study and gender as moderators (PROCESS model 92, Hayes, 2017), and additionally calculated moderated mediation indices to assess field and gender differences in the indirect effects (Hayes, 2015). Continuous variables were standardized prior to model estimation in PROCESS to obtain standardized regression coefficients (β) and standardized indirect effect

[15] Bonferroni correction was applied for post-hoc tests, as only relevant comparisons were conducted, avoiding exhaustive pairwise comparisons.

indices. According to Cohen's guidelines (Cohen, 1988), β values between 0.10–0.29 indicate small effects, between 0.30–0.49 medium effects, and 0.50 or higher large effects. Indirect mediating effects and the index of moderated mediation were evaluated using 95% confidence intervals (CIs) estimated using bootstrapping with 10000 samples. If the CI did not include zero, the indirect effect and the index of moderated mediation were considered statistically significant at the 0.05 level (Hayes, 2017).

Results

Quality checks

Three participants reported insufficient effort in completing the tasks (i.e., a rating of less than 6 out of 10) and were therefore excluded from all statistical analyses. In addition, one participant did not complete the quality control questions due to an oversight.

A total of 103 participants reported remembering the numeracy test questions: 51 remembered fewer than 5 questions, 39 remembered between 6 and 10 and 13 recalled more than 10. Only 8 participants reported that they remembered the answers and 23 partially remembered them. No significant differences in numeracy were found between these groups ($F(3, 113) = 0.94$, $p = .422$; Supplementary Figure 6).

Ten participants reported being distracted during the numeracy test and 96 during the completion of the questionnaires. However, their numeracy performance did not differ from that of the other participants ($F(2, 114) = 0.19$, $p = .824$; Supplementary Figure 7).

Regarding the drop-out status, a significant difference was only found for math anxiety ($F(1, 199) = 3.91$, $p = .049$): participants who completed the follow-up had slightly lower math anxiety compared to those who dropped out ($d = 0.31$, $M_{drop\text{-}out} = 24.49$, $SD_{drop\text{-}out} = 8.40$). Drop-out status did not interact with gender or field of study, and the drop-out effect was not statistically significant for other dependent variables (all p-values > .05).

Demographic and academic characteristics

Descriptive statistics are shown in Table 11. A significant main effect of field ($F(1, 114) = 8.93$, $p = .003$) and a significant interaction between field and gender ($F(1, 114) = 4.99$, $p = .027$) were found for age. Women in the HUM field were significantly older than men in HUM ($M_{womenHUM} = 20.52$, $M_{menHUM} = 19.54$, $t(112) = 2.77$, $p = .007$, $d = 0.52$) and women in STEM ($M_{womenSTEM} = 19.22$, $t(128) = -4.62$, $p < .001$, $d = -0.82$). In addition, there was a significant main effect of field for math knowledge at university entry, as measured by the final high school grade in mathematics ($F(1, 114) = 5.00$, $p = .027$). For ECTS, a significant effect of time was observed ($F(1, 108) = 7.39$, $p = .008$). In the case of math ECTS, significant main effects of field ($F(1, 109) = 58.54$, $p < .001$) and time ($F(1, 109) = 28.93$, $p < .001$) and with their interaction ($F(1, 109) = 28.99$, $p < .001$), were observed. Only in STEM did the number of ECTS in math increase over time ($t(60) = -5.78$, $p < .001$, $d = -0.95$). No significant effect was found for socio-economic status.

Table 11. Descriptive statistics for the study variables.

		Whole sample		HUM		STEM		Women		Men	
		N	*M* (*SD*) [range]	*N*	*M* (*SD*) [range]	*N*	*M* (*SD*) [range]	*N*	*M* (*SD*) [range]	*N*	*M* (*SD*) [range]
Age	T1	118	19.65 (1.47) [18-27]	57	20.04 (1.95) [18-27]	61	19.3 (0.61) [18-21]	65	19.8 (1.72) [18-27]	53	19.47 (1.08) [18-25]
SES[a]	T1	111	4.40 (1.90) [2-8]	52	4.23 (1.83) [2-8]	59	4.54 (1.96) [2-8]	61	4.49 (1.98) [2-8]	50	4.28 (1.81) [2-7]
Math grade in high school	T1	118	7.99 (1.27) [6-10]	57	7.72 (1.24) [6-10]	61	8.25 (1.26) [6-10]	65	8.05 (1.26) [6-10]	53	7.92 (1.30) [6-10]
ECTS	T1	118	17.34 (20.04) [0-96]	57	17.41 (17.38) [0-90]	61	17.28 (22.39) [0-96]	65	20.81 (21.25) [0-96]	53	13.09 (17.73) [0-90]
	T2[b]	112	106.88 (39.38) [18-180]	51	115.04 (32.56) [24-180]	61	100.07 (43.38) [18-180]	60	104.48 (41.97) [24-180]	52	109.65 (36.39) [18-180]
ECTS in math	T1	118	4.60 (12.12) [0-81]	57	1.02 (4.71) [0-30]	61	7.95 (15.56) [0-81]	65	3.38 (10.22) [0-66]	53	6.09 (14.06) [0-81]
	T2 [b]	113	16.64 (25.52) [0-141]	52	1.04 (2.71) [0-12]	61	29.93 (28.61) [0-141]	61	15.33 (22.26) [0-119]	52	18.17 (29.02) [0-141]
Numeracy	T1	118	0.63 (0.19) [0.2-1]	57	0.60 (0.20) [0.27-0.93]	61	0.65 (0.18) [0.20-1]	65	0.58 (0.18) [0.27-0.93]	53	0.68 (0.19) 0.2-1
	T2	118	0.65 (0.17) [0.20-1]	57	0.60 (0.18) [0.20-0.93]	61	0.70 (0.14) [0.40-1]	65	0.62 (0.17) [0.2-0.93]	53	0.69 (0.16) [0.33-1]
Math anxiety	T1	118	21.98 (7.70) [9-45]	57	24.67 (8.24) [9-45]	61	19.48 (6.24) [9-35]	65	23.11 (7.56) [11-45]	53	20.60 (7.72) [9-41]
	T2	118	20 (7.27) [9-45]	57	21.46 (8.35) [9-45]	61	18.64 (5.82) [9-38]	65	20.48 (7.50) [9-45]	53	19.42 (6.99) [9-35]
Neuroticism	T1	118	3.15 (0.73) [1.38-4.75]	57	3.34 (0.68) [2-4.75]	61	2.98 (0.74) [1.38-4.5]	65	3.33 (0.67) [1.88-4.75]	53	2.93 (0.76) [1.38-4.50]
	T2	118	3.21 (0.79) [1.5-5]	57	3.35 (0.77) [1.5-4.62]	61	3.08 (0.79) [1.50-5]	65	3.44 (0.69) [1.75-4.88]	53	2.93 (0.81) [1.50-5]

Notes. [a] SES = socio-economic status. It corresponds to the highest level of education completed by the parents, based on the International Standard Classification of Education (ISCED). Seven responses were discarded because they were too general to determine the corresponding ISCED level. [b] The responses of the five participants who left university are missing at T2. In addition, one participant did not provide the total number of ECTS at T2.

Time changes and correlations

Descriptive statistics for numeracy, math anxiety and neuroticism are reported in Table 11 and visually presented in Supplementary Figure 8.

The ANOVA on numeracy revealed significant main effects for field ($F(1, 114) = 9.46$, $p = .003$) and gender ($F(1, 114) = 11.03$, $p = .001$), with STEM students and men outperforming HUM students and women, respectively. For math anxiety, there were significant main effects of field ($F(1, 114) = 12.38$, $p < .001$) and time ($F(1, 114) = 12.84$, $p < .001$), as well as a significant interaction between time and fields ($F(1, 114) = 4.80$, $p = .031$). HUM students showed a small decrease in math anxiety from T1 to T2 ($t(56) = 3.72$, $p < .001$, $d = 0.39$), whereas STEM students did not ($t(60) = 1.21$, $p = .232$, $d = 0.14$). The ANOVA on neuroticism revealed significant main effects of field ($F(1, 114) = 9.07$, $p = .003$) and gender ($F(1, 114) = 15.95$, $p < .001$), with HUM students and women scoring higher than STEM students and men, respectively. The results did not change when we repeated the ANOVAs excluding the five students who left university and when age was included as covariate.

The correlations between the main variables at T1 and T2 are shown in Table 12. Numeracy is negatively correlated with math anxiety in all subgroups at both time points. The negative correlation between numeracy and neuroticism is only significant at T2 and only for HUM students. Math anxiety and neuroticism are positively correlated.

Table 12. Correlations between the main variables at T1 and T2. Significance levels are specified as follows: * $p < .05$; ** $p < .01$; *** $p < .001$.

	Correlations	Whole sample	HUM	STEM	Women	Men
T1	Numeracy - Math anxiey	-0.36***	-0.39**	-0.29*	-0.24	-0.41**
	Numeracy - Neuroticism	-0.14	-0.08	-0.13	-0.01	-0.16
	Math anxiety - Neuroticism	0.35***	0.34**	0.20	0.30*	0.38**
T2	Numeracy - Math anxiey	-0.40***	-0.30*	-0.42***	-0.34**	-0.44***
	Numeracy - Neuroticism	-0.19*	-0.28*	-0.03	-0.02	-0.25
	Math anxiety - Neuroticism	0.22*	0.25	0.18	0.15	0.34*

Path analyses

Significant associations from the path analyses with math anxiety as the predictor are shown in Figure 3a (see Supplementary Table 6 for full results). The total effect of math anxiety at T1 on numeracy at T2 was significant (-0.37, $p < .001$, CI [-0.55; -0.21]). The association between math anxiety at T1 and numeracy at T1 was significant and of medium magnitude. Both math anxiety and numeracy at T1 were strongly associated with their respective scores at T2. In addition, numeracy at T1 was significantly and negatively associated with math anxiety at T2, with a small effect size. The indirect effect of math anxiety at T1 on numeracy at T2 via numeracy at T1 was small but significant (-0.21, CI [-0.42; -0.13]). No other direct or indirect pathways were significant.

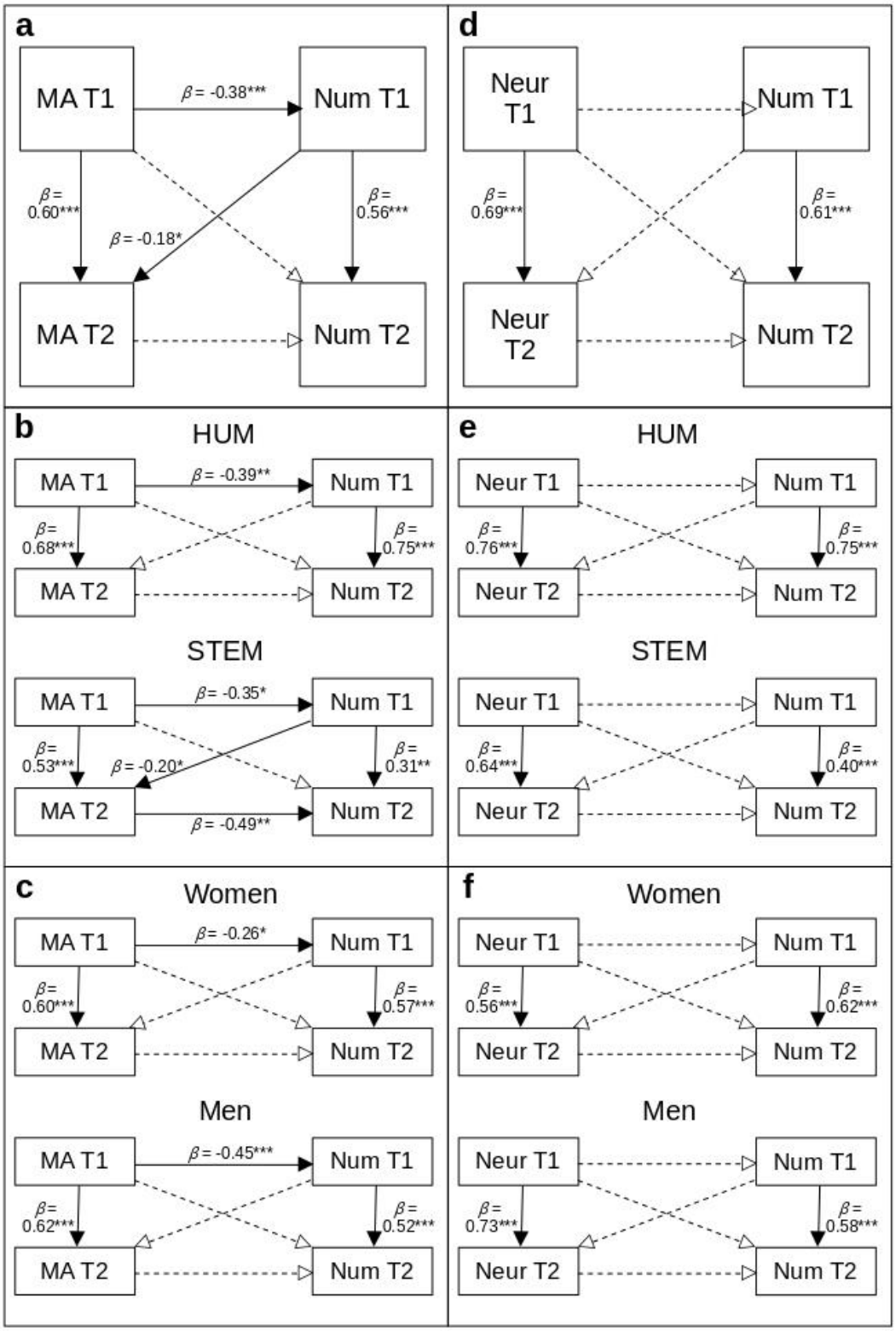
When field of study was included as a moderator (Figure 3b), significant interactions were found between field and numeracy at T1 ($\beta = 0.44$, $p = .003$, CI [0.14; 0.73]) and between field and math anxiety at T2 ($\beta = 0.63$, $p = .001$, CI [0.25; 1.00]) in predicting numeracy at T2. The effect of numeracy at T1 on numeracy at T2 was positive in both fields, with a small-to-medium effect size in STEM and a strong effect in HUM. The effect of math anxiety at T2 on numeracy at T2 was medium to strong and negative in STEM, but not significant in HUM. The interaction between field and math anxiety at T1 in predicting numeracy at T2 was also significant ($\beta = 0.44$, $p = 0.021$, CI [-

0.81; -0]), although the simple effects for HUM (β = -0.20, p = .117) and STEM (β = 0.24, p = .092) did not reach statistical significance. The indirect effect of math anxiety at T1 on numeracy at T2 via numeracy at T1 was small but significant for both groups (STEM: -0.11, CI [-0.24; -0.01]; HUM: -0.29, CI [-0.46; -0.14]; index of moderated mediation: -0.19, CI [-0.38; 0.01]). In the STEM group, the indirect path through math anxiety at T2 was also small but significant (-0.25, CI [-0.49; -0.07]; index of moderated mediation: 0.35, CI [0.13; 0.62]). No pathways were significantly moderated by gender (Figure 3c).

Figure 3d shows the significant associations in the path analyses with neuroticism as a predictor. Full results are reported in Supplementary Table 7. The total effect of neuroticism at T1 on numeracy at T2 was small but significant (-0.19, p = 0.036, CI [-0.37; -0.01]). However, only the associations between neuroticism and numeracy at T1 and their respective scores at T2 were significant. No other direct or indirect pathway reached significance, and no moderating effects of field of study or gender were found (Figures 3e and 3f).

The results did not change when we repeated the path analyses excluding the five students who left university and including age as a covariate.

Figure 3. Models of the longitudinal relationships between non-cognitive factors and numeracy. All estimates are standardized. Dashed lines indicate non-significant paths. Significance levels are indicated as follows: * p < .05; ** p < .01; *** p < .001. MA = math anxiety; Num = Numeracy; Neur = Neuroticism. Panels: a) Mediation analysis with math anxiety as predictor. b) Moderated mediation with math anxiety as predictor and field of study as moderator. c) Moderated mediation with math anxiety as predictor and gender as moderator. d) Mediation analysis with neuroticism as predictor. e) Moderated mediation with neuroticism as predictor and field of study as moderator. f) Moderated mediation with neuroticism as predictor and gender as moderator.


a
MA T1
β = -0.38***
Num T1
β = 0.60***
β = -0.18*
β = 0.56***
MA T2
Num T2
d
Neur T1
Num T1
β = 0.69***
β = 0.61***
Neur T2
Num T2
b
HUM
MA T1
β = -0.39**
Num T1
β = 0.68***
β = 0.75***
MA T2
Num T2
STEM
MA T1
β = -0.35*
Num T1
β = 0.53***
β = -0.20*
β = 0.31**
MA T2
β = -0.49**
Num T2
e
HUM
Neur T1
Num T1
β = 0.76***
β = 0.75***
Neur T2
Num T2
STEM
Neur T1
Num T1
β = 0.64***
β = 0.40***
Neur T2
Num T2
c
Women
MA T1
β = -0.26*
Num T1
β = 0.60***
β = 0.57***
MA T2
Num T2
Men
MA T1
β = -0.45***
Num T1
β = 0.62***
β = 0.52***
MA T2
Num T2
f
Women
Neur T1
Num T1
β = 0.56***
β = 0.62***
Neur T2
Num T2
Men
Neur T1
Num T1
β = 0.73***
β = 0.58***
Neur T2
Num T2

Discussion

Although non-cognitive factors are often cited as contributing to numeracy acquisition (e.g., Cerni et al., 2021; Dowker et al., 2016), most studies have investigated these associations cross-sectionally, providing limited evidence on the predictive role of non-cognitive factors. In this longitudinal study, we investigated the relationship between numeracy and non-cognitive factors—specifically math anxiety and the personality trait of neuroticism—among undergraduate students. We assessed these variables at two points in time: when students were at the beginning of a bachelor's programme in STEM or HUM (T1) and two years later (T2).

The first aim was to investigate changes in numeracy, math anxiety and neuroticism during the bachelor's programme. We observed differences between T1 and T2 only in math anxiety, which showed a small but significant decrease over time, particularly among HUM students, while remaining stable among STEM students. This finding supports previous research highlighting the heterogeneity of math anxiety developmental pathways (Ahmed, 2018; Wang, Oh, et al., 2020). The decrease in math anxiety among HUM students may be due to socialization processes (for a similar interpretation in secondary school students, see Wigfield & Eccles, 1989): in HUM programmes, where math is not a core subject, students value math less than in STEM programmes or as they did in high school. Therefore, there is less social comparison in math competence, and this may consequently reduce anxiety. Another possible explanation of the decrease in math anxiety, especially in HUM students, is the brain reorganization during late adolescence. The adolescent brain undergoes a maturation process marked by increased activity in frontal and prefrontal regions, which are functionally connected to areas involved in fear processing, such as the amygdala, and regulate their activation (e.g., Xie et al., 2021). Studies indicate that this increased activity is inversely correlated with anxiety levels as adolescents age (Tamura et al., 2012).

Numeracy and neuroticism, however, did not change between T1 and T2. The stability of neuroticism was expected, given that personality is defined as a set of individual characteristics that

are relatively stable (e.g., McCrae & Costa, 1999), especially in adulthood (Bleidorn et al., 2021). The stability of numeracy is consistent with findings suggesting that numeracy tends to remain stable in adulthood (Lechner et al., 2021), which contradicts previous cross-sectional findings showing a decline in HUM students (Rumiati et al., 2018). Furthermore, the correlation patterns between numeracy and non-cognitive factors were consistent at T1 and T2. Numeracy was negatively correlated with math anxiety in all groups and with neuroticism, particularly in HUM, while the correlation between neuroticism and math anxiety was positive, in line with the results reported in the previous studies (Chapters 2 and 3).

Next, we conducted path analyses to examine the longitudinal relationships between non-cognitive factors and numeracy. We found that math anxiety at T1 influenced future numeracy, but this effect was indirect (for similar findings in primary school, see Cargnelutti et al., 2017). Specifically, higher math anxiety at T1 was associated with lower numeracy at T1, which in turn was associated with lower numeracy at T2. In contrast, the indirect effect of math anxiety at T1 through math anxiety at T2 was not significant. This suggests that math anxiety affects students' concurrent numeracy at the beginning of their studies and consequently their numeracy at the end of the bachelor's degree, while the effect of math anxiety diminishes over time, although individual differences may exist. In fact, when we examined the moderating role of the field of study, we found that for STEM students the indirect path through math anxiety at T2 was also significant. Furthermore, the association between numeracy at T1 and T2 was stronger for HUM students than for STEM students. These findings suggest that the mechanisms by which math anxiety affects future numeracy may vary depending on the educational context, with the impact of math anxiety being particularly reduced in fields where mathematics does not play a relevant role in the academic careers.

Interestingly, math anxiety at T2 was associated with numeracy at T1, suggesting that early lower numeracy affects future math anxiety. Indeed, several studies have suggested a reciprocal

effect of math anxiety and numeracy (in primary school: Gunderson et al., 2018; Lichtenfeld et al., 2023; Szczygieł et al., 2024; in secondary school: Pekrun et al., 2017): not only is higher math anxiety is associated with later lower numeracy, but earlier lower math achievement can also predict later higher math anxiety. Our findings extend this evidence into early adulthood, highlighting a vicious cycle in which lower numeracy exacerbates anxiety. In our sample, this was particularly evident for STEM students, but not for HUM. STEM students, who place higher value on mathematics, may be particularly vulnerable to developing math anxiety if their numeracy skills are lower than those of other students in the same field.

In terms of neuroticism at T1, it was significantly associated with numeracy at T2, but the effect size was small, and none of the indirect pathways tested (i.e., through numeracy at T1, through neuroticism at T2, or both) were significant. These findings provide further evidence for the role of personality in numeracy outcomes but the strength of this evidence is limited. The lack of statistical significance of the indirect effects does not rule out the possibility of mediation effects, or of reciprocal influences with numeracy, as seen with math anxiety. Further studies with larger sample sizes and greater statistical power are needed to fully explore the mechanisms underlying the influence of personality on numeracy.

Finally, it is worth noting that the field of study moderated the effects examined, while gender did not, consistent with the study presented in Chapter 3. This finding supports the notion that differences related to the choice of the field of study may provide more explanatory power than gender in understanding individual variability in numeracy in higher education. Students in STEM and HUM fields are likely to differ not only in their exposure to mathematics coursework but also in personality traits, math-related attitudes, and interests that influenced their field choice. These field-specific differences appear more significant than gender differences in relation to numeracy outcomes. This does not rule out the existence of gender differences, since we found that women obtained lower scores in numeracy and reported higher neuroticism than men (e.g., Borgonovi et

al., 2021; Schmitt et al., 2008). The mechanisms underlying men's and women's performance in mathematics may be influenced by other individual characteristics that are not evaluated in this study, such as math self-concept (e.g., Rossi et al., 2022).

These results should be interpreted with a number of limitations. First, the dropout rate in our study was high. The sample decreased by 42% from T1 to T2 and, importantly, participants who did not complete the follow-up reported higher average math anxiety than those who did. Therefore, the sample is likely biased by self-selection, which limits the generalizability of our findings. Second, the sample size of the present study was small, which prevented us from using more sophisticated statistical techniques, such as structural equation modelling, which has often been used in similar study designs (e.g., Cargnelutti et al., 2017; Ma & Xu, 2004; Sorvo et al., 2019, 2022). Path analysis based on regression models, i.e., the approach used in this study, does not account for measurement error, thus making the estimation of direct and indirect effects less precise than with structural equation modelling. Given the limited number of observations in this sample, it was not guaranteed to produce stable unbiased estimates (e.g., Kline, 2005).

In conclusion, we have shown that math anxiety and, to a lesser extent, neuroticism, measured at the beginning of a bachelor’s programme, are associated with numeracy performance two years later. In particular, the effect of math anxiety is primarily driven by its association with concurrent numeracy, and by later math anxiety in STEM students. Despite the limitations, these findings advance our understanding of the long-term relationships between non-cognitive factors and numeracy and highlight the importance of considering bidirectional effects and differences between fields of study to gain a comprehensive understanding of these complex mechanisms.

CHAPTER 5

Study 4. Physiological correlates of numeracy in higher education

Adapted from Lunardon, M., Cerni, T., Zanon, M., & Rumiati, R. I. (2024). Physiological correlates of numeracy in higher education. PsyArXiv. https://doi.org/10.31234/osf.io/adnw9

Abstract

Physiological responses offer a promising avenue for investigating the emotional states associated with task performance. However, studies examining the physiological correlates of mathematical performance remain limited and inconsistent. Here we investigated the relationship between numeracy and three measures of physiological arousal (salivary cortisol, skin conductance, and heart rate variability) in 130 university students. We aimed to determine whether these associations varied across different levels of self-reported math anxiety and neuroticism. The results show that increased numeracy was associated with an overall increase in cortisol and, in students with low neuroticism, with an increase or decrease in skin conductance in different fields of study. In addition, different profiles of math anxiety, neuroticism, and physiological responses emerged, displaying different numeracy performance. No modulation by math anxiety and gender was found. These findings highlight that differences in neuroticism and between fields of study should be considered for a comprehensive interpretation of physiological arousal in relation to numeracy.

Introduction

The results of the previous chapters have been the relationships between non-cognitive factors and numeracy both cross-sectionally (Chapters 2 and 3) and longitudinally (Chapter 4) among university students. In these studies, as in most of the literature, non-cognitive factors were assessed using self-report questionnaires. These instruments are reliable and efficient for assessing math anxiety and personality (Dowker et al., 2016; John et al., 1991). However, self-reports require individuals to retrospectively assess their past experiences and emotions, which may not accurately reflect their psychological experience during a task (Orbach et al., 2019, 2020).

Physiological changes during anxiety-provoking mathematical tasks can provide a more immediate and objective way to tracking emotional and psychological responses (see Chapter 1 for a review). Physiological measures such as cortisol levels, skin conductance level (SCL) and heart

rate variability (HRV) are commonly used as indicators of the activity of the hypothalamic-pituitary-adrenal (HPA) axis and the autonomic nervous system (ANS). These systems work together to maintain internal homeostasis in response to external demands and ensure an appropriate behavioural response (Kreibig & Gendolla, 2014).

Increased salivary cortisol, increased SCL and decreased HRV can be considered signs of physiological arousal (Berntson et al., 1997; Boucsein, 2012; Laborde et al., 2017; Russell & Lightman, 2019) and are traditionally associated with changes in affective states, including those related to mathematics (Mammarella et al., 2023). These changes can potentially affect performance on numeracy tests, although results have been mixed. Some studies found that greater arousal was associated with lower performance (Daker et al., 2023; Tang et al., 2021), while others reported associations with better performance (Mattarella-Micke et al., 2011).

The biopsychosocial model explains this varying relationship between physiological arousal and test performance. Individual differences in how a context or task is appraised play a crucial role (Blascovich & Mendes, 2010; Mendes & Park, 2014). When individuals are faced with a goal-relevant situation, their appraisal of the situation as challenging or threatening can influence how they interpret physiological arousal, leading to different behavioural outcomes. Whether a situation is viewed as challenging or threatening can be influenced by dispositional and affective factors, such as self-reported math anxiety and neuroticism (Ramirez et al., 2018; Tomaka & Magoc, 2021).

Students with higher math anxiety or neuroticism may feel threatened by a math test situation and engage in avoidance behaviours, whereas those with lower levels of these traits are more likely to feel challenged and respond proactively to achieve their goals. In this context, physiological arousal is not just a proxy for non-cognitive factors measured by self-report.

In addition, our previous findings (Chapters 2-4) suggest that differences in field of study and gender should be taken into account. For example, neuroticism was negatively associated with numeracy, but only among HUM students, for whom mathematics is not a core part of the

curriculum. Among STEM students, no significant relationship was found between neuroticism and numeracy (Chapter 3). Furthermore, when looking at gender differences, we observed a significant positive association between numeracy and neuroticism among women, which was stronger at higher levels of math anxiety. Conversely, no such association was found for men (Chapter 2). Therefore, neuroticism alone may not determine how a situation is evaluated; differences in neuroticism should be considered alongside a student's field of study and gender.

The choice of a particular degree programme is influenced by a variety of personal and affective factors, which may contribute differentially to numeracy in different fields (Cerni et al., 2021). People who choose a humanities degree programme may be driven by the desire to avoid mathematics, which is likely to be influenced by math anxiety (Ahmed, 2018; Beilock & Maloney, 2015; Schmitz et al., 2023). Consequently, humanities students with high neuroticism may be particularly prone to perceiving a numeracy test situation as threatening, as mathematics does not appeal to them, and they are likely to be less familiar with numerical content than STEM students. In contrast, students in STEM fields may have developed more positive attitudes toward mathematics and have spent more time engaged in mathematics learning. This familiarity can buffer them against intense physiological arousal when confronted with math-related tasks, even if they also report high neuroticism, as these tasks are likely not perceived as threatening. These field differences in math-related arousal point to broader distinctions in how personal and affective characteristics shape students' learning experiences across academic disciplines.

Gender differences in attitudes towards mathematics are often reported. Women typically report higher levels of math anxiety and lower levels of confidence in their math abilities compared to men (Betz, 1978; Mejía-Rodríguez et al., 2021; Stoet et al., 2016). Women are also less represented in STEM programmes (Eurostat, 2022) and are subject to the stereotype that mathematics is a male domain (Eccles & Jacobs, 1986), which can lead to different response patterns in men and women, such as a greater physiological arousal in women rather than in men

during a numerical task (Osborne, 2006). In the case of women, those high in neuroticism may pay more attention to physiological arousal, which in the context of a math-related situation may be interpreted as a challenge rather than a threat, as they may be accustomed to these feelings in this particular context.

The present study

The primary aim of the present study was to examine individual differences in the physiological correlates of numeracy performance in a sample of university students. To achieve this, we adopted two approaches: we analysed the association between physiological indices and numeracy performance (variable-centred approach), and we explored within-person configurations of physiological responses, math anxiety and neuroticism (person-centred approach) (Woo et al., 2024).

We measured physiological changes using salivary cortisol concentration, SCL and HRV, to take into account multiple systems involved in physiological reactivity, such as the HPA and the sympathetic and parasympathetic branches of the ANS. Specifically, we collected one saliva sample before and one after the numeracy test, and we recorded electrodermal activity and electrocardiogram data while students performed the numeracy test. The numeracy test consisted of a series of word problems designed to assess quantitative and mathematical-logical reasoning in the Italian university students (ANVUR, 2016).

Using the variable-centred approach, for each physiological response, we estimated its association with test performance. If physiological responses represent a negative affective state, we expected that a decrease in physiological responses (increase in salivary cortisol concentration, increase in SCL and decrease in HRV) would correspond to better performance, similar to the effect of self-reported math anxiety. However, we cannot exclude the possibility that increases in physiological response are associated with better performance, reflecting effective task engagement.

In addition, we examined whether the associations between physiological responses and performance were influenced by self-reported math anxiety and neuroticism (collectively referred to as “trait variables”). These trait variables affect how likely an individual is to perceive a situation as threatening — either specifically for mathematics in the case of math anxiety, or generally across situations in the case of neuroticism. In line with the biopsychosocial model, we expected that an increase in physiological response would be associated with a decrease in numeracy performance in individuals with higher levels of the trait variables. Conversely, for individuals with lower levels of these variables, better performance might be associated with an increase in physiological response, suggesting that they perceive the numeracy test as challenging and exert mental effort to support effective test performance. We also investigated whether these effects varied by field of study, particularly between STEM and humanities university programmes, and by gender, as these factors were observed to moderate the association between numeracy and the trait variables, particularly neuroticism.

Using the person-centred approach, we investigated the existence of different student profiles based on physiological responses and trait variables, and whether these profiles differed in their numeracy performance. Given that there is no clear relationship between physiological responses and psychological states, we expected to find heterogeneous profiles. For example, we might find a group of participants with higher levels of physiological responses and trait variables, including those more threatened by the numeracy test and therefore performed lower. We might also find participants with a profile characterised by low trait variables and high physiological responses, who are mentally engaged in the task and therefore perform better in the numeracy task. We did not exclude the possibility that other profiles might emerge, as this is the first time such analysis is applied with multiple physiological data in the mathematical domain. We then investigated whether these profiles are distributed differently across fields of study and gender, and whether, within these groups, the association between profiles and numeracy performance varies within these groups.

Applying these two approaches to the same dataset — one designed to discover general variable associations across a priori groups, and a data-driven approach designed to discover emerging groups and differences between them — can provide a comprehensive view of the physiological correlates of numeracy performance and how they differ across individuals.

Materials and Methods

Participants

We recruited 131 students enrolled at an Italian university in a bachelor's or master's degree programme in socio-humanities (HUM, including literature and arts, psychology, foreign languages, history and philosophy, social and political sciences) or STEM[16] (including mathematics, zootechnics and ecology, engineering, physics, biotechnologies, biology, statistics, chemistry) and aged between 18 and 30 years. Individuals with a history of developmental and/or learning disabilities and chronic medication use were excluded. One subject was excluded because of missing physiological and numeracy responses due to a technical failure during the laboratory session. The final sample consisted of 130 students: 67 from HUM programmes (34 women) and 63 from STEM programmes (31 women). Demographic and academic characteristics are shown in Table 13.

Informed consent was obtained before each of the two study sessions (see Procedure). Upon completion of both sessions, participants received 20 euros as compensation. The study was approved by the SISSA Ethics Committee (approval number Ib/2022/3). It was conducted according to the guidelines of the Declaration of Helsinki and of the Italian law on copyright for the reproduction of material on the Internet.

Power analysis was performed using G*Power statistical software (Faul et al., 2009). Assuming a power of 0.80 and an alpha level of 0.05, a medium correlation effect (i.e., 0.30)

[16] HUM or STEM were categorised according to the official classification made by the Italian Ministry of University and Research (Decree Law 942/2020, Attachment A)

requires a sample size of 84. To find a medium Cohen's f2 effect size (i.e., 0.15) for multiple regressions with 9 predictors (the most complex model we fitted), a sample of 114 is required. In all our analyses, the number of observations exceeded these minimum sample sizes.

Materials

Numeracy test

To measure numeracy, we used the TECO-T (TEst of COmpetence) developed by ANVUR (Agenzia Nazionale per la Valutazione del sistema Universitario e della Ricerca, Italian National Agency for the Evaluation of University and Research) to assess students' generic numeracy skills acquired during higher education degrees (Rumiati et al., 2018). The numeracy test assessed logical and quantitative thinking skills, which are not related to curricular teaching. The test consisted of 15 multiple-choice questions, each consisting of a word problem and four response options. The questions were divided into three modules. In the "Graphs and Tables module" (3 items), participants had to extract information from a graph or a table to infer relationships between variables. In the Logical Reasoning module (9 items), participants had to draw conclusions on the bases of some numerical or verbal premises. To answer the questions in the Infographics module (3 items), participants had to infer information about car fuel consumption and pollution from visually represented data. There was no time constraint was imposed. Item scores were 1 (correct) and 0 (incorrect). The TECO-T was standardised on a representative sample of 827 Italian undergraduate students (ANVUR, 2016, 2021) and a Chronbach's alpha of 0.83 was reported (ANVUR, 2016). In our sample the Chronbach's alpha was 0.62. The lower reliability observed in our sample may stem from two factors: (1) our participants were limited to STEM and humanities students, unlike the broader sample in the original study that also included social sciences and health sciences students, and (2) the test administration differed, with our study conducted remotely without direct

assistance, whereas the original study had participants complete the test in groups with a tutor present.

Neuroticism

We used the Big Five Inventory (BFI) (John et al., 1991) (English version available online: https://www.ocf.berkeley.edu/~johnlab/bfi.htm; Italian version: Ubbiali et al., 2013) to assess trait neuroticism, which is addressed by eight of the scale's 44 total items. Each item corresponds to a statement and participants have to rate their agreement on a five-point Likert scale, with 1 indicating 'strongly disagree' and 5 indicating 'strongly agree'. The mean score was calculated, and higher scores correspond to higher neuroticism. The Chronbach's alpha for neuroticism in our sample was 0.84.

Math anxiety

Math anxiety was measured using the Italian version of the Abbreviated Math Anxiety Scale (AMAS) (Hopko et al., 2003; Primi et al., 2014), which consists of 9 items. We contacted the first author of the Italian standardisation paper to obtain the scale. Each item represents a mathematical learning or testing situation. Participants had to select, on a five-point Likert scale, the level of anxiety they experienced in the situation. The individual total score was calculated as the sum of the item scores, with higher scores corresponding to higher math anxiety. In our sample we observed a Cronbach's alpha of 0.90.

Intelligence quotient

A reduced nine-item form of the Raven's Standard Progressive Matrices was used (Bilker et al., 2012). The individual score on the nine-item scale was converted into a prediction of the total score on the 60-item scale using the formula reported by Bilker et al. (2012). The predicted total

score was converted into an IQ score according to age-appropriate standardisation (Raven, 1938; Valseschini, & Del Ton, 1973). The authors reported satisfying internal consistency (Chronbach's alpha: 0.80; Bilker et al., 2012). In our sample the Chronbach's alpha was 0.60. Similarly to the numeracy test, the lower reliability could be due to the characteristics of the sample -in the original study, participants were aged between 16 and 77, while in our sample participants are young adults- and the administration type -paper and pencil and face-to-face administration in the original study and computerised remote administration in the present study-.

Basic arithmetical skill

We used the Arithmetic Fact Retrieval task from a standardised battery designed to diagnose learning disabilities in university students and adults (Montesano et al., 2020). This task assessed the automaticity of solution retrieval. Participants had to solve a series of operations, presented auditorily one at a time, as accurately and quickly as possible, and type in their answer within 5 seconds. There were 6 additions, 5 subtractions, 12 multiplications, 5 divisions, 2 square roots (30 operations in total). Before calculating the accuracy rate, we excluded responses whose time was less than 3 SD from the sample mean response time (0.08% of total items). This test displayed a good test-retest reliability (0.85), as reported in the standardisation manual (Montesano et al., 2020).

Salivary cortisol

Two saliva samples were collected from each participant (see Procedure) using the Salivette® Cortisol (Sarstedt AG. & Co. KG, Germany). The saliva samples were stored at 0.5°C. Within four days from collection, the saliva samples were transported in a thermal bag and delivered to an external laboratory for the analysis (Policlinico Triestino S.p.a., Italy). The samples were centrifuged at 1000 rpm for 2 minutes. Cortisol levels were then quantified by the electrochemiluminescence immunoassay (ECLIA) using Elecsys Cortisol II immunoassay analyzers

(Roche Diagnostics GmbH, Germany). Raw cortisol concentrations before and after the test are shown in Figure 4.1. We calculated the change in cortisol concentration as the difference between the post-test and pre-test concentrations, divided by the pre-test concentration (for a similar procedure. see Sarkar et al., 2014).

Electrophysiological data recording

A BIOPAC MP150 system (BIOPAC System Inc.) was used to record both electrodermal (EDA) and electrocardiogram (ECG) signals.

The EDA signal was recorded using an EDA100C-MRI amplifier module (BIOPAC) and two reusable electrodes (TSD203 transducer, BIOPAC) placed on the volar surfaces of the distal phalanges of the index and middle fingers of the non-dominant hand. The low-pass filter on the amplifier was set to 10 Hz, while no high-pass filter was set (high-pass filter set to DC). The amplifier gain was set to 5μS/V and the EDA signal was digitalised at a sampling rate of 2 kHz.

The ECG signal was recorded using an ECG100C MRI amplifier module (BIOPAC) and two disposable electrodes (EL503 general purpose electrodes, BIOPAC). A lead II configuration was used, with the negative electrode placed on the right clavicle and the positive electrode on the left lower rib. The ground electrode was not used because of the simultaneous recording of EDA, as indicated by the manufacturer of the amplifier. The high-pass and low-pass filters on the amplifier were set to 1 and 35 Hz, respectively, and a 50-Hz notch filter was engaged. The amplifier gain was set to 1000 and the ECG signal was digitised at sampling rate of 2 kHz.

Electrophysiological data analysis

We visually inspected the EDA and ECG signals using the Matlab software (v.2021a). We discarded the EDA recording of two participants (two women in the STEM group), the first because of too many motion artefacts and the second because of lack of signal in part of the recording. We

also discarded the ECG recording of three participants (one woman in the STEM group, and one woman and one man in the HUM group), because of motion artefacts (two participants) and one ventricular extrasystole of which the participant was unaware. Finally, we excluded both the EDA and the ECG recordings of two participants (one man and one woman in the STEM and HUM groups, respectively) due to technical failure of the electrophysiological recording.

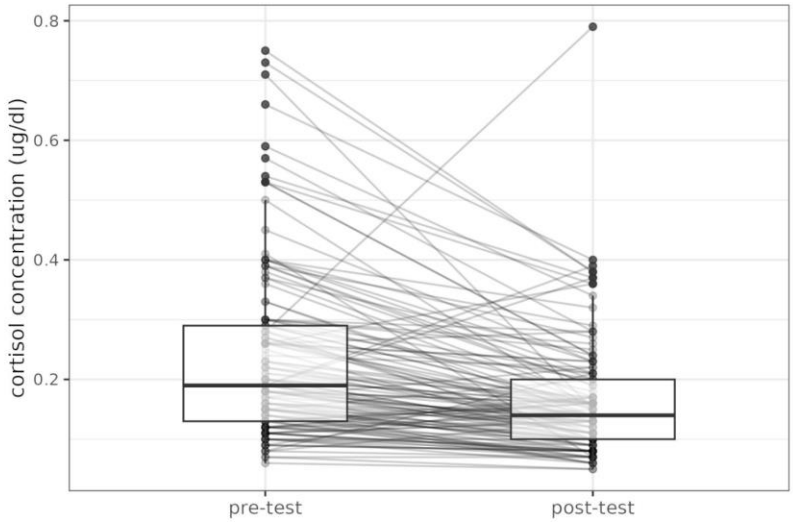
The EDA signal was down-sampled to 25 Hz and decomposed into tonic and phasic components using the convex optimization approach with the cvxEDA algorithm for Matlab (Greco et al., 2016) (https://github.com/lciti/cvxEDA). To assess the changes in skin conductance level during the execution of the numeracy task, we calculated the mean of the tonic component of EDA in successive 1-minute intervals with a 50% overlap (moving average approach). Figure 4.2b shows each participant's skin conductance over the course of the numeracy test. We assessed the rate of change of SCL during the execution of the numeracy test: for each participant's data, a linear regression model was fitted with raw SCL as the dependent variable and time as the independent variable (Figure 4.2a) (Pfister et al., 2013). The individually estimated slope was retained as an index of the rate of the SCL of change during the numeracy test (for a similar approach in EEG, see Perone et al., 2023).

The ECG signals were pre-processed with an in-house Matlab script to extract interbeat intervals (R-R intervals in seconds). We then performed heart rate variability (HRV) analysis based on power spectral density analysis using the RHRV package for the R software (García Martínez et al., 2017). First, the interbeat intervals were sampled at 4 Hz. The HRV was then separated into its frequency components using the Fast-Fourier transform method. We considered the high frequency band (HF-HRV), set at 0.15-0.4 Hz, as indicated by the Task Force of the European Society of Cardiology and the North American Society of Pacing Electrophysiology (Task Force of The European Society of Cardiology and The North American Society of Pacing and Electrophysiology, 1996), which represents parasympathetic cardiac control (Berntson et al., 1997). Similarly to the

EDA signals, we calculated the mean HF-HRV value in successive 1-minute intervals with a 50% overlap. In Figures 4.3 we plotted the HF-HRV at baseline and during the numeracy test. Similar to the formula used for cortisol, we calculated the change in HF-HRV as the difference between the first 5 minutes of the numeracy test and the 5-minute baseline, divided by the baseline, after averaging the HF-HRV values over the windows. Indeed, parasympathetic control was expected to peak in the first few seconds of the test, unlike SCL, which can vary during the task (Mammarella et al., 2023).

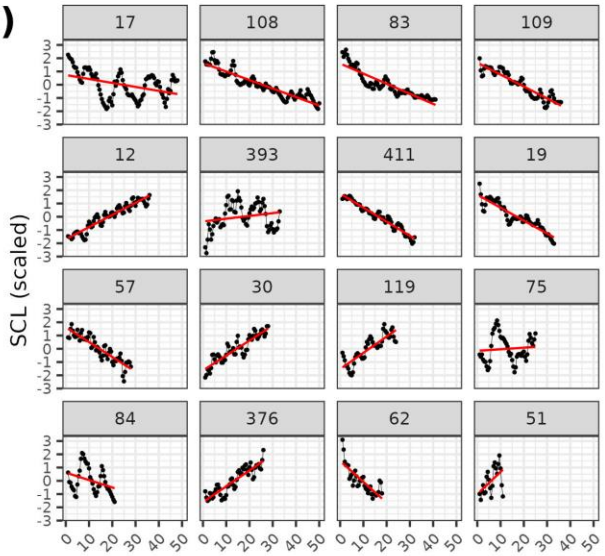
Figure 4. Raw physiological data. 1) Concentration of salivary cortisol before and after the test. 2) SCL values (z-scores) represented in two formats: a) Individual plots show SCL over time for each participant, illustrating within-participant changes, where the red line indicates the rate of change that varies in direction and degree. b) Colour-coded SCL z-scores across time for each participant, with rows representing individuals, ordered by numeracy accuracy from top (highest) to bottom (lowest), allowing for generalized comparisons. 3) HF-HRV values (z-scores) also represented in two formats: a) Individual plots display HF-HRV over time, with the dotted line marking the start of the numeracy test, demonstrating HF-HRV stability. b) Color-coded HF-HRV z-scores over time for each participant, again ordered by numeracy accuracy, generalizing the patterns observed in the individual plots. BL = Baseline.

1) Salivary cortisol

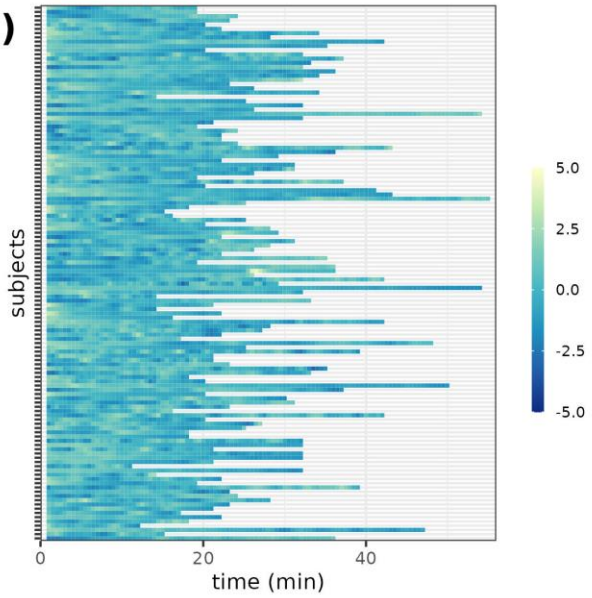


2) SCL

a)

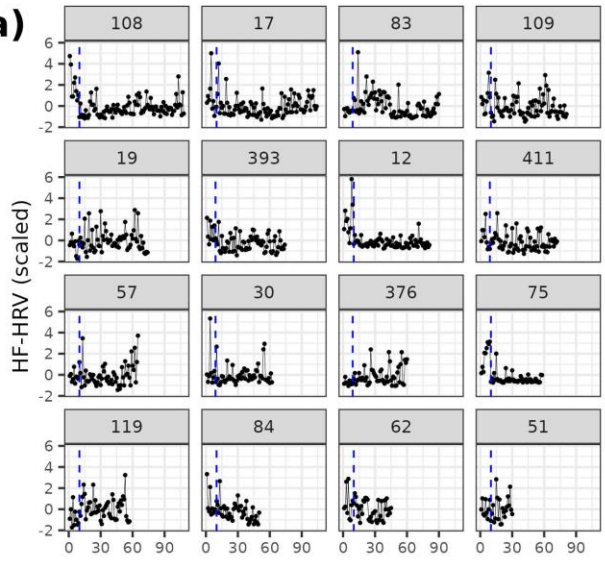


b)

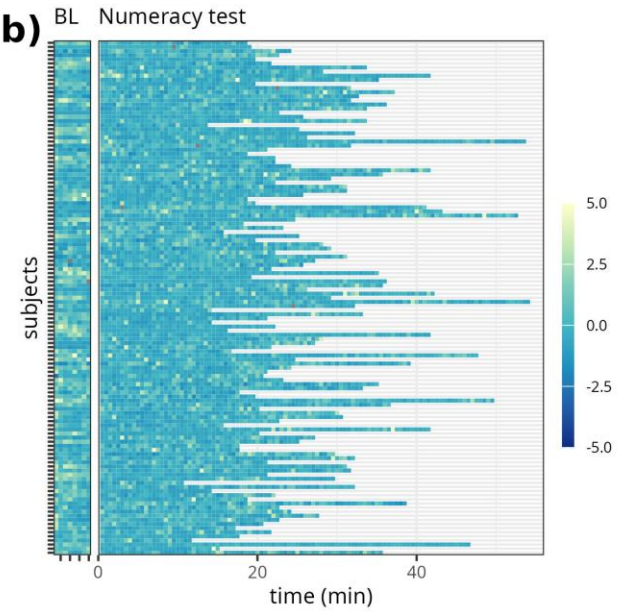


3) HF-HRV

a)



b)



Procedure

The study was conducted from May 2022 to February 2023. Participants were recruited through online channels (Facebook, SISSA-CNS-Sona-System).

The study consisted of two sessions. The first session was online and included questions about personal information, the math anxiety and personality questionnaires, the Raven's Matrices and the Arithmetic Fact Retrieval task. Other tasks and questionnaires were administered during this session, but these are not discussed here as they are not part of the present study. Participants received instructions and links to the online questionnaires by email. The non-cognitive measures and the Raven's Matrices were administered via Google Forms. The Arithmetic Fact Retrieval task was administered via the Pavlovia platform (https://pavlovia.org/).

The second session took place in the laboratory. Participants were told beforehand that they would have had to complete a cognitive test with a simultaneous physiological recording. The mathematical nature of the test was not specified. According to general guidelines (Dimolareva et al., 2018; Laborde et al., 2017), participants were asked not to smoke, eat, brush their teeth or perform any physical activity one hour before the test session. In addition, all the sessions were scheduled between 15:00. and 17:00 to minimise circadian variation between participants. On arrival at the laboratory, participants provided an initial saliva sample. They were then prepared for the electrophysiological recordings (i.e., EDA and ECG recordings). Participants were asked to remain seated during the experiment and to avoid unnecessary movement to minimise artefacts in the signals. The baseline condition was then recorded for 5 minutes at rest. After receiving instructions, participants completed the numeracy test, while the EDA and ECG signals were recorded. Finally, the second saliva sample was collected.

The numeracy test was administered through the PsychoPy software (Peirce et al., 2019).

Data analysis

We computed descriptive statistics for all variables collected and tested differences between fields of study [HUM vs. STEM] and gender [Women vs. Men] with a series of 2x2 ANOVAs. We also computed Spearman's rank correlations to test the relationship between the variables and two multiple linear regression analyses to test the associations of physiological measures an their interactions with field and gender with math anxiety and neuroticism, respectively.

We ran separate hierarchical regressions for each physiological index (i.e., SCL rate of change, HF-HRV change and cortisol change) to examine their contribution to numeracy and the role of math anxiety and of each intergroup variable (i.e., field of study and gender) (variable-centred approach). In each model, the dependent variable was the proportion of correct answers in the numeracy test and the covariates were IQ and basic arithmetic skills (added in step 0). In step 1, we entered the physiological index as a regressor to assess its association with numeracy scores. In step 2-MA, we added math anxiety and its interaction with the physiological index to assess whether the effect of the physiological index depended on the math anxiety level. In step 3-MA, the triple interaction between the intergroup variable, math anxiety and the physiological index was included to assess differences related to field of study (3-MA-F) and gender (3-MA-G), respectively.

We ran the same hierarchical regressions with math anxiety replaced by neuroticism (steps 2-N, 3-N-F and 3-N-G) to answer the same questions about neuroticism.

We assessed the contribution of the physiological indices to numeracy and their interactions with math anxiety, neuroticism and the intergroup variables in terms of regression coefficients. We also reported variance explained as a measure of model performance. Continuous regressors were standardised before entering the models. Missing values for SCL rate of change and HF-HRV change (see Electrophysiological data analysis) were replaced with the value obtained

through multivariate imputation. Univariate outliers (i.e., ± 3.29 standard deviations from the mean, Tabachnick & Fidell, 2013) were removed from the analysis (2 for cortisol change and 1 for SCL rate of change and HRV change). In addition to *p*-values, we also reported confidence intervals (CIs) for regression coefficients, in accordance with current recommendations (Cumming, 2014).

Finally, to explore the presence of different profiles of trait and physiological measures (person-centred approach), we performed *k*-mean cluster analysis on math anxiety, neuroticism, cortisol change, SCL rate of change, and HF-HRV change. Before clustering, the variables were standardised, missing values were replaced by the multivariate imputed scores and univariate outliers were removed. The optimal number of profiles, *k*, was selected using the *NbClust* package in R (Charrad et al., 2014): 30 indices are calculated, by combining the number of clusters and distance measures, and the best clustering solution is proposed (for a detailed description, see Charrad et al., 2014). In addition, we examined the within-cluster sum of squares and the Calinski-Harabasz index (Giordani et al., 2020) to further explore the best number of clusters. We tested for differences between profiles in the clustering variables using a series of one-way ANOVAs with profile as the between-subject factor. We then tested whether profiles differed in numeracy scores using a one-way ANOVA with numeracy as the dependent variable and profile as the factor; a significant main effect was further tested using Bonferroni-Holm-corrected post hoc tests. Two $\chi 2$ tests were then used to test whether the profiles differed within fields of study and gender. The interaction between profile and field of study and between profile and gender in explaining the variance in numeracy was tested with two 2 x *k* ANOVAs and a significant interaction was further tested with Bonferroni-Holm corrected post hoc tests.

All statistical analyses were performed using R v.4.1.1 (R Core Team, 2020).

Results

Descriptive statistics and correlations

Descriptive statistics are reported in Table 13 and visually presented in Supplementary Figures 9 and 10. The ANOVA indicated significant main effects of field of study for numeracy ($F(1,126) = 12.86$, $p < .001$, $\eta^2_p = 0.09$), math anxiety ($F(1,126) = 12.27$, $p = .001$, $\eta^2_p = 0.09$), cortisol change ($F(1,126) = 4.93$, $p = .028$, $\eta^2_p = 0.04$) and basic arithmetic skills ($F(1,126) = 6.41$, $p = .013$, $\eta^2_p = 0.05$). STEM students scored higher in numeracy (Cohen's $d = -0.84$) and basic arithmetic skills (Cohen's $d = -0.60$), and lower in math anxiety (Cohen's $d = 0.76$) than HUM students. A significant main effect of gender emerged for math anxiety ($F(1,126) = 6.04$, $p = .015$, $\eta^2_p = 0.05$) and neuroticism ($F(1,126) = 8.72$, $p = .004$, $\eta^2_p = 0.05$), where women reported higher scores than men (math anxiety: Cohen's $d = 0.48$; neuroticism: Cohen's $d = 0.69$). The interaction between field and gender was significant for cortisol change ($F(1,126) = 6.70$, $p = .011$, $\eta^2_p = 0.05$), but no post-hoc comparison was statistically significant (all $p_{Tukey} > .10$).

Correlation coefficients are reported in Table 14 and separately for HUM and STEM and for women and men in Supplementary Tables 8 and 9, respectively. Numeracy was negatively associated with neuroticism, math anxiety, and positively associated with IQ and basic arithmetic skills. The correlation between numeracy and neuroticism was significant within HUM ($r = -.355$, $p < .01$) and female students ($r = -.256$, $p < .05$). Neuroticism and math anxiety are positively correlated in the overall sample and in all subgroups except for men (HUM: $r = -.377$, $p < .01$; STEM: $r = -.332$, $p < .01$; women: $r = -.278$, $p < .05$). The correlations of physiological indices with numeracy, neuroticism or math anxiety were not significant, except for a significant negative correlation between numeracy and SCL rate of change for STEM students ($r = -.257$, $p < .05$).

The results of the multiple linear regressions assessing the association of physiological indexes with math anxiety and neuroticism are reported in Supplementary Table 10. The models

explained 15% of the variance in math anxiety and 3% in neuroticism, with no significant main or interaction effects.

Table 13. Mean, standard deviation and range for the demographic and academic variables, numeracy, neuroticism, math anxiety and the covariates for the whole sample and separately for HUM, STEM, female and male students.

	Whole sample	HUM	STEM	Women	Men
	M (*SD*) [range]	*M* (*SD*) [range]	*M* (*SD*) [range]	*M* (*SD*) [range]	*M* (*SD*) [range]
Demographic and academic variables					
Age	22.79 (2.38) [19-29]	22.76 (2.34) [19-29]	22.83 (2.44) [19-29]	22.89 (2.16) [20-28]	22.69 (2.60) [19-29]
ECTS[a]	82.03 (56.04) [0-244.25]	89.93 (56.45) [0-244.25]	73.62 (54.79) [0-226]	89.23 (54.73) [0-244.25]	74.82 (56.82) [0-180]
Mean grade at university	24.27 (7.7) [0-29.83]	23.20 (9.39) [0-29.83]	25.40 (5.18) [0-29.83]	25.21 (6.04) [0-29.83]	23.32 (9.00) [0-29.83]
Numeracy	0.73 (0.15) [0.27-0.93]	0.68 (0.17) [0.27-0.93]	0.80 (0.11) [0.47-0.93]	0.71 (0.16) [0.27-0.93]	0.75 (0.15) [0.27-0.93]
Math anxiety	21.20 (7.94) [9-45]	23.94 (8.07) [9-45]	18.29 (6.72) [9-42]	23.08 (8.30) [9-45]	19.32 (7.14) [9-43]
Neuroticism	3.14 (0.81) [1.38-5]	3.06 (0.78) [1.38-5]	3.23 (0.83) [1.5-4.62]	3.41 (0.75) [1.75-5]	2.88 (0.79) [1.38-4.38]
Physiological indices					
Cortisol change	-0.22 (0.40) [-0.83-1.82]	-0.24 (0.41) [-0.83-1.82]	-0.20 (0.39) [-0.79-1.62]	-0.22 (0.38) [-0.83-1.62]	-0.22 (0.42) [-0.79-1.82]
SCL rate of change	-0.01 (0.05) [-0.2-0.11]	-0.01 (0.05) [-0.11-0.11]	-0.02 (0.04) [-0.2-0.05]	-0.01 (0.05) [-0.2-0.11]	-0.01 (0.04) [-0.14-0.09]
HF-HRV change	0.37 (5.06) [-0.86-56.12]	0.77 (7.06) [-0.86-56.12]	-0.04 (0.62) [-0.79-1.78]	-0.08 (0.63) [-0.75-2.69]	0.82 (7.11) [-0.86-56.12]
Covariates					

	Whole sample	HUM	STEM	Women	Men
IQ	122.05 (9.10) [82-128]	120.19 (10.78) [82-128]	124.02 (6.40) [100-128]	121.85 (9.43) [86-128]	122.25 (8.82) [82-128]
Basic arithmetic skills	0.83 (0.12) [0.32-1]	0.79 (0.14) [0.32-1]	0.87 (0.09) [0.61-1]	0.81 (0.12) [0.36-1]	0.85 (0.13) [0.32-1]

Note. [a]ECTS = European Transfer and Accumulation System university credit. This value indicates the accomplished general learning outcomes.

Table 14. Spearman's rank correlations in the whole sample.

	1.	2.	3.	4.	5.	6.	7.	8.
1. Numeracy	1							
2. Math anxiety	-0.515***	1						
3. Neuroticism	-0.194*	0.281**	1					
4. Cortisol change	0.112	0.015	-0.071	1				
5. SCL rate of change	0.005	0.063	0.012	0.003	1			
6. HF-HRV change	0.072	-0.119	0.001	-0.020	-0.115	1		
7. IQ	0.424***	-0.217*	-0.047	-0.092	-0.002	0.155	1	
8. Basic arithmetic skills	0.487***	-0.363***	-0.070	0.046	0.032	0.019	0.212*	1

Note. * indicates $p < .05$. ** indicates $p < .01$. *** indicates $p < .001$.

Hierarchical regressions

Standardised coefficients and CI of the main predictors in the hierarchical regression analysis examining the effect of cortisol change on numeracy are reported in Table 15. The model results are presented in full in Supplementary Table 12. Since cortisol change was significantly correlated with the time participants took to complete the test (see Supplementary Table 11), we included test completion time as a covariate. Cortisol change was significantly associated with numeracy, explaining an additional 3.30% of the variance beyond the covariates already in the model: as the difference between post-test and pre-test cortisol increases, numeracy increases (Figure 5a). Math anxiety had a significant negative association with numeracy (11.30% increase in variance explained in step 2-MA), but its interaction with cortisol change was not significant. Field of study, but not gender, was a significant model predictor (increase in variance explained in step 3-MA-F: 1.30%; in step 3-MA-G: 0.30%). The interactions of cortisol change and math anxiety with both fields and gender were not significant. Similar to math anxiety, inserting neuroticism as model predictor beyond covariates and cortisol change significantly contributed to numeracy performance, but its interaction with cortisol change did not (explained variance increase in step 2-N: 1.90%). Field of study was again a significant regressor, while gender and its interactions with neuroticism and cortisol change did not contribute significantly to the model (change in variance explained in step 3-N-F: 6.20%; in step 3-N-G: -1.30%).

Table 15. Main regressors of the hierarchical regression models testing the association of numeracy with cortisol change and its interactions with math anxiety, neuroticism, field of study and gender.

	Predictors									R^2 adj.
	Cortisol	MA	Cortisol × MA	Field	Cortisol × Field	(Cortisol × MA) × Field	Gender	Cortisol × Gender	(Cortisol × MA) × Gender	
	β [CI]	*β* [CI]	*β* [CI]	*β* [CI]	*β* [CI]	*β* [CI]	*β* [CI]	*β* [CI]	*β* [CI]	
Step 1	0.20 [0.05 – 0.34] **									0.335
Step 2-MA	0.18 [0.05 – 0.31] **	-0.38 [0.52 – -0.23] ***	0.10 [-0.03 – 0.23]							0.448
Step 3-MA-F	0.14 [-0.04 – 0.32]	-0.39 [-0.59 – -0.18] ***	0.17 [-0.01 – 0.35]	0.33 [0.03 – 0.63] *	0.01 [-0.26 – 0.28]	-0.23 [-0.50 – 0.05]				0.461
Step 3-MA-G	0.12 [-0.08 – 0.33]	-0.48 [-0.67 – -0.29] ***	0.11 [-0.06 – 0.29]	-	-	-	-0.07 [-0.34 – 0.20]	0.09 [-0.19 – 0.37]	-0.02 [-0.30 – 0.26]	0.445

	Predictors									R^2 adj.
	Cortisol	Neur	Cortisol × Neur	Field	Cortisol × Field	(Cortisol × Neur) × Field	Gender	Cortisol × Gender	(Cortisol × Neur) × Gender	
	β [CI]	*β* [CI]	*β* [CI]	*β* [CI]	*β* [CI]	*β* [CI]	*β* [CI]	*β* [CI]	*β* [CI]	
Step 1	0.20 [0.05 – 0.34] **									0.335
Step 2-N	0.18 [0.03 – 0.32] *	-0.16 [-0.30 – -0.01] *	0.08 [-0.06 – 0.22]							0.354
Step 3-N-F	0.23 [0.02 – 0.44] *	-0.28 [-0.49 – -0.08] *	0.22 [-0.02 – 0.47]	0.49 [0.19 – 0.78] **	-0.09 [-0.40 – 0.21]	-0.25 [-0.57 – 0.06]				0.416
Step 3-N-G	0.08 [-0.16 – 0.31]	-0.2 [-0.43 – 0.03]	0.17 [-0.04 – 0.37]	-	-	-	-0.04 [-0.35 – 0.27]	0.14 [-0.18 – 0.46]	-0.15 [-0.46 – 0.17]	0.341

Note. Abbreviations: Cortisol = cortisol change; MA = math anxiety; Neur = Neuroticism. In all models, $n = 128$. * indicates $p < .05$. ** indicates $p < .01$. *** indicates $p < .001$. Field code: HUM = 0; STEM = 1. Gender code: Woman = 0; Man = 1.

Table 16 and Supplementary Table 13 report the hierarchical regression results for the effect of SCL rate of change on numeracy test performance. SCL rate of change did not significantly predict numeracy, and the variance explained decreased by 0.30%. Math anxiety was significantly and negatively associated with numeracy, with an increase of 10.40% in explained variance, but its interaction with SCL rate of change was not significant (step 2-MA). Field of study, but not gender, was a significant regressor, but neither interacted significantly with SCL rate of change and math anxiety (change in explained variance for step 3-MA-F: 2.80%; for 3-MA-G: 0.50%). Neuroticism had a significant negative contribution in the model, with an increase in explained variance of 2.70%, with no significant interactions with SCL rate of change (step 2-N). Field of study and its triple interaction with SCL rate of change and neuroticism were significant (increase in explained variance in step 3-N-F: 8.20%). We conducted a simple slope analysis to further explore this interaction (Figure 5b). At low levels of neuroticism (-1 *SD*), the rate of change in SCL was positively associated with numeracy in HUM (trend = 0.02, CI [-0.01; 0.05], p_{Tukey} = .208) and negatively in STEM (trend = -0.06, CI [-0.13; 0.003], p_{Tukey} = .065), but these values were not statistically significant. At high levels of neuroticism (+1 *SD*) the trend for HUM was reversed and both trends were not significant (HUM: trend = -0.03, CI [-0.08; 0.02], p_{Tukey} = .184; STEM: trend = -0.004, CI [-0.05; 0.04], p_{Tukey} = .862). The difference in trend between HUM and STEM was significant for low neuroticism ($t(119) = 2.23$, p_{Tukey} = .028) but not for high neuroticism ($t(119) = -0.81$, p_{Tukey} = .421). Gender and its interactions were not significant (change in explained variance in step 3-N-G: - 1.10%).

Table 16. Main regressors of the hierarchical regression models testing the association of numeracy with SCL rate of change and its interactions with math anxiety, neuroticism, field of study and gender.

	Predictors									R^2 adj.
	SCL	MA	SCL × MA	Field	SCL × Field	(SCL × MA) × Field	Gender	SCL × Gender	(SCL × MA) × Gender	
	β [CI]	*β* [CI]	*β* [CI]	*β* [CI]	*β* [CI]	*β* [CI]	*β* [CI]	*β* [CI]	*β* [CI]	
Step 1	-0.05 [-0.20 – 0.09]									0.307
Step 2-MA	-0.02 [-0.16 – 0.12]	-0.37 [-0.52 – -0.22] ***	0.02 [-0.12 – 0.16]							0.411
Step 3-MA-F	0.05 [-0.11 – 0.21]	-0.46 [-0.66 – -0.26] ***	-0.04 [-0.18 – 0.11]	0.31 [0.02 – 0.60] *	-0.13 [-0.45 – 0.18]	0.18 [-0.21 – 0.57]				0.439
Step 3-MA-G	0.07 [-0.14 – 0.28]	-0.48 [-0.69 – -0.28] ***	0.01 [-0.18 – 0.21]	-	-	-	-0.04 [-0.32 – 0.24]	-0.18 [-0.50 – 0.14]	0.02 [-0.34 – 0.37]	0.416
	Predictors									R^2 adj.
	SCL	Neur	SCL × Neur	Field	SCL × Field	(SCL × Neur) × Field	Gender	SCL × Gender	(SCL × Neur) × Gender	
	β [CI]	*β* [CI]	*β* [CI]	*β* [CI]	*β* [CI]	*β* [CI]	*β* [CI]	*β* [CI]	*β* [CI]	
Step 1	-0.05 [-0.20 – 0.09]									0.307
Step 2-N	-0.07 [-0.21 – 0.08]	-0.16 [-0.30 – -0.01] *	-0.09 [-0.23 – 0.05]							0.334
Step 3-N-F	-0.03 [-0.21 – 0.14]	-0.29 [-0.49 – -0.08] *	-0.16 [-0.34 – 0.02]	0.51 [0.23 – 0.80] ***	-0.17 [-0.49 – 0.14]	0.34 [0.04 – 0.65] *				0.416
Step 3-N-G	0.04 [-0.17 – 0.24]	-0.12 [-0.36 – 0.11]	-0.12 [-0.35 – 0.10]	-	-	-	0.04 [-0.27 – 0.35]	-0.20 [-0.50 – 0.09]	0.04 [-0.25 – 0.34]	0.323

Note. Abbreviations: SCL = SCL rate of change; MA = math anxiety; Neur = Neuroticism. In all models, $n = 129$. * indicates $p < .05$. ** indicates $p < .01$. *** indicates $p < .001$. Field code: HUM = 0; STEM = 1. Gender code: Woman = 0; Man = 1.

Figure 5. Significant effects of the physiological indices in the hierarchical regressions. Regression lines are displayed. Dots represent individual raw data. a) Main effect of cortisol change on numeracy. b) Interaction between SCL rate of change, neuroticism and field of study.

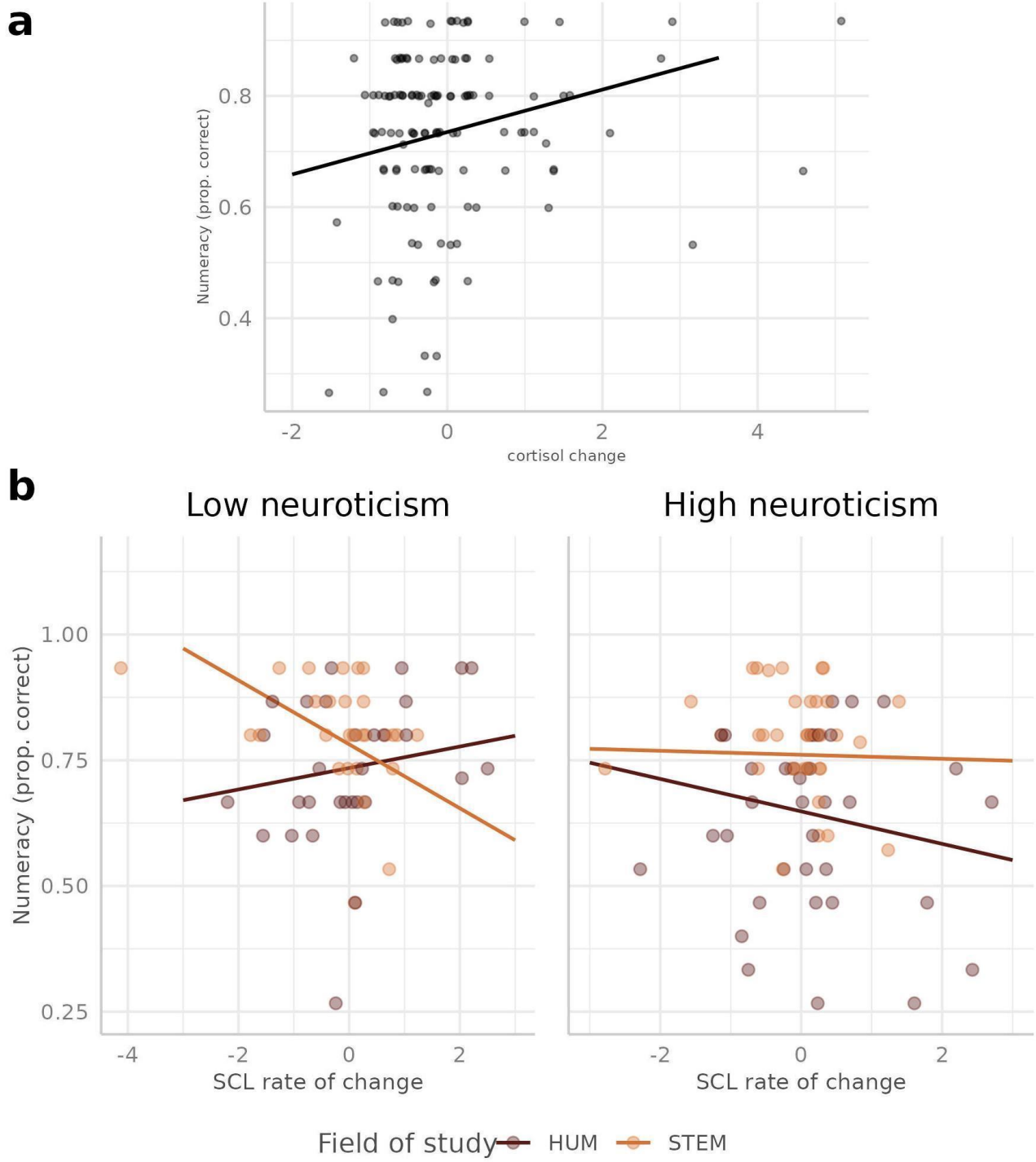


Table 17 and Supplementary Table 14 report the hierarchical regression results for the effect of HF-HRV change on numeracy. HF-HRV change did not significantly predict numeracy (change in explained variance: 0.50%). Math anxiety was significantly and negatively associated with numeracy, but it did not interact significantly with HF-HRV (increase in variance explained in step 2-MA: 11%). Field of study, but not gender, was a significant regressor, but neither of them significantly interacted with SCL rate of change and neuroticism (increase in variance explained for step 3-MA-F: 2.80%; for 3-MA-G: 0.40%). Similar to math anxiety, neuroticism significantly and negatively contributed to numeracy, but it did not interact with HF-HRV (increase in variance explained in step 2-N: 2.20%). Field of study was again a significant regressor, while gender, and their interactions with neuroticism and cortisol change did not add significant contribution to the model (change in variance explained in step 3-N-F: 7.70%; in step 3-N-G: 0.40%).

Table 17. Main regressors of the hierarchical regression models testing the association of numeracy with HF-HRV change and its interactions with math anxiety, neuroticism, field of study and gender.

	Predictors									R^2 adj.
	HRV	MA	HRV × MA	Field	HRV × Field	(HRV × MA) × Field	Gender	HRV × Gender	(HRV × MA) × Gender	
	β [CI]	β [CI]	β [CI]	β [CI]	β [CI]	β [CI]	β [CI]	β [CI]	β [CI]	
Step 1	0.10 [-0.05 – 0.25]									0.315
Step 2-MA	0.08 [-0.06 – 0.22]	-0.34 [-0.49 – -0.18] *	0.11 [-0.07 – 0.28]							0.425
Step 3-MA-F	0.16 [-0.02 – 0.35]	-0.40 [-0.61 – -0.19]	0.12 [-0.13 – 0.37]	0.34 [0.05 – 0.64]	-0.17 [-0.45 – 0.12]	-0.04 [-0.39 – 0.32]				0.453
Step 3-MA-G	0.04 [-0.15 – 0.24]	-0.47 [-0.68 – -0.27] **	0.04 [-0.21 – 0.29]	-	-	-	0.00 [-0.28 – 0.28]	0.17 [-0.14 – 0.49]	0.21 [-0.18 – 0.61]	0.429
	Predictors									R^2 adj.
	HRV	Neur	HRV × Neur	Field	HRV × Field	(HRV × Neur) × Field	Gender	HRV × Gender	(HRV × Neur) × Gender	
	β [CI]	β [CI]	β [CI]	β [CI]	β [CI]	β [CI]	β [CI]	β [CI]	β [CI]	
Step 1	0.10 [-0.05 – 0.25]									0.315
Step 2-N	0.10 [-0.04 – 0.25]	-0.15 [-0.30 – -0.01]	0.08 [-0.06 – 0.23]							0.337
Step 3-N-F	0.21 [0.02 – 0.40] *	-0.32 [-0.52 – -0.12]	0.07 [-0.15 – 0.30]	0.54 [0.25 – 0.82] *	-0.23 [-0.50 – 0.05]	-0.02 [-0.30 – 0.27]				0.414
Step 3-N-G	0.02 [-0.20 – 0.24]	-0.10 [-0.34 – 0.13]	0.26 [0.01 – 0.51] *	-	-	-	-0.01 [-0.31 – 0.30]	0.05 [-0.28 – 0.38]	-0.30 [-0.63 – 0.04]	0.333

Note. Abbreviations: HRV = HF-HRV change; MA = math anxiety; Neur = Neuroticism. In all models, $n = 129$. * indicates $p < .05$. ** indicates $p < .01$. *** indicates $p < .001$. Field code: HUM = 0; STEM = 1. Gender code: Woman = 0; Man = 1.

Cluster analysis

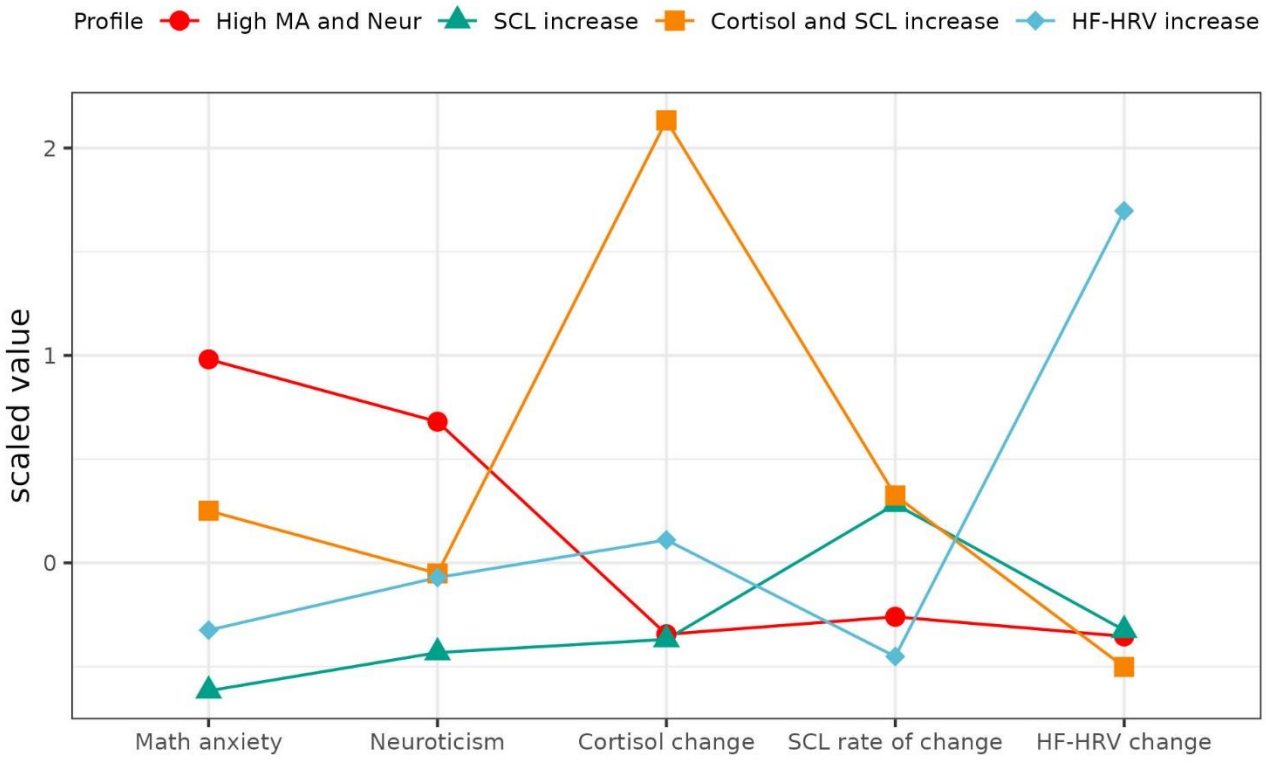
According to the majority rule implemented by the *NbClust* function, the optimal solution was a four-cluster grouping. Inspection of the within-cluster sum of squares and the Calinski-Harabasz index supports this choice (see Supplementary Figure 11). The *k*-means algorithm was therefore run with $k = 4$. The descriptive statistics for each profile, reported in Table 18 and Figure 6, show the standardised scores for each profile. The profiles have been named descriptively for ease of identification:

- Profile 1: *High math anxiety and neuroticism*, characterised by high levels in math anxiety and neuroticism and a decrease in cortisol, SCL and HF-HRV.
- Profile 2: *SCL increase*, characterised by an increase in SCL, a decrease in cortisol and HF-HRV and low levels of math anxiety and neuroticism.
- Profile 3. *Cortisol and SCL increase*, characterised by an increase in cortisol and SCL, a decrease in HF-HRV and medium math anxiety and low neuroticism.
- Profile 4. *HF-HRV increase*, characterised by an increase in HF-HRV, a decrease in cortisol and SCL, low math anxiety and neuroticism.

Table 18. Descriptive statistics and ANOVA results between profiles.

	Profile				ANOVA		
	Cortisol and SCL increase	HF-HRV increase	High math anxiety and neuroticism	SCL increase			
n	14	22	37	53			
HUM/STEM	6/8	11/11	23/14	25/28			
Women/Men	7/7	10/12	26/11	20/33			
	M (*SD*)	*M* (*SD*)	*M* (*SD*)	*M* (*SD*)	*F* (3, 122)	*p*	η^2_p
Math anxiety	23.43 (7.31)	18.86 (5.19)	29.22 (7.31)	16.55 (4.3)	36.32	<.001	0.47
Neuroticism	3.11 (0.95)	3.09 (0.67)	3.71 (0.63)	2.79 (0.76)	11.31	<.001	0.22
Cortisol change	0.44 (0.32)	-0.21 (0.28)	-0.36 (0.15)	-0.37 (0.17)	62.20	<.001	0.60
SCL rate of change	0.004 (0.05)	-0.03 (0.04)	-0.02 (0.04)	0.003 (0.04)	4.60	0.004	0.10
HRV change	-0.39 (0.32)	0.97 (0.56)	-0.30 (0.31)	-0.28 (0.37)	65.52	<.001	0.62
Numeracy (prop. correct)	0.75 (0.12)	0.77 (0.11)	0.65 (0.19)	0.76 (0.14)	4.64	0.004	0.10

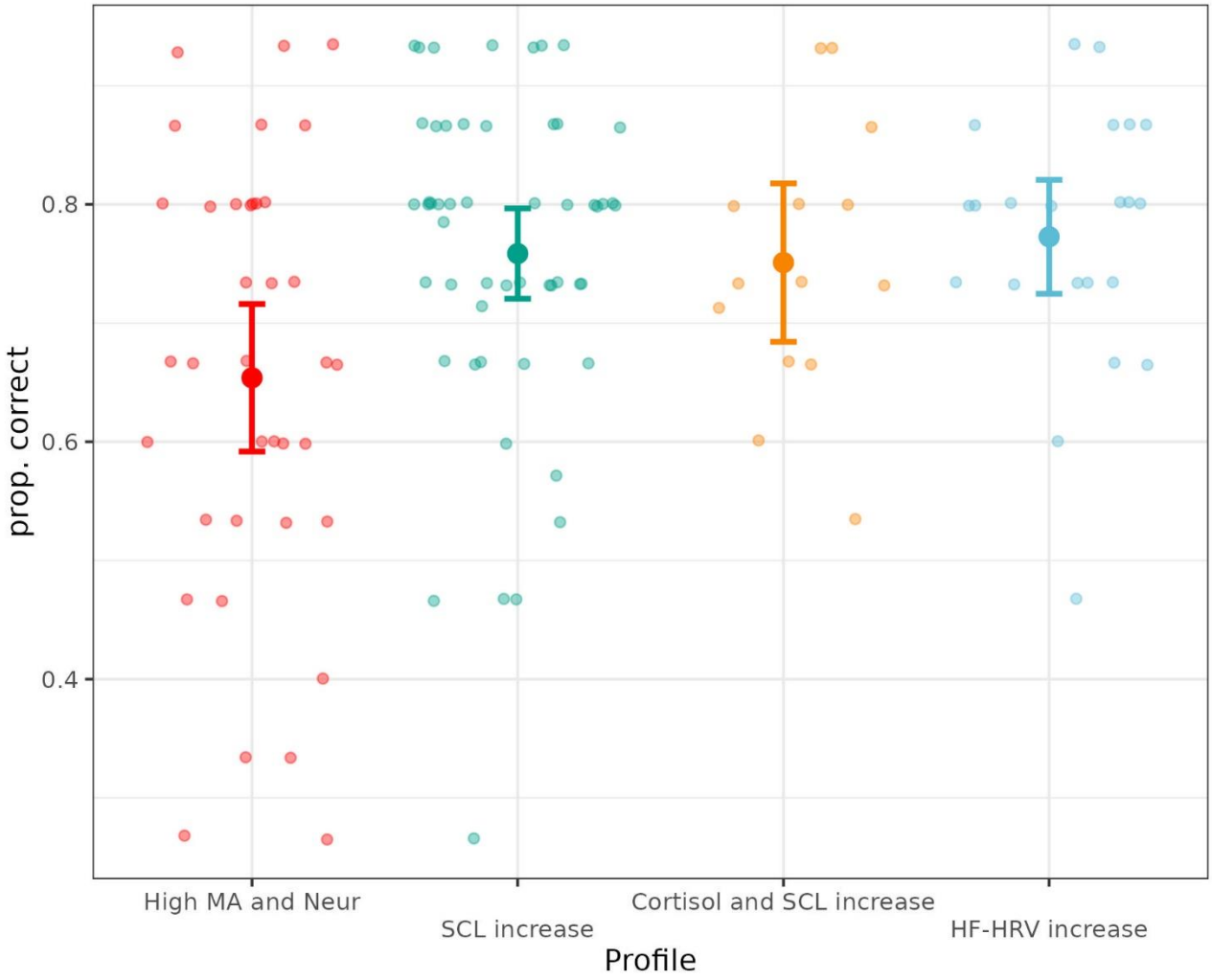
Figure 6. Standardised values of each profile in each variable considered in the cluster analysis.



We compared the identified profiles in terms of numeracy performance (Figure 7). The main effect of profile was significant (Table 18): the numeracy score of individuals in the High

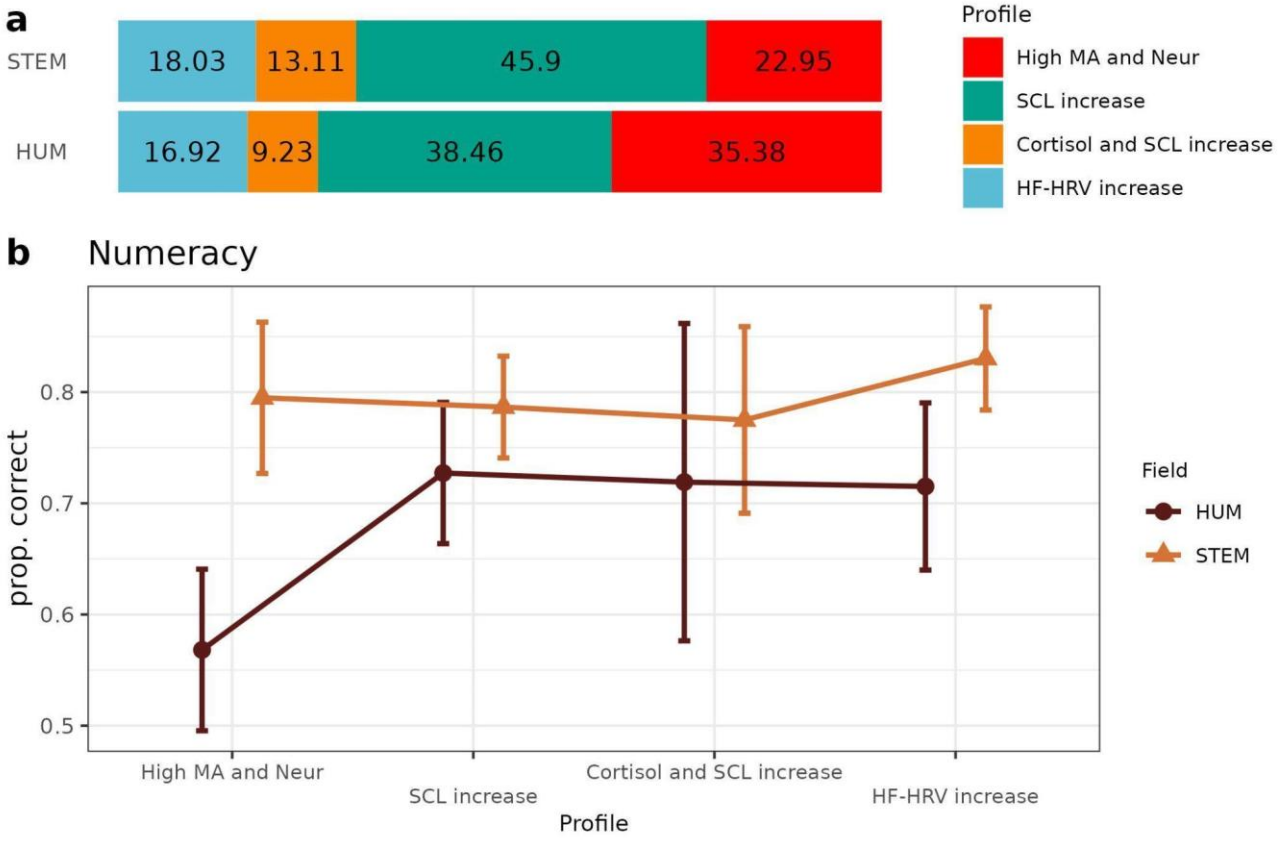
math anxiety and neuroticism profile was lower than the score of individuals in the SCL increase ($t(122) = -3.31$, $p_{Tukey} = .007$, Cohen's $d = -0.71$) and in the HF-HRV increase ($t(122) = -2.99$, $p_{Tukey} = .018$, Cohen's $d = -0.80$) profiles.

Figure 7. Numeracy scores in the four profiles.



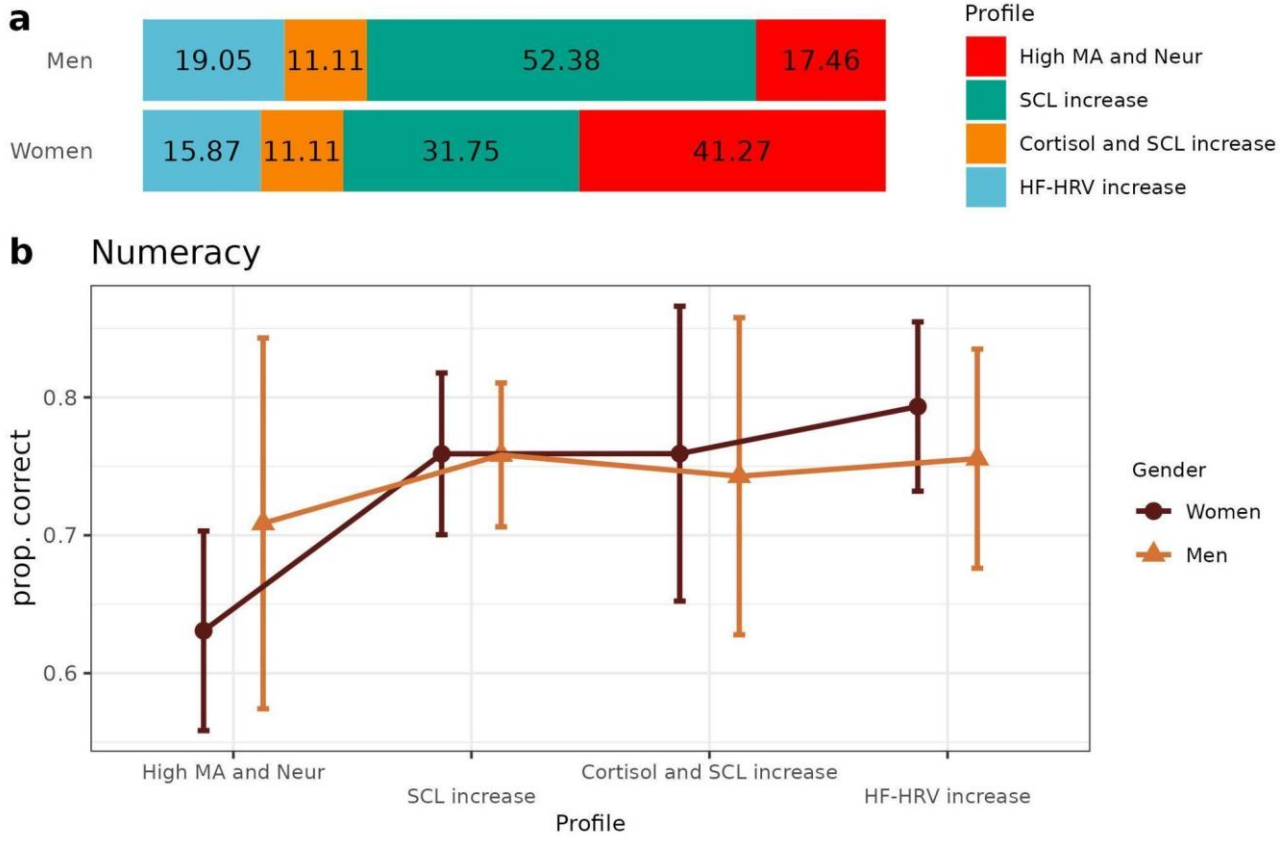
We then tested whether students in STEM and HUM differed in the proportion of individuals with a particular profile (Figure 8a): the χ^2 test was not significant ($\chi^2_3 = 2.52$, $p = .472$), suggesting that the four profiles were equally distributed within fields of study. The 2x4 ANOVA with numeracy as dependent variable showed a significant field by profile interaction ($F(3, 118) = 3.05$, $p = .031$, $\eta^2_p = 0.07$): HUM students with a High math anxiety and neuroticism profile had a significantly lower numeracy scores compared to all other groups (SCL increase in HUM: $t(118) = -4.15$, $p_{Tukey} = .002$, Cohen's $d = -1.20$; High MA and neuroticism in STEM: $t(118) = -5.04$, $p_{Tukey} < .001$, Cohen's $d = -1.71$; SCL increase in STEM: $t(118) = -5.84$, $p_{Tukey} < .001$, Cohen's $d = -1.64$; Cortisol and SCL increase in STEM: $t(118) = -3.79$, $p_{Tukey} = .006$, Cohen's $d = -1.56$; HF-HRV increase in STEM: $t(118) = -5.38$, $p_{Tukey} < .001$, Cohen's $d = -1.97$), except the HUM students with Cortisol and SCL increase and HF-HRV increase profiles (figure 8b).

Figure 8. Profiles and fields of study. a) Profiles distribution in HUM and STEM. Numbers indicate the percentage of students with a given profile in HUM or STEM fields. b) Numeracy scores in the profiles separately for HUM and STEM.



Finally, we tested whether there was a difference in the proportion of individuals with a particular profile based on gender (Figure 9a); the χ^2 test was significant ($\chi^2_3 = 9.45$, $p = .024$): women were more likely to be in the High math anxiety and neuroticism profile, whereas men were more likely to be in the SCL increase and in the HF-HRV increase profiles. The interaction between gender and profile in the 2x4 ANOVA with numeracy as dependent variable was not significant ($F(3, 118) = 0.78$, $p = .505$, $\eta^2_p = 0.02$; figure 9b).

Figure 9. Profiles and gender. a) Profiles distribution in women and men. Numbers indicate the percentile of women and men with a given profile. b) Numeracy scores in the profiles separately for women and men.



Discussion

In the present study, we investigated the physiological correlates of numeracy performance and how they vary with math anxiety and neuroticism. Participants completed self-report questionnaires to assess these trait variables, and we measured changes in salivary cortisol concentration, skin conductance level and heart rate variability associated with performing a numeracy test. We adopted two analytical strategies: first, we estimated the associations between numeracy performance and physiological measures and their modulation by math anxiety and neuroticism (variable-centred approach); second, we explored the presence of different profiles of physiological responses and trait variables, and whether these profiles show differences in numeracy performance (person-centred approach). Overall, the relationship between numeracy and physiological response appears to vary according to the physiological system considered and individual differences in neuroticism and field of study.

The association between numeracy and physiological responses

We observed a significant positive association between numeracy performance and changes in salivary cortisol: as salivary cortisol increases, performance improves. A similar finding has been reported in people with low math anxiety (Mattarella-Micke et al., 2011). In our study, however, we did not find a significant modulation of math anxiety or neuroticism in the association between cortisol change and numeracy performance. In the context of the present study, cortisol changes may be related to sustained mental effort that supports overall test performance. However, cortisol levels on average decreased from pre- to post-test, likely reflecting natural diurnal decline. It is possible that the numeracy test did not induce a detectable cortisol response by the test end, especially for participants who took longer to complete it. More frequent salivary cortisol sampling throughout the test could offer a clearer profile of stress responses.

In addition, we found a significant interaction between the rate of change in SCL and neuroticism when considering the field of study. At lower levels of neuroticism, the rate of change in SCL was differentially associated with numeracy performance in STEM and HUM students: an increase in SCL during the test tended to be associated with lower performance for STEM students and higher performance in HUM students, although neither effect reached statistical significance. At higher levels of neuroticism, there was no evidence of a different association between the rate of change in SCL and numeracy performance between the groups. This result is partly in line with our expectations based on the biopsychosocial model, at least for HUM students: HUM students with low neuroticism may interpret the increase in SCL as a challenging cue, leading to an approach behaviour that favours performance. However, contrary to our expectations, there is no evidence that students with high levels of neuroticism are more likely to interpret the situation as threatening. Instead, this tendency emerged for STEM students with low neuroticism, which is contrary to the predictions of the biopsychosocial model. Different motivational mechanisms may be activated in this group. In STEM disciplines, mathematics is a core skill. In a task with which they should be familiar, experiencing physiological arousal may seem unfamiliar, activating intrusive thoughts that distract them from the task and leading to poorer performance compared to students who do not experience physiological arousal. However, the magnitude of this effect is rather small, and this explanation is speculative, as the design of this experiment does not allow conscious thoughts to be checked during the test. Further studies should investigate this effect in more detail.

Finally, no significant association with numeracy was found for HF-HRV change. This contrasts with previous studies showing that lower levels of HRV, indicating increased stress during arithmetic tasks (Mammarella et al., 2023), were associated with poorer arithmetic performance (Tang et al., 2021). This discrepancy may be due to differences in the HRV metrics used. In the study by Tang and colleagues (2021), HRV was measured as respiratory sinus arrhythmia, which is similarly derived from the high-frequency spectral band of HRV but is more sensitive to the

influence of respiration on heart rate (Shaffer & Ginsberg, 2017). Respiratory sinus arrhythmia may be a more sensitive index than HF-HRV in the context of mathematical testing. Furthermore, the participants in the study of Tang and colleagues (2021) were middle school students, unlike our sample of young adults. Given that HRV tends to decrease with age (Umetani et al., 1998), it may be more difficult to observe significant decreases in HRV in adults compared to younger individuals.

Profiles of physiological and trait measures

Different profiles of physiological and trait measures emerged in our sample. Partly in line with our expectations, we found three profiles characterised by low math anxiety and neuroticism and high physiological reactivity, differing in the type of physiological response: one profile characterised by an increase in SCL, another by an increase in both cortisol and SCL, and a third by an increase in HF-HRV. As expected in line with the biopsychosocial model, these profiles, with low trait variables and high physiological response, showed a better numeracy performance than the fourth profile we identified, characterised by high math anxiety and neuroticism and small decreases in physiological measures. Unexpectedly, we did not find profiles with high levels of both trait measures and physiological measures, suggesting a dissociation between self-reported and physiological measures.

Trait measures seem to be particularly related to underperformance in the numeracy test, and this is particularly true for students in HUM. Interestingly, the performance of STEM students with high math anxiety and neuroticism does not seem to be impaired by these negative affects, as students perform similarly to students with the other profiles. This is in line with previous studies showing that the negative association between numeracy and neuroticism was present in HUM but not STEM students (Chapter 3). Notably, performance variability within profiles also differs: the high math anxiety and neuroticism group exhibits greater variability, encompassing both very low

and very high numeracy scores. This suggests that while negative affectivity may be often sufficient to explain underperformance, it may be not always necessary. Furthermore, the lack of alignment between affective traits and physiological measures suggests distinct mechanisms may underlie their respective influences on numeracy performance (e.g., Daker et al., 2023), which were not captured by our experimental design.

While the distribution of profiles was similar between STEM and HUM students, a gender difference emerged: women were more likely to have a profile characterised by high math anxiety and neuroticism, whereas men were more likely to display a profile with an increase in SCL or HRV. This is consistent with findings that women tend to report higher math anxiety and neuroticism compared to men (Schmitt et al., 2008; Stoet et al., 2016). However, within-profile differences in numeracy performance between men and women did not emerge, suggesting that differences in numeracy performance between men and women may be independent of the specific configuration of trait and physiological measures.

Insights and implications

The relationship between numeracy performance and physiological responses to the numeracy test appears to be complex and heterogeneous. Different regulatory systems may play different roles in performance and interact differently with individual differences. Recruitment of the HPA axis, as indicated by increases in salivary cortisol, is positively associated with performance and is likely to represent sustained mental effort that facilitates test execution. Conversely, the role of the rate of change of SCL appears to vary according to neuroticism and field of study. Taken together, greater physiological responses do not appear to coexist with high levels of math anxiety and neuroticism, and these trait variables appear to be specifically related to underperformance on the numeracy test. These findings have important implications for how we conceptualise emotion trait variables, particularly math anxiety.

Given the consistent negative association between self-reported math anxiety and math performance in the literature (Barroso et al., 2021; Caviola et al., 2022; Zhang et al., 2019), one might expect to find a homogeneous association between physiological responses and numeracy and the presence of a profile with high levels of math anxiety and physiological responses. However, we did not find such evidence, suggesting that self-reported math anxiety may be separable from physiological responses. This is not surprising given that previous results on the correlation between self-reported math anxiety and physiological responses have yielded inconsistent results, with small effects (Demedts et al., 2023; Qu et al., 2020). As posited by the biopsychosocial model, biological systems, context and individual characteristics are intertwined, and behaviour is the product of their interactions in many domains, including mathematics (Szucs & Mammarella, 2024). Consequently, it is important to be cautious when defining physiological responses as proxies of self-reported math anxiety. Instead, self-reported and physiological measures should be examined together for a comprehensive understanding of numeracy performance.

Moreover, the modulatory effect of trait variables on the association between physiological response (specifically, rate of change in SCL) and performance, which emerged only when differences between fields of study were taken into account, was limited to neuroticism. This is interesting because one would expect math anxiety to be more relevant in the context of a numerical task, as it is a more specific measure. One possible explanation is related to the type of task we used. Unlike previous studies (Mattarella-Micke et al., 2011; Pizzie & Kraemer, 2021; Salvia et al., 2013; Tang et al., 2021), which used arithmetic equations, we used a test consisting of word problems, the correct solution of which requires a link between mathematical and linguistic understanding (Daroczy et al., 2015). Neuroticism may be more relevant in this higher-order multifaceted task, as it captures general, rather than subject-specific, individual differences. To the best of our knowledge, no experimental study has systematically tested whether the effect of math

anxiety on math performance depends on the test format, either word problems or arithmetic equations. Investigating this aspect might be an interesting way to better clarify the nature of math anxiety.

Another observation concerns the role of the field of study and gender. We found some differences between fields of study in the associations of physiological and trait variables with numeracy, which may reflect the different motivation and familiarity of these students with math tests, as mentioned above. However, there was no significant gender difference in the association of physiological and trait measures with numeracy. The only significant gender difference was found in the distribution of profiles, consistent with evidence that women report higher levels of math anxiety and neuroticism. However, there is no evidence that these variables are more strongly related to numeracy performance in women than in men. These findings point to the need to consider gender differences together with other characteristics that may explain discrepancies between men and women, such as differences in other math-related attitudes like math self-concept (Rossi et al., 2022).

Overall, these observations invite a broader reflection on the conceptualization of math anxiety. Anxiety is a multifaceted construct involving at least two distinct components: cognitive and affective (Wigfield & Meece, 1988). The cognitive component includes thoughts of worry and fear about underperformance in mathematics, which are readily assessed through self-reports. In contrast, the affective component involves emotional responses like discomfort, fear, and nervousness, which may overlap with physical sensations. These aspects appear to be partly independent, as indicated by the low correlations observed in the literature, and their influence on performance may vary according to individual characteristics, such as self-beliefs, or situational factors that shape situational appraisal, as suggested by the biopsychosocial model. Consequently, theories of math anxiety should be extended to account for this heterogeneity in the construct."

Limitations

The results presented here should be considered with a number of limitations.

First, we did not administer a non-numerical test, so we cannot conclude that the reported results are specific to the mathematical domain. The responses we observed in this study may represent a general response to testing procedures. Future studies should include non-mathematical tests and a measure of test anxiety to control for anxiety experienced in evaluative settings.

Second, our experimental design is observational, which limits the interpretation of physiological changes as specific psychological states, such as particular emotions or motivational states. Future research should include different experimental conditions, such as manipulating stress (Mammarella et al., 2023) or task difficulty (Demedts et al., 2022, 2023), to infer what the physiological measure might represent, as well as including self-reported measures of anxiety during the test (i.e., state anxiety) to test their correspondence with physiological activation.

Third, our sample size is relatively small, resulting in limited statistical power to detect small effects. Therefore, the absence of effects should be interpreted with caution. However, it should be noted that our sample size (N = 130) is larger than other studies that analysed physiological recordings from 73 (Mattarella-Micke et al., 2011), 52 (Pizzie & Kraemer, 2021), or even 30 (Salvia et al., 2013) participants.

Fourthly, participation in the study was voluntary. Although we advertised it as a general cognitive skills project to avoid dropout from participants with particularly negative attitudes towards mathematics, we cannot exclude the possibility that individuals who chose to participate may be systematically different from those who did not (selection bias). This may limit the representativeness of the sample and the generalizability of the results to the whole population of university students.

Finally, our experimental design did not include physiological recording during the anticipation of the numeracy test. We focused on physiological responses during the test. However,

previous evidence suggests that responses recorded before the test may be particularly relevant (Daker et al., 2023; Qu et al., 2020). Trait variables may influence this phase more than the test itself, as anxiety is often associated with anticipating the stressful event (Bradley et al., 2008; Klados et al., 2017).

Conclusion

In conclusion, the present study has shown that performance in a numeracy test among university students is associated with certain physiological responses. Students who showed an increase in cortisol from pre- to post-test scored higher. In addition, the relationship between the rate of change in SCL and performance varied across different levels of neuroticism and fields of study. Profiles characterized by different levels of math anxiety, neuroticism and physiological response also emerged, with lower numeracy performance with higher math anxiety, higher neuroticism, and lower physiological response, particularly among HUM students. These findings highlight the complex interplay between numeracy performance, physiological correlates, and individual differences in negative emotions and career choice. They emphasise the need to examine these factors together in order to gain a comprehensive understanding of numeracy performance.

CHAPTER 6

General discussion

Experts from various fields of psychology, as well as other disciplines such as education and economics, have long sought to identify the factors that contribute to numeracy. The promotion of numeracy is a key objective of many national and international institutions, given its crucial role in both individual and societal outcomes (Butterworth et al., 2011; Parsons & Bynner, 2005). This focus has led to the development of assessment programmes designed to monitor numeracy development across the lifespan (Mullis et al., 2020; OECD, 2013; Tout et al., 2021; Italian programs: ANVUR, 2018; INVALSI, 2024), as well as research projects aimed at understanding what supports performance on these assessments.

A significant body of research has examined the cognitive factors associated with numeracy and math achievement (Geary, 2011; Ludewig et al., 2020; S. Song & Su, 2022). However, a growing body of evidence highlights the influence of affective and dispositional factors, from childhood through adolescence and into adulthood (Caviola et al., 2022; Malanchini et al., 2024; Rammstedt et al., 2016). One particularly relevant period for young adults is the transition from compulsory education to university. During this phase, especially in Italy, students choose academic programmes that correspond to their interests and aspirations. This decision is influenced not only by cognitive abilities but also by emotional factors, such as math anxiety, personal dispositions such as personality traits, and socio-cultural influences, including gender stereotypes. These factors play a crucial role in determining whether students choose to pursue fields with substantial mathematical content or choose to avoid mathematics altogether. Understanding the interplay between non-cognitive factors and students' numeracy, as well as the differences between fields of study, is essential for promoting numeracy beyond compulsory education. Addressing this issue is key to promoting numeracy in higher education and preparing students for future success.

Overall, the empirical work presented in this thesis focused on two non-cognitive factors — math anxiety and personality — to explore their associations with numeracy in university students. To assess numeracy, I used a test designed to measure transversal cognitive competencies in

university students (Rumiati et al., 2018), where numeracy encompasses logical and quantitative reasoning skills independent of specific curricular education. A variety of methodological approaches were used, including large-scale, longitudinal, and physiological studies, recruiting students from science, technology, engineering and mathematics (STEM) and humanities (HUM) programmes. These two fields differ in the mathematical content covered during curricular training, with STEM students typically more accustomed to numerical problem solving than HUM students. Furthermore, STEM and HUM programmes often have different gender distributions (Eurostat, 2022) and given the well-documented gender differences in math-related skills and attitudes (for a review, see Leder, 2019), I made a concerted effort to recruit an equal number of men and women in each field.

Gender differences in STEM fields were the focus of Study 1 (Chapter 2). Here, women represent a unique sample, as they have survived the "bottleneck" represented by the university choice, which deprives young women of science fields (Ceci et al., 2014). In this study, I investigated whether the non-cognitive mechanisms underlying numeracy differ between women and men enrolled in STEM programmes. Although these students are supposed to be good at mastering numeracy, the results showed that performance on the numeracy test still correlated with math anxiety, especially for women. In addition, neuroticism had a different association with numeracy for men and women (Figure 10). For women, neuroticism mediated the relationship between math anxiety and numeracy: math anxiety was positively associated with neuroticism, which in turn was positively associated with numeracy. Interestingly, neuroticism appeared to play a positive role that was stronger the higher the math anxiety reported by women.

This raised questions: Could neuroticism make a positive contribution to numeracy in general, or is this effect specific to women in STEM? Are these findings independent of other personality traits? To explore these questions, I conducted a large-scale study (N = 410, Study 2, Chapter 3) which included both STEM and HUM students, allowing for a more detailed

examination of the interaction between field of study and gender. Neuroticism was the only personality trait that was consistently associated with numeracy, even after controlling for other personality traits and for cognitive factors such as intelligence quotient and basic numerical skills. The effect of neuroticism differed by field of study: among HUM students, neuroticism was negatively associated with numeracy, whereas no such association was found among STEM students. Additionally, differently from what was found in Study 1, no significant gender difference in the association between numeracy and neuroticism emerged within the STEM group. However, these findings only reflect cross-sectional associations (Figure 10).

To determine whether non-cognitive factors predict later numeracy, I conducted a longitudinal study (Study 3, Chapter 4) of a subset of first-year university students from the previous sample (from Study 1). I assessed them again two years later and found that math anxiety and neuroticism predicted later numeracy. While the effect of neuroticism was small, the effect of math anxiety was medium in size and fully mediated by its association with earlier numeracy. Differences also emerged between HUM and STEM students: the link between early and later numeracy was stronger for HUM students, whereas for STEM students, math anxiety influenced later numeracy through both early numeracy and changes in math anxiety over time (Figure 10). Notably, math anxiety decreased over time, especially for HUM students, while numeracy and neuroticism remained stable.

These behavioural studies highlight the importance of emotional experiences in numeracy performance in higher education and confirm the negative role of math anxiety (Barroso et al., 2021; Caviola et al., 2022; Zhang et al., 2019). This effect is evident for both HUM and STEM students (Daker et al., 2021) and persists over time (Cargnelutti et al., 2017; Ching, 2017; Pantoja et al., 2020; Sorvo et al., 2022; Vukovic et al., 2013). Furthermore, these findings highlight the important role of personality, particularly neuroticism. Among the five personality traits, neuroticism — which is closely tied to emotional experience — played an important role, although

its effect was weaker than that of math anxiety, especially over time. The effect of neuroticism varied according to the students' field of study. For students in non-scientific disciplines, a tendency towards negative emotional responses such as anxiety, worry and irritability, was associated with lower numeracy scores. This differential association may partly be explained by students with different levels of neuroticism and different math attitudes and anxiety choosing different fields of study (Ahmed, 2018; Cuder et al., 2024; Vedel, 2016). Another explanation is that HUM and STEM programmes thus represent different learning environments, characterized by different demands, socialization processes, and values, especially with regards to mathematics. These environments provide different opportunities for the expression of neuroticism in relation to numeracy, as suggested by trait activation theory (Tett et al., 2021). Interestingly, in STEM women, Study 1 suggested a positive association between neuroticism and numeracy, indicating that higher levels of neuroticism might not necessarily impede performance. However, this result was not replicated in Study 2. The positive association, while present in STEM women also in the second study although it did not reach statistical significance (see Supplementary Figure 5e), was likely small, and when analysed within a complex statistical model that included additional variables, the power to detect this effect may have been reduced. It is also possible that the influence of other correlated personality traits absorbed the effect of neuroticism (see Supplementary Table 5).

However, it is important to note that these studies relied on self-report questionnaires to assess math anxiety and neuroticism, which are *trait*-based measures that reflect conscious evaluations of past experiences. These evaluations may be biased by individual beliefs and may not correspond to the *state* feelings experienced during the numeracy test. As previously suggested (e.g., Cipora et al., 2022), self-report measures should be complemented by assessments of state characteristics to gain a more complete understanding of emotional and psychological phenomena.

In Study 4 (Chapter 5), I measured physiological arousal during the numeracy test using indicators such as cortisol changes, skin conductance level (SCL) and heart rate variability (HRV).

Using both variable-centred and person-centred approaches, I examined whether these physiological responses were associated with performance and whether individual differences, such as self-reported math anxiety, neuroticism, field of study, and gender, influenced these associations. The results showed variability in these relationships depending on the physiological measure and individual factors. Specifically, an increase in cortisol was associated with better overall performance. In contrast, the association between SCL and numeracy varied with neuroticism in different ways across fields of study: an increase in SCL was associated with lower performance for STEM students, but with higher performance for HUM students. Furthermore, while both STEM and HUM students were equally likely to have profiles characterized by high math anxiety and neuroticism combined with low physiological responses, this profile was only associated with numeracy performance for HUM students.

The latter study further demonstrates the different psychophysiological mechanisms underlying numeracy in different fields of study. In particular, it also shows that physiological arousal during a numeracy test does not necessarily correspond to self-reported measures. The associations between physiological responses and numeracy, as well as between physiological responses and self-reported non-cognitive factors, were weak and inconsistent. This is not surprising, given the mixed findings in the literature (Demedts et al., 2023; Mattarella-Micke et al., 2011; Pizzie & Kraemer, 2021; Qu et al., 2020). However, this raises questions about the measurement of complex psychological constructs (see Daker et al., 2023). Constructs such as “anxiety” and “personality” are multifaceted, and self-reports and physiological responses may capture different aspects of these constructs. For example, it has been suggested that anxiety has two components — cognitive and affective (Wigfield & Meece, 1988). The cognitive component includes worrying thoughts about not doing well in mathematics, which are easily captured by self-report. The affective component captures emotional responses such as discomfort, fear, and nervousness, which may overlap with bodily sensations. Feelings of worry may be more relevant

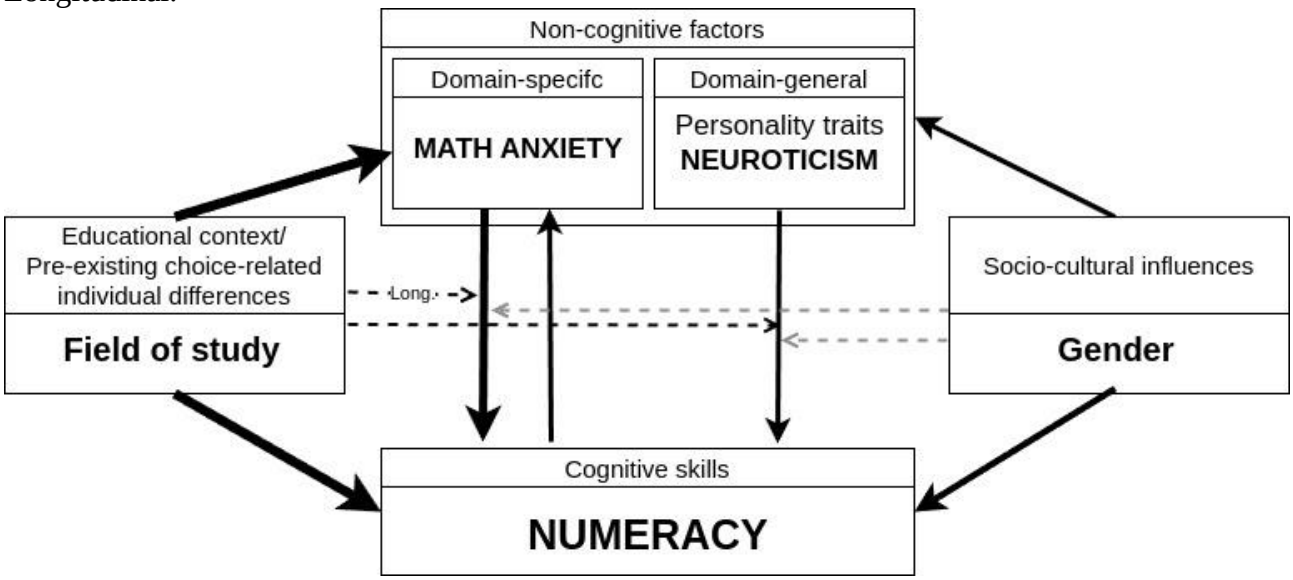
for performance, whereas the effect of the physiological arousal may depend on its appraisal. According to the biopsychosocial model, physiological responses have no intrinsic meaning; their impact on performance depends on how individuals interpret these reactions in real time, which is influenced by their beliefs about themselves in general, and in the context of mathematics (Mendes & Park, 2014; Ramirez et al., 2018).

Another possible explanation for the lack of significant physiological responses and the discrepancy with self-report measures lies in the type of numeracy test and the test conditions. While previous studies mainly used arithmetic equations (Mattarella-Micke et al., 2011; Pizzie & Kraemer, 2021; Salvia et al., 2013; Tang et al., 2021), the numeracy test in these studies consisted of word problems that required not only quantitative and logical reasoning but also text comprehension (Daroczy et al., 2015). This test represents a higher order task, the difficulty of which is also influenced by non-mathematical factors. Furthermore, participants were not under time constraints and were encouraged to do their best with the assurance that their performance would not affect their compensation. In this setting, the stakes of the test are very low. It is likely that the numerical content of the problems alone does not elicit strong physiological responses by itself. Other task-related factors, such as perceived stress (Mammarella et al., 2023) or task difficulty (Demedts et al., 2023), may interact with the math-related content to elicit arousal.

The findings of my thesis, summarised in Figure 10, suggest that the claim that negative emotions, whether math-specific or not, are always detrimental to numeracy is too simplistic. First, the causal link from non-cognitive factors to numeracy performance should not be seen as unidirectional. The longitudinal Study 3 (Chapter 4) points to the possibility of a bidirectional relationship between numeracy and math anxiety. This suggests that not only does early math anxiety affect later numeracy, but that lower numeracy may also lead to increased math anxiety, creating a vicious cycle that has already been identified in younger students (Gunderson et al., 2018; Lichtenfeld et al., 2023; Pekrun et al., 2017; Szczygieł et al., 2024). Second, the nature of the

association between non-cognitive factors and numeracy varies. While negative emotions are often associated with poorer numeracy, there are instances where negative emotions have no measurable effect or where individuals perform well despite experiencing them (see also Cipora et al., 2022). In order to better understand the role of non-cognitive factors, it is therefore important to consider individual differences. Differences in students' choice of study programmes with more or less math may help to explain the relationship between non-cognitive factors and numeracy in higher education. In particular, differences related to fields of study may be more significant than gender differences among university students. Gender differences in mathematics have long attracted the attention of psychological researchers and educators, and the assumption that mathematics is a male domain has persisted, making it difficult to eradicate (for a review, see Girelli, 2022). This does not exclude the existence of gender differences (see Chapters 2-5, and Borgonovi et al., 2021; Schmitt et al., 2017; Stoet et al., 2016). However, these differences may not be as pervasive as traditionally thought and may be explained by other individual differences. The fact that differences related to the choice of the field of study are stronger and more consistent than gender differences offers an encouraging perspective, suggesting that women are not inherently weaker in mathematics. Equal opportunities for boys and girls to engage with mathematics from an early age can help them develop their potential and interest in the field, free from the socio-cultural biases tied to gender roles.

Figure 10. Graphical representation of the thesis' findings. The arrows represent the associations investigated in this work but it is worth noting that field of study, as the result of an individual choice, can be as well be influenced by non-cognitive factors and numeracy. Dashed lines indicate moderation effects. Dashed lines indicate moderation effects. The size and colour of the arrows represent the strength of the effects: larger and darker arrows indicate larger effects. Long. = Longitudinal.



My thesis also provides empirical evidence that can guide interventions to promote numeracy in higher education. Since mathematics is a core subject taught in all Italian high schools, attitudes formed during math education, such as math anxiety, may continue to negatively affect numeracy after high school, regardless of career choice. Therefore, programmes aimed at reducing math anxiety should target all students. On the other hand, for humanities students, promoting emotional stability could serve as another potential mechanism to support numeracy. Intervention programmes could focus on cognitive reappraisal of the numeracy test and of the psychophysiological responses it elicits (Ramirez et al., 2018). Rather than suppressing negative emotions about mathematics, individuals should be encouraged to reframe them and learn to benefit from the struggle. It is important to note that these findings may be valuable in both educational and clinical contexts. Some studies suggest that, in certain cases, math anxiety may meet the criteria for a specific phobia (Ashcraft & Ridley, 2005; Lazarus, 1974). When negative emotional experiences, whether general

or math-specific, become overwhelming and significantly impair well-being, clinical professionals could use these findings to develop effective remediation strategies.

Furthermore, the results of my thesis may be of interest to political economists interested in education, particularly those concerned with the assessment of cognitive capital. Large-scale cognitive competency tests, such as those developed by ANVUR, assess acquired knowledge and the ability to apply it (Heckman & Kautz, 2014), contributing to a nation's human capital (Rindermann, 2018). My findings suggest that human capital does not only consists of pure cognition alone but is shaped by affective and motivational mechanisms that are intertwined with cognitive processes. These non-cognitive factors are equally relevant for both individual and national growth.

However, the results of this thesis should be interpreted with a number of limitations. Firstly, the generalisability of the findings is limited. On the one hand, some studies included overlapping participant samples (i.e., Study 1-3), which may reduce sample diversity. On the other hand, all participants were students enrolled in an Italian university, which limits the generalizability of the findings to other countries. Educational systems vary between countries (Hadjar & Gross, 2016), and these differences may influence how non-cognitive factors interact with numeracy. Second, none of the studies included non-mathematical measures, making it difficult to determine whether the observed associations are specific to numeracy or extend to other cognitive competencies, such as literacy. Third, my thesis includes only observational studies. This limits the ability to make causal claims about the observed associations. Future experimental studies that manipulate test conditions, such as time constraints (Caviola et al., 2017), perceived stress (Mammarella et al., 2023) or task difficulty (Demedts et al., 2022, 2023) would provide a better understanding of the circumstances under which non-cognitive factors play an important role. Finally, accuracy in the numeracy test was the only recorded performance measure. An interesting variable to explore

further is response time, as reaction times are valuable indicators of underlying psychological processes as stand-alone measures (Pachella, 1974).

In conclusion, my thesis, bridging cognition, affective and dispositional characteristics, gender and career choice, highlights the importance of considering emotional and dispositional factors in relation to numeracy in higher education. Numeracy is widely recognised as an essential life skill, yet many individuals are unable to fully realise their potential in this area due to gender stereotypes (Spencer et al., 1999), early negative experiences of mathematics (Hunt & Maloney, 2022; Jansen et al., 2013), or the common perception that mathematics is inherently difficult (Fritz et al., 2019). This highlights the importance of examining not only the cognitive underpinnings, but also the ways in which mathematics is experienced and how this impacts on numeracy. Numeracy is part of our everyday lives, and it is crucial to understand how university programmes can support its development, regardless of the specific course chosen.

> Mathematics is [...] this imagination that educates us to the invisible [...] and has taken us far, far away, through time and space.
>
> CHIARA VALERIO, *Storia umana della matematica [Human history of mathematics]*

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Appendix

Numeracy test

I provide here the English translation of the numeracy test version 1 (used in Studies 1-3) and version 2 (used in Study 4).
Correct answers are marked in bold.

Version 1

Module 1 - Graphs and tables

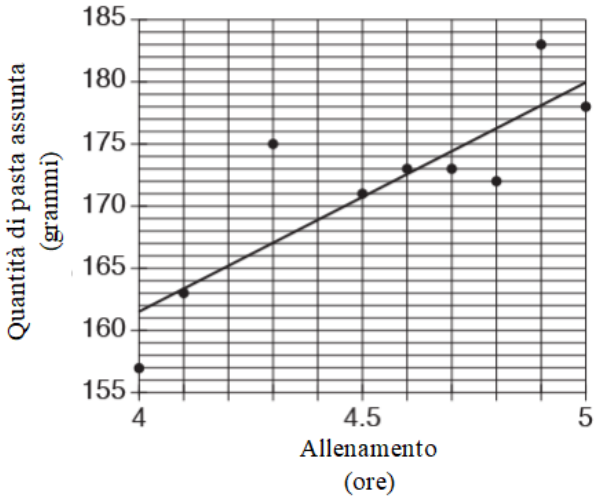
Stamp classification [Q1 and Q2]
The table classifies the 130 stamps owned by a collector based on their shape (rectangular, square, and triangular) and their origin (Italy, France, and Germany).

	Rectangular	Square	Triangular
Italy	77	1	5
France	7	13	9
Germany	6	1	11

Q1. Which is the average number of all the stamps from Italy across shapes?
*Response options. 1*4 - 28 - **43** – 93

Q2. Which is the percentage of stamps from Germany on the total of rectangular stamps?
Response options. **6.7%** - 7.1% - 20.0% - 33.3%

Physical exercise hours and the pasta intake of 9 people [Q3-Q5]
The graph shows the relationship between the hours of physical exercise performed by 9 people and the amount of pasta consumed. The line of best fit is also shown.



[*y axis: "Amount of pasta intake (grams)"; x axis: "Exercise (hours)"*]

Q3. How many of the 9 people eat an amount of pasta differing more than 3 grams from the amount predicted by the line?
Response options. 3 - **4** - 6 - 9

Q4. According to the approximation line, how much pasta does a person exercising **4.45 hours** eat?
Response options. 169 grams - **170 grams** - 171 grams - It cannot be computed.

Q5. Which of the following is the best interpretation of the approximation line slope in this problem?
Response options. The amount of pasta intake cannot predict the exercise hours. - **The pasta intake increases of dozens of grams for one hour of exercise.** - The pasta intake increases of 30 grams for one hour exercise. - The exercise hours cannot predict the pasta intake.

Module 2 - Logical reasoning

Q6. Some people play with numbers. The rules are the following: the numbers divisible by 9 are worth 6 points, the numbers divisible by 4 are worth 4 points. Which of the following numbers has the lowest value?
Response options. 63 - **120** - 126 – 135

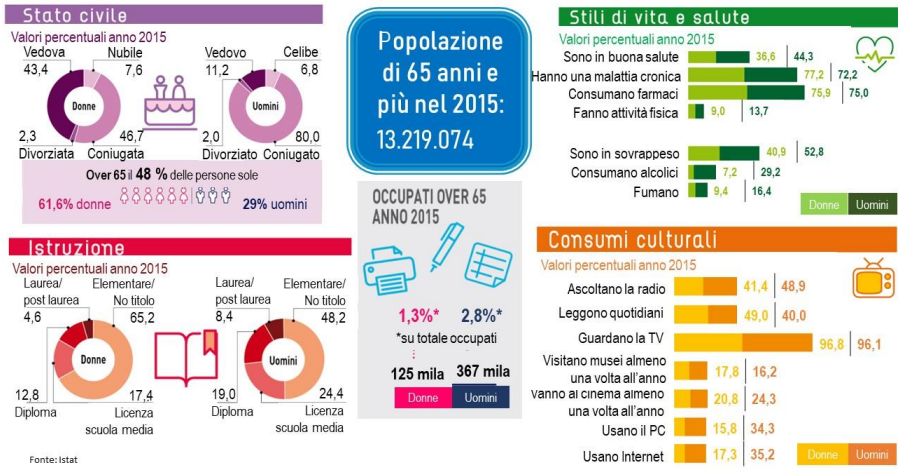
Q7. Complete this series with the missing number: 7, 8, 11, 13, 15, 18, …
Response options. **19** - 20 - 21 – 22

Q8. A picture taken from Mars surface with a camera typically takes 11.2 gigabytes. A control station on the Earth can receive data from a space ship at the speed of 3 megabyte per second for a total of 11 hours per day. One gigabyte corresponds to 1024 megabyte. Which is the highest number of pictures that the control station can receive from the camera every day?
Response options. 3 - **10** - 93 – 347

Q9. To tidy up the garage, Anna alone takes 6 hours, Luca alone takes 10 hours, Benedetta alone takes 15 hours. How many hours would the three of them take if they tidied up the garage together?
Response options. **3 hours** - 9 hours - 10 hours - 31 hours

Q10. Giuseppe has three sisters, Monica, Carla and Veronica. At least one of the sisters has green eyes. Knowing that: if Monica has green eyes, then Carla has green eyes too; if Veronica has green eyes, then Monica has green eyes too; only one between Carla and Veronica has green eyes; it is possible to conclude that:
Response options. Monica, Carla and Veronica have green eyes. - Carla does not have green eyes, but Monica does. - Veronica has green eyes. - **Carla has green eyes.**

Module 3 – Infographics
The over-65 population in Italy [Q11-Q15]



Q11. According to the data in the infographics, in which of the following cultural activities men and women differ the most?
Response options. Internet surfing - Listening to the radio - Watching TV - **PC use**

Q12. According to the data in the infographics, which statement is true about the health of the over 65?
Response options. Men and women have the same likelihood of developing a chronic disease. - Men and women have the same likelihood of being in good health. - **Men have a lower likelihood to develop a chronic disease than to consume drugs** - Women have a lower likelihood to smoke than to do physical activity.

Q13. According to the data in the infographics, we can state that in the over-65 population...
Response options. the women with the middle school diploma are the 7.0% more than the men - **The women with a high school diploma are the 6.2% less than the men** - the women with the primary school diploma are the 17.3% less than the man - The men with a degree are 4.2% more than the women

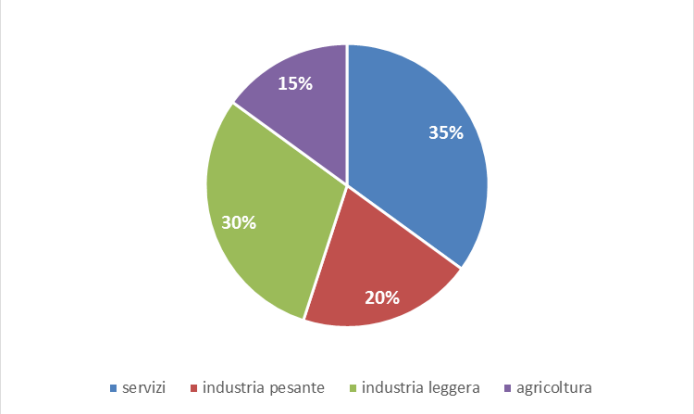
Q14. According to the data in the infographics, which group is more numerous?
Response options. **Widowed women compared to widowed men** - divorced women compared to married women - widowed men compared to married men – unmarried men compared to unmarried women

Q15. According to the data in the infographics, which is the overall percentage of occupied men and women over the total of the over-65 population?
Response options. 1.3% - 2.8% - **3.7%** - 4.1%

Version 2

Module 1 - Graphs and tables

The following table and chart present some data regarding the distribution of the population, the distribution of workers in various productive sectors, and the number of people employed in the different productive sectors in the city of Castelluccio [Q1-Q3]



[*services – heavy industry – light industry – agriculture*]

Fasce di età	Popolazione	Occupati %	N. occupati agricoltura	N. occupati industria leggera	N. occupati industria pesante	N. occupati servizi
15-21	50.000	30%	3.000	2.000	1.000	18.000
22-30	80.000	40%	4.000	20.000	8.000	5.500
31-50	40.000	70%	10.000	15.500	5.000	9.500
51-65	15.000	40%	5.000	1.000	4.000	500

[*Age ranges – Population - % employed – N. employed agriculture – N. employed light industry – N. employed heavy industry – N. employed services*]

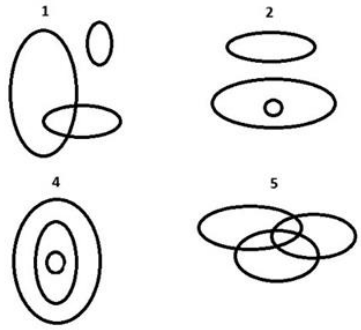
Q1. In the age group between 22-30 years, what percentage of the total individuals in this age group works in heavy industry?
Response options. **10%** - 20% - 40% - 80%

Q2. Relative to the total population, what is the percentage of workers employed in heavy industry and agriculture?
Response options. 10% - **30%** - 40% - 50%

Q3. What is the average number of people employed in heavy industry across all age groups (from 15 to 65 years)?
Response options. 1000 – **4500** – 8000 - 18000

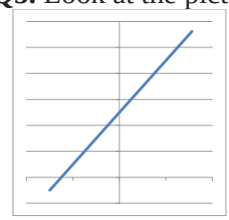
Module 2 - Logical reasoning

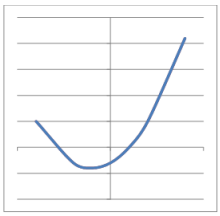
Q4. Look at the picture and answer

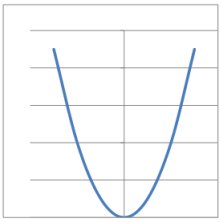


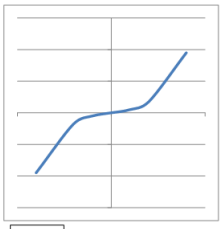
Indicate which diagram corresponds to the relationship: students, people who speak two languages, infants.
Response options. **Number 1** – number 2 – number 3 – number 4

Q5. Look at the picture and answer


Fig. 1


Fig. 2


Fig. 3

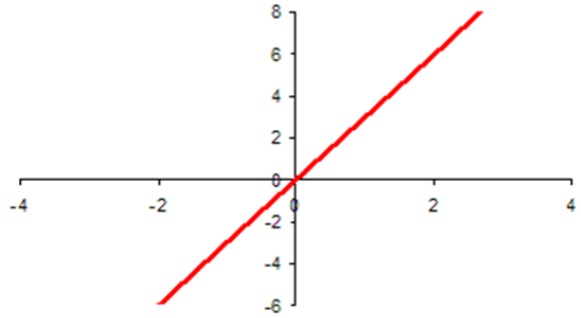

Fig. 4

Which graph represent the following function: y = 8x + 20?
Response options. **Fig.1** – Fig.2 – Fig.3 – Fig.4

Q6. During an experiment, a 25-minute film is continuously shown throughout the day, with a 5-minute interval between each screening. The show starts at 9:30 AM and ends at 6:00 PM. How many times is the film shown in full during the day?
Response options. 9 – 14 – 16 – **17**

Q7. In her savings account, Francesca has deposited €2000. Her financial advisor informed her that each year she will earn a 10% profit. How much will her total savings amount to after 3 years?
Response options. 2040 euro – 2400 – 2462 euro – **2662 euro**

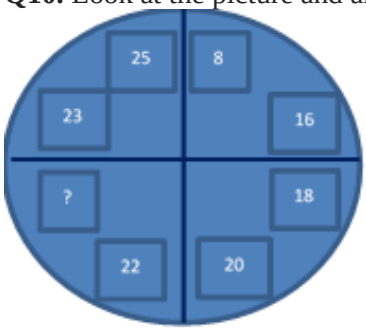
Q8. Look at the picture and answer



Which of the following functions represent this figure?
Response options. **y = 3x** – y = 6x – y = 4x + 3 – y = 2x-3/2

Q9. If AxA – 3X – $(A)^2$ = 4A + 5 with A = 10. Then X is equal to…
Response options. -45 - **-15** – 45 – 135

Q10. Look at the picture and answer



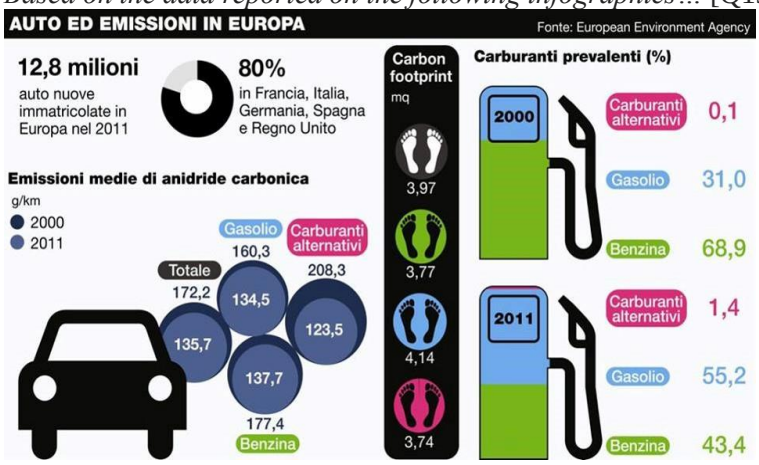
Which number completes the series?
Response options. 9 – **11** – 12 – 24

Q11. Alessio and Alberto are two running enthusiasts and often train together. Every morning, Alessio wakes up early and trains before going to work, but if he stays up late the night before, he might not wake up in time the next morning. When Alberto trains with Alessio, they never miss a workout because Alberto wakes Alessio up on time. Which of the following statements is necessarily true?
Response options. If Alessio is training in the morning, then Alberto is with him – If Alberto is present, then he has woken Alessio up – If Alessio wakes up on time, then he trains without Alberto – **If Alberto is present, then Alessio is training**

Q12. Marta takes 4 days to build a bookshelf. Giovanni takes 6 days, and Lucia takes 12 days. How much time will the three of them take together to build the same bookshelf?
Response options. 18 hours – 36 hours – **48 hours** – 72 hours

Module 3 – Infographics

Based on the data reported on the following infographics… [Q13-Q15]



Q13. What is the number of newly registered cars in 2011 in France, Italy, Germany, Spain, and the United Kingdom?
Response options. 850000 – **10240000** – 11350000 – 12000000

Q14. It is possible to say that between 2000 and 2011 the average emissions…
Response options. **Of carbon dioxide [*anidride carbonica]* decreased by 36.5 g/km -** of diesel engines [*gasolio*] decreased by 37.7 g/km – of gasoline engines [*benzina*] increased by 2 g/km – of alternative fuel engines [*carburanti alternativi*] decreased by 74.8 g/km

Q15. It is possible to say that, for the same distance traveled by cars…
Response options. alternative fuel engines in 2000 were less polluting than diesel – **diesel engines in 2000 were less polluting than gasoline** – diesel engines in 2011 were more polluting than gasoline – alternative fuel engines in 2011 were more polluting than gasoline

Supplementary material Study 1

Supplementary Table 1. Number of participants attending the different STEM degree courses divided by gender.

Degree	**Women**	**Men**	**Total**
Agrarian and forestry sciences	0	1	1
Architecture	0	1	1
Biology	7	3	10
Biotechnologies	8	1	9
Chemistry	1	2	3
Cultural heritage conservation and restoration	0	1	1
Environmental sciences	1	2	3
Environmental and civil engineering	1	0	1
Exercise and sport sciences	3	2	5
Food science and technology	3	1	4
Geology	0	1	1
Industrial engineering (e.g. energy, aerospatial, management engineering	7	9	16
Informatics	2	4	6
Information engineering (e.g. informatics and biomedical engineering)	9	11	20
Mathematics	12	16	28
Pharmaceutical sciences	1	0	1
Physics	6	11	17
Statistics	8	4	12
Zootechnics	1	0	1
Total	70	70	140

Supplementary Table 2. Results of simple mediation and moderated mediation when control variables are included as covariates (N = 134[a]).

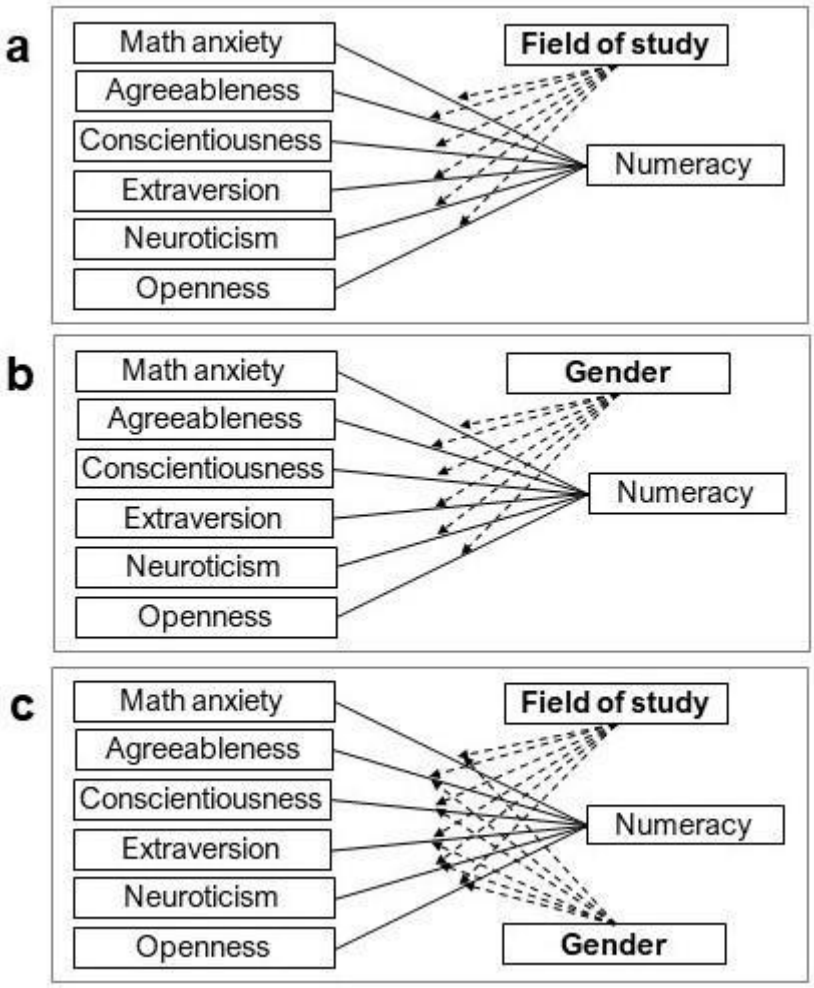
	β	p	CI	R^2
Mediation				
Outcome: Neuroticism (mediator)				0.16
Age	0.001	.994	-0.28 – 0.28	
Socio-economic status	-0.12	.156	-0.29 – 0.05	
Math grade in high school	0.13	.221	-0.08 – 0.33	
Average grade in university	-0.02	.802	-0.22 – 0.17	
Total ECTS	-0.18	.332	-0.55 – 0.19	
ECTS in math	-0.06	.537	-0.29 – 0.15	
Level of education	0.31	.086	-0.04 – 0.66	
Math anxiety (*a*)	0.36	<.001	0.18 - 0.54	
Outcome: numeracy (dependent variable)				0.14
Age	-0.09	.512	-0.37 – 0.18	
Socio-economic status	-0.10	.245	-0.26 – 0.07	
Math grade in high school	0.05	.606	-0.15 – 0.25	
Average grade in university	0.03	.723	-0.16 – 0.22	
Total ECTS	-0.09	.640	-0.45 – 0.28	
ECTS in math	0.25	.021	0.04 – 0.46	
Level of education	0.07	.680	-0.28 – 0.42	
Math anxiety (*c'*)	-0.21	.030	-0.40 - -0.02	
Neuroticism (*b*)	0.03	.74	-0.14 – 0.20	
Total effect (*c*)	-0.19	<.029	-0.37 - -0.02	
Indirect effect (*ab*)	0.01		-0.05 – 0.07	
Moderated mediation				
Outcome: Neuroticism (mediator)				0.16
Age	0.001	.994	-0.28 – 0.28	
Socio-economic status	-0.12	.156	-0.29 – 0.05	
Math grade in high school	0.13	.221	-0.08 – 0.33	
Average grade in university	-0.02	.802	-0.22 – 0.17	
Total ECTS	-0.18	.332	-0.55 – 0.19	
ECTS in math	-0.06	.537	-0.29 – 0.15	

Level of education	0.31	.086	-0.04 – 0.66	
Math anxiety (*a*)	0.36	<.001	0.17 - 0.54	
Outcome: numeracy (dependent variable)				0.21
Age	-0.10	.466	-0.37 – 0.17	
Socio-economic status	-0.09	.261	-0.26 – 0.07	
Math grade in high school	0.06	.563	-0.14 – 0.25	
Average grade in university	0.04	.659	-0.15 – 0.23	
Total ECTS	-0.14	.447	-0.50 – 0.22	
ECTS in math	0.26	.016	0.05 – 0,46	
Level of education	0.13	.459	-0.22 – 0.48	
Math anxiety	-0.09	.472	-0.33 – 0.15	
Neuroticism	-0.07	.533	-0.31 – 0.16	
Gender (women = 1)	-0.44	.014	-0.79 - -0.09	
Math anxiety x gender (moderation of *c'*)	-0.19	.287	-0.53 – 0.16	
Neuroticism x gender (moderation of *b*)	0.38	.034	0.03 – 0.74	
Conditional effect of mediator (*b*)				
Men	-0.07	.533	-0.31 – 0.16	
Women	0.31	.023	0.04 – 0.57	
Conditional direct effect (*c'*)				
Men	-0.09	0.471	-0.32 – 0.15	
Women	-0.27	.048	-0.54 - -0.003	
Conditional indirect effect (*ab*)				
Men	-0.03		-0.13 – 0.06	
Women	0.11		0.03 – 0.23	
Index of moderated mediation	0.14		0.01 – 0.30	

Note. [a] 6 participants were removed from the analysis because of missing data.

Supplementary material Study 2

Supplementary Figure 1. Illustration of the relationships tested for a) research question 1.a, b) research question 1.b and c) research question 1.c.



Supplementary Table 3. Descriptive statistics for the study variables and ANOVA results assessing field and gender differences.

	HUM	STEM	Women	Men	ANOVA results						
						Field of study		Gender		Field x Gender	
	M (SD)	*M* (SD)	*M* (SD)	*M* (SD)	residuals	*F*	*p*	*F*	*p*	*F*	*p*
Demographic and academic variables											
Age	21.28 (2.32)	20.75 (1.85)	21.12 (2.20)	20.90 (2.02)	406	6.16	.013	2.07	.151	0.80	.371
SES [a]	4.13 (1.87)	4.55 (1.94)	4.28 (1.89)	4.42 (1.93)	385[a]	3.29	.070	0.69	.406	0.18	.675
Level of education	14.99 (1.00)	14.97 (1.00)	14.98 (1.00)	14.97 (1.00)	406	0.00	.987	0.01	.933	0.04	.834
Math grade in high school	7.30 (1.30)	8.25 (1.25)	7.91 (1.34)	7.66 (1.38)	405[b]	28.48	<.001	1.10	.295	0.04	.840
Average grade in university	26.47 (2.53)	25.91 (2.46)	26.18 (2.57)	26.2 (2.44)	321[c]	4.74	.030	0.31	.581	1.01	.315
Total ECTS	61.29 (59.98)	71.56 (61.28)	71.2 (59.79)	62.07 (61.54)	406	0.02	.878	5.45	.020	3.36	.067
ECTS in math	2.26 (10.15)	24.04 (36.32)	11.35 (25.18)	15.29 (32.13)	406	31.09	<.001	1.14	.286	0.08	.779
Numeracy											
Proportion of correct answers	0.56 (0.18)	0.68 (0.16)	0.59 (0.17)	0.66 (0.18)	406	25.26	<.001	8.47	.004	0.30	.583
Noncognitive factors											
Math anxiety	25.86 (8.29)	19.91 (6.30)	24.2 (7.96)	21.51 (7.67)	406	35.4	<.001	8.35	.004	0.00	.974
Agreeableness	3.56 (0.63)	3.57 (0.65)	3.56 (0.66)	3.57 (0.62)	406	0.09	.764	0.05	.817	0.24	.627
Conscientiousness	3.45 (0.74)	3.5 (0.68)	3.57 (0.72)	3.39 (0.7)	406	0.04	.840	4.04	.045	0.09	.769
Extraversion	3.01 (0.86)	2.96 (0.78)	3.06 (0.76)	2.92 (0.86)	406	1.78	.183	4.56	.033	1.50	.222
Neuroticism	3.24 (0.71)	3.13 (0.80)	3.36 (0.74)	3.02 (0.75)	406	0.04	.847	3.96	.047	3.78	.052
Openness to experience	3.90 (0.65)	3.62 (0.60)	3.76 (0.63)	3.74 (0.65)	406	11.90	.001	0.37	.545	0.14	.708

Cognitive factors											
IQ	118.46 (10.92)	123.40 (7.57)	120.55 (10.00)	121.39 (9.36)	406	22.30	<.001	3.05	.082	1.81	.179
Number ordering (P score)	1.73 (0.44)	1.57 (0.35)	1.69 (0.36)	1.61 (0.44)	404[d]	7.26	.007	2.00	.158	0.08	.778
Number line (PAE)	4.44 (4.68)	3.75 (4.41)	4.73 (5.51)	3.48 (3.31)	403[d]	5.62	.018	10.44	.001	2.92	.088
Mental calculation (accuracy rate)	0.65 (0.22)	0.79 (0.18)	0.70 (0.21)	0.74 (0.21)	406	25.81	<.001	4.17	.042	0.01	.917
Fact retrieval (accuracy rate)	0.81 (0.13)	0.89 (0.11)	0.83 (0.12)	0.87 (0.13)	405[d]	18.27	<.001	3.83	.051	0.07	.796
Approximate calculation (accuracy rate)	0.53 (0.19)	0.57 (0.17)	0.51 (0.17)	0.59 (0.18)	406	1.01	.316	6.67	.010	1.02	.313

Notes. [a]SES corresponds to the parents' highest level of completed education, based on the International Standard Classification of Education (ISCED). Twenty-one answers were discarded because overly generic to establish the corresponding ISCED level. [b]One datapoint was missing because a participant provided an invalid answer. [c]Sixty-one participants were at the beginning of the university course and had not taken exams yet, while 24 participants provided an invalid answer. They were not included in this analysis. [d]Because of errors in online data saving, two results in the number ordering, three in the number line and one in the fact retrieval tasks were missing.

Supplementary Table 4. Number of participants attending the different degree courses, divided by gender.

HUM				STEM			
	Women	Men	Total		Women	Men	Total
Communication sciences	1	1	2	Biological sciences	9	2	11
Cultural heritage	13	8	21	Biotechnology	17	2	19
Education and training sciences	6	0	6	Chemical sciences	2	2	4
Education sciences and philosophy	6	0	6	Civil and environmental engineering	3	1	4
Figurative arts	2	12	14	Computer sciences	6	15	21
History	6	21	27	Food science and technologies	3	1	4
Linguistic mediation	13	16	29	Industrial engineering	10	12	22
Literature	12	13	25	Information engineering	15	17	32
Modern languages and cultures	26	12	38	Mathematics	14	18	32
Philosophy	8	10	18	Pharmaceutical sciences and technologies	1	0	1
Tourism sciences	1	0	1	Physics	13	18	31
History and philosophy	0	14	14	Science and technology for the environment and nature	1	3	4
				Sport science	3	3	6
				Statistics	8	5	13
				Zootechnics	1	0	1
				Agricultural forestry sciences	0	1	1
				Architectural sciences	0	1	1
				Geological sciences	0	1	1
				Technologies for cultural heritage	0	1	1
Total	94	107	201		106	103	209

Materials

Here we report additional details on the tasks and questionnaires used in the study.

Noncognitive factors

Personality. We employed the Italian version of the Big Five Inventory (BFI, Ubbiali et al., 2013). The Italian items are reported in the Ubbiali and colleagues' article. The English version available online: https://www.ocf.berkeley.edu/~johnlab/bfi.htm. There are 44 items in total, of which eight for Extroversion and nine for each of the remaining traits (Openness, Conscientiousness, Extroversion, Agreeableness, Neuroticism). Each item corresponds to a statement and participants have to rate their agreement on a five-point Likert scale, with 1 indicating "Strongly disagree" and 5 "Strongly agree".

Math anxiety. We used the Italian version of the Abbreviated Math Anxiety Scale (AMAS) (Primi et al., 2014), which consists of 9 items. We contacted the first author to obtain the scale.

Cognitive tasks

Intelligent quotient. A reduced nine-item form of the Raven's Standard Progressive Matrices was used (Bilker et al., 2012). The individual score on the nine-item scale was transformed in the prediction of the total score on the 60-item scale applying the formula reported by Bilker et al. (2012). The predicted total score was converted into an IQ score according to age-appropriate standardization (Raven, 1938; Valseschini, & Del Ton, 1973).

Basic numerical skills.

Arithmetic skills.

The *Mental calculation task* entails 3 additions, 2 subtractions, 2 multiplications and 3 divisions (10 in total). Participants are instructed to solve as accurately and fast as possible 10 operations, presented in auditory form one at the time, and they have 30 seconds to digit their answer on the computer keyboard. Before computing the accuracy rate, we excluded fast responses as outliers: we chose a speed threshold according to the normative data: responses faster or equal to 5 seconds (i.e., less than the time employed by the lower 5^{th} percentile of the standardization sample) were removed (0.50% of the total number of items).

The *Arithmetic facts retrieval task* entailed a similar procedure as the Mental arithmetic task, but in this case, participants were presented with easier operations and had 5 seconds to digit their answer. There were 6 additions, 5 subtractions, 12 multiplications, 5 divisions, 2 square roots (30 in total). Before computing the accuracy rate, we excluded fast responses as outliers: since there is no normative data for response time, responses whose time was below 3 *SD* from the sample RT mean were removed (0.14% of total items).

The *Approximate calculation task* evaluates the ability to reason with numerical magnitude. The operations were difficult, and participants were asked not to execute a computation, but to choose among three options the correct result. Participants had one minute to solve as many as they could of the 16 trials.

*Number line estimation***.** The target numbers were: 12, 48, 116, 263, 477, 526, 734, 805, 882, and 958. For training trials, participants had to place 600, 322 and 29 (randomly chosen numbers). Responses inserted before two seconds from trial beginning were not collected as assumed to be too fast. Very slow responses (response times above 3 *SD*) were removed (0.83% of total items). RT below 3 *SD* were not present.

Number ordering. The triads were presented in the middle of the screen one at the time, for a total of 8 practice trials (with feedback to each response) and 48 test trials (without feedback). Before computing the composite score, we removed outlier responses: RT above 3 *SD*: 1.79% of total items; RT below 3 *SD* were not present.

Numeracy test

The items of the present numeracy test entailed the same structure and the same difficulty level as the TECO-T: an ANVUR member, expert in achievement test development, reviewed the design and the contents of the present test. The questions were grouped into three modules of five questions each. In the “Graphs and Tables module,” participants had to extract information from a graph (3 items) or a table (2 items) to infer relations between variables. In the “Logical reasoning” items, conclusions had to be drawn based on some numerical or verbal premises. To answer the questions of the “Infographics" module, participants had to infer information from visually represented data concerning the elderly population in Italy. Participants had 40 min to complete the test: we used the Apps Script tool in Google Form to build a function that forces the form to close after 40 min.

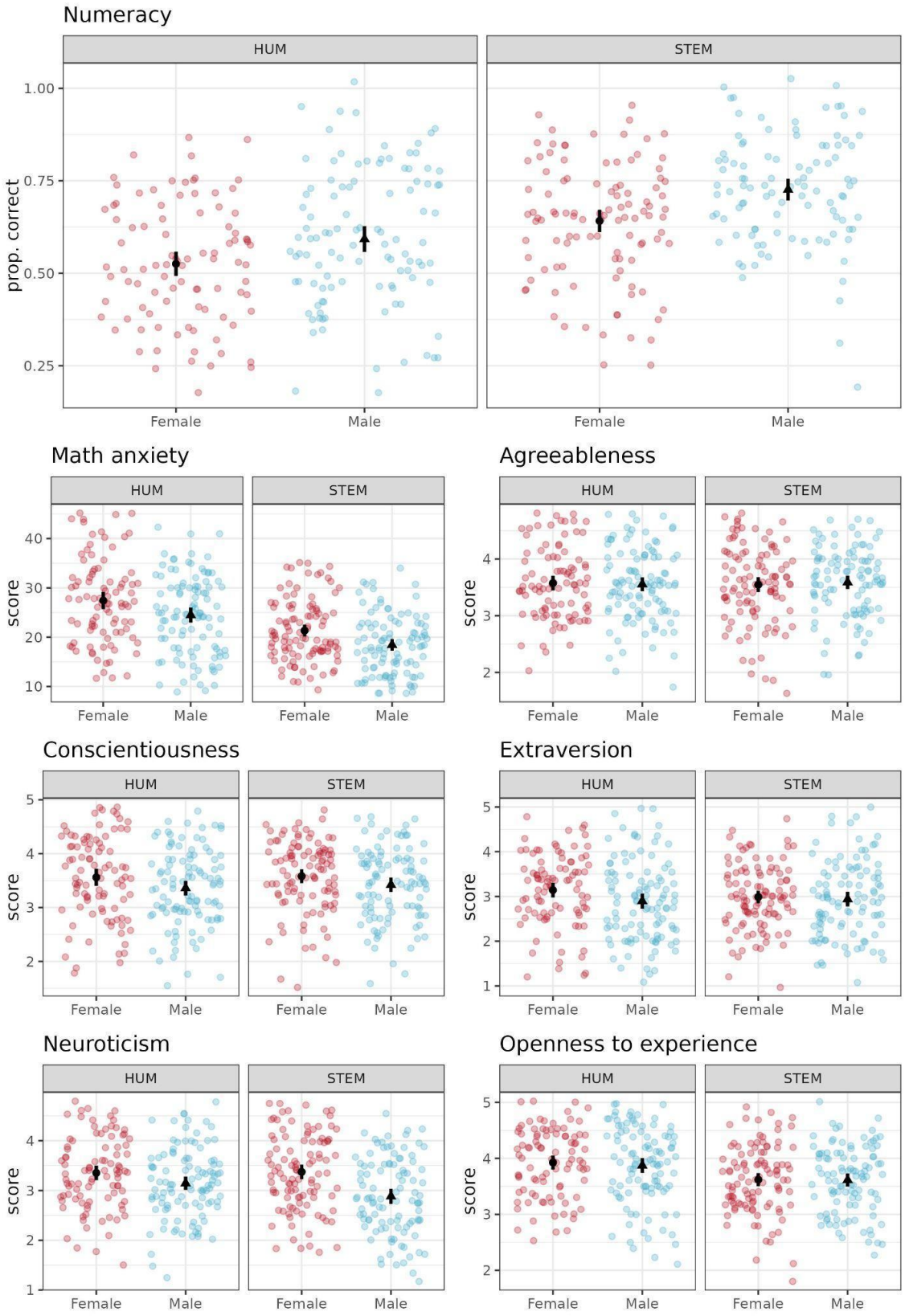
Supplementary Table 5. Correlations between the main study variables, mean (M) and standard deviation (SD) on the overall sample.

Variable	*M*	*SD*	1	2	3	4	5	6	7	8	9	10	11	12	13
1. Numeracy	0.62	0.18													
2. Math anxiety	22.82	7.92	-.42** [-.49, -.33]												
3. Agreeableness	3.57	0.64	-.03 [-.12, .07]	.05 [-.00, .15]											
4. Conscientiousness	3.48	0.71	-.04 [-.14, .06]	-.10* [-.19, -.00]	.14** [.04, .23]										
5. Extraversion	2.99	0.82	-.09 [-.19, .01]	.00 [-.10, .09]	.20** [.11, .29]	.26** [.17, .35]									
6. Neuroticism	3.19	0.76	-.12* [-.21, -.02]	.25** [.16, .34]	-.12* [-.21, -.02]	-.22** [-.31, -.13]	-.21** [-.30, -.11]								
7. Openness	3.75	0.64	-.10 [-.19, .00]	.05 [-.05, .15]	.13* [.03, .22]	.12* [.02, .21]	.29** [.20, .38]	-.04 [-.13, .06]							
8. IQ	120.98	9.67	.50** [.42, .57]	-.35** [-.43, -.26]	.03 [-.07, .13]	-.15** [-.24, -.05]	-.14** [-.23, -.04]	-.06 [-.15, .04]	-.06 [-.16, .03]						
9. Number	1.65	0.4	-.16**	.19**	.01	-.01	.03	.00	.20**	-.09					

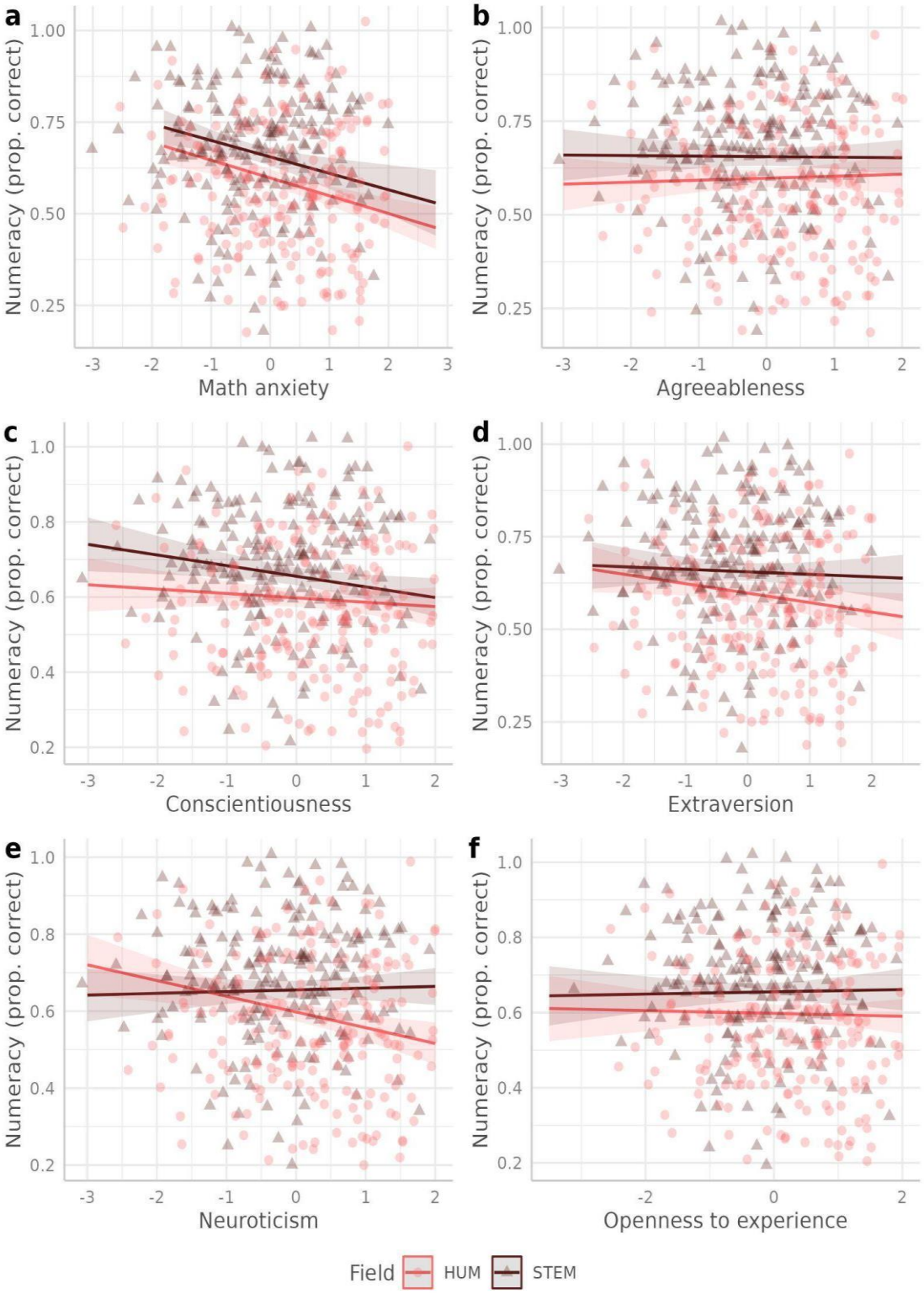
ordering			[-.26, -.07]	[.09, .28]	[-.09, .10]	[-.11, .08]	[-.06, .13]	[-.10, .10]	[.10, .29]	[-.19, .01]				
10. Number line	4.09	4.55	-.24** [-.33, -.14]	.09 [-.00, .19]	-.03 [-.13, .06]	.04 [-.06, .14]	-.03 [-.13, .07]	.11* [.02, .21]	.07 [-.03, .16]	-.21** [-.30, -.11]	.06 [-.03, .16]			
11. Mental calculation	0.72	0.21	.27** [.18, .36]	-.40** [-.48, -.31]	.00 [-.09, .10]	.12* [.02, .21]	-.02 [-.12, .08]	-.10* [-.19, -.00]	-.10* [-.20, -.00]	.20** [.11, .29]	-.27** [-.36, -.18]	-.18** [-.27, -.08]		
12. Fact retrieval	0.85	0.13	.34** [.25, .42]	-.34** [-.42, -.25]	-.02 [-.12, .08]	.08 [-.01, .18]	-.07 [-.16, .03]	-.14** [-.23, -.04]	-.17** [-.27, -.08]	.20** [.10, .29]	-.31** [-.39, -.21]	-.30** [-.39, -.21]	.60** [.53, .66]	
13. Approximate calculation	0.55	0.18	.25** [.16, .34]	-.15** [-.25, -.06]	-.04 [-.13, .06]	-.02 [-.12, .08]	-.09 [-.18, .01]	-.11* [-.20, -.01]	-.08 [-.18, .01]	.11* [.02, .21]	-.37** [-.45, -.28]	-.19** [-.29, -.10]	.24** [.14, .33]	.27** [.18, .36]
14. Field of study			.34*** [.26,.43]	-.38*** [-.46, -.29]	.00 [.09, .10]	.03 [-.06, .13]	-.03 [-.13, .07]	-.07 [-.17, .02]	-.22*** [-.31, -.13]	.26*** [.16, .34]	-.20*** [.10, .29]	-.08 [-.17, .02]	.33*** [.24, .41]	.29*** [.20, .38]
15. Gender			.20*** [.11, .29]	-.17** [-.26, -.07]	.01 [-.09, 0.10]	-.13* [-.22, -.03]	-0.09 [-0.18,0.01]	-.23*** [-.32, -.13]	-.01 [-.11, .08]	.04 [-.05, .14]	-.10* [.01, .02]	-.14** [-.23, -.04]	.12* [.02, .21]	.13** [.03, .23]

Note. For correlations between continuous variables, Pearson's r was computed. For correlations of gender and field of study with continuous variables, the point biserial correlation coefficient was computed. Values in square brackets indicate the 95% confidence interval for each correlation. * indicates $p < .05$. ** indicates $p < .01$. *** indicates $p < .001$. Field code: HUM = 0; STEM = 1. Gender code: Woman = 0; Man = 1.

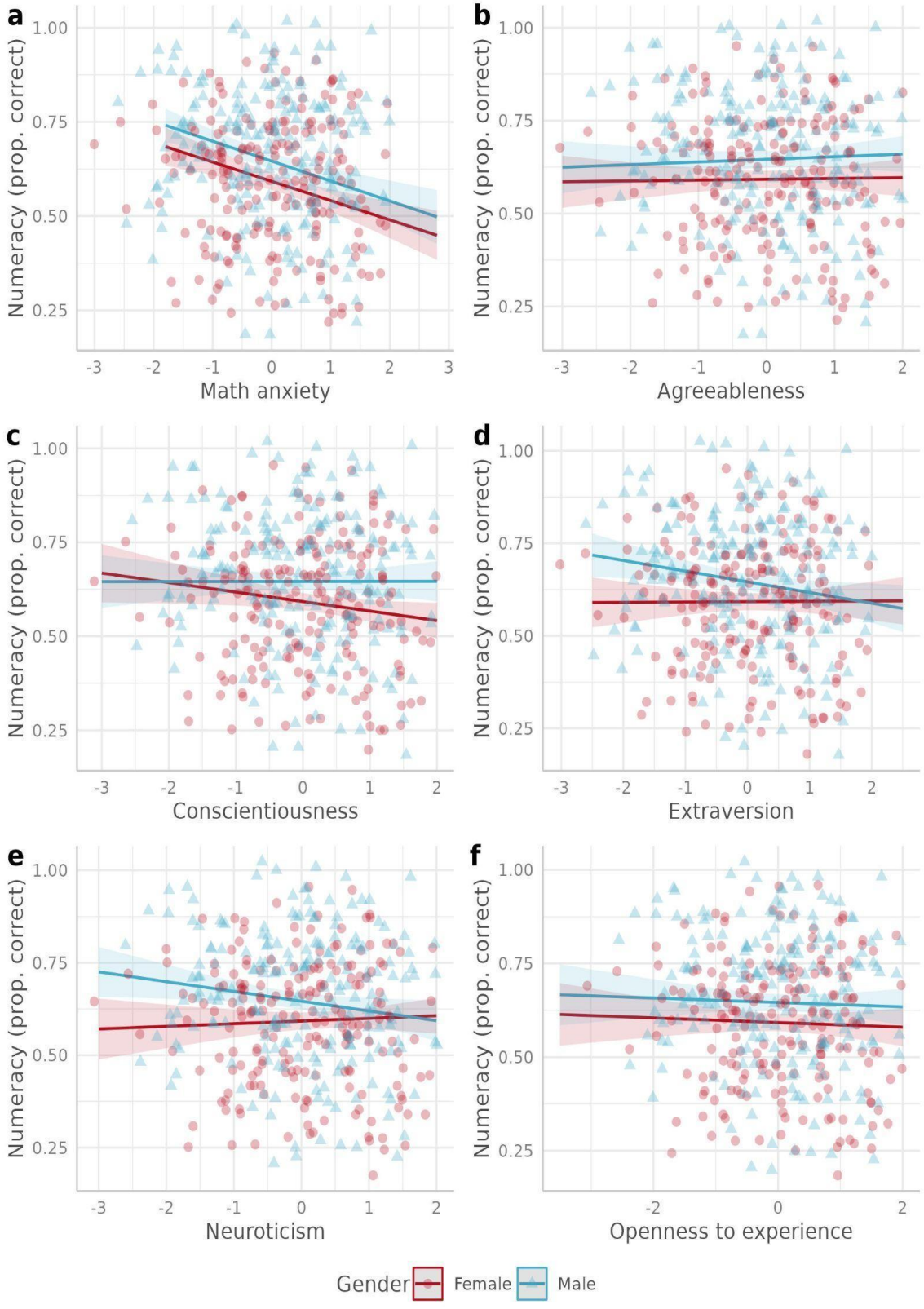
Supplementary Figure 2. Mean scores for numeracy and the noncognitive factors across fields of study and gender. Error bars represent 95% confidence intervals. Transparent points represent individual scores.



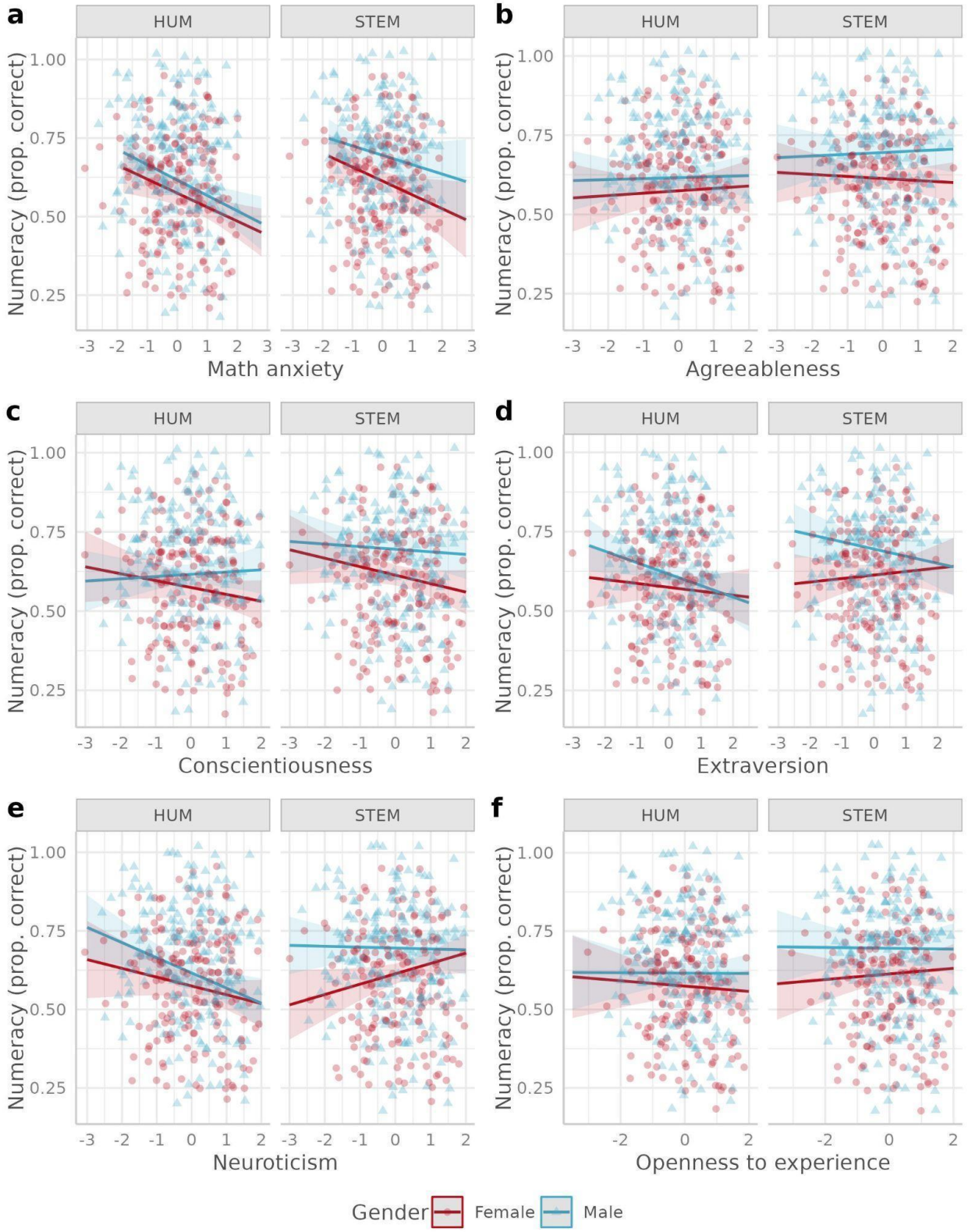
Supplementary Figure 3. Interactions between field of study and noncognitive factors in predicting numeracy (Model 1). Regression lines and 95% confidence intervals for the two groups are displayed. Dots represent individual raw data. The x-axis represents standardized scores for: a) math anxiety; b) agreeableness; c) conscientiousness; d) extraversion; e) neuroticism (reported also in the main text); f) openness to experience.



Supplementary Figure 4. Interactions between gender and noncognitive factors in predicting numeracy (Model 2). Regression lines and 95% confidence intervals for the two groups are displayed. Dots represent individual raw data. The x-axis represents standardized scores for: a) math anxiety; b) agreeableness; c) conscientiousness; d) extraversion; e) neuroticism (reported also in the main text); f) openness to experience.

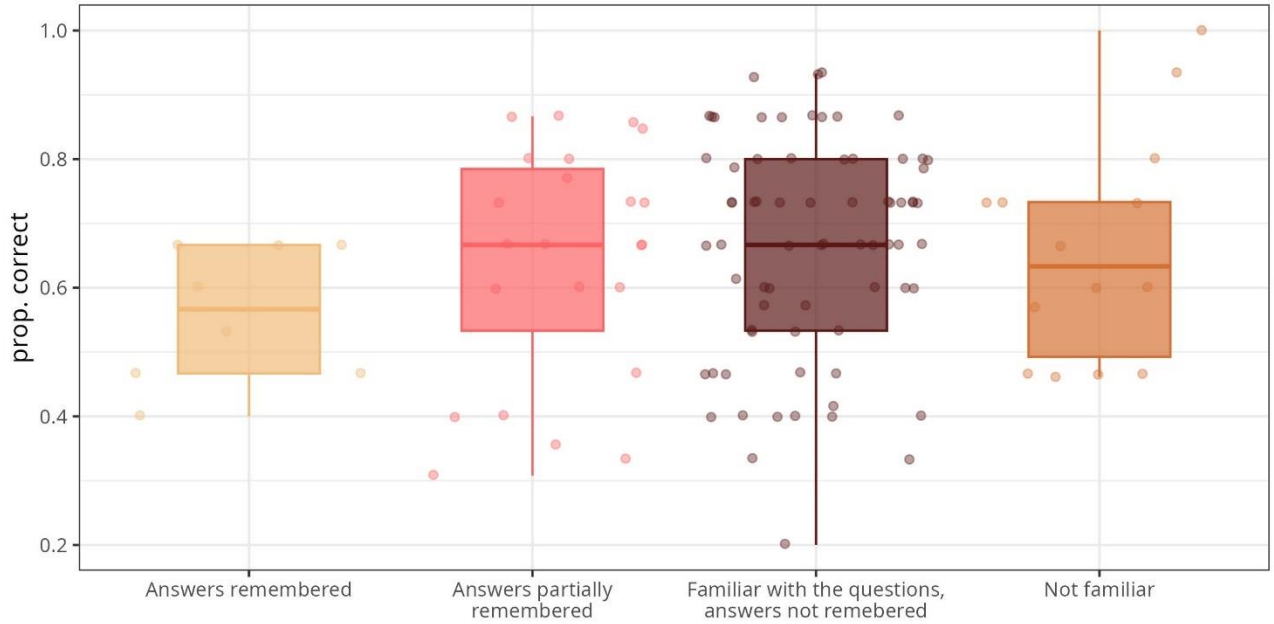


Supplementary Figure 5. Interactions between field of study, gender and noncognitive factors in predicting numeracy (Model 3). Regression lines and 95% confidence intervals for the two groups are displayed. Dots represent individual raw data. The x-axis represents standardized scores for: a) math anxiety; b) agreeableness; c) conscientiousness; d) extraversion; e) neuroticism; f) openness to experience.

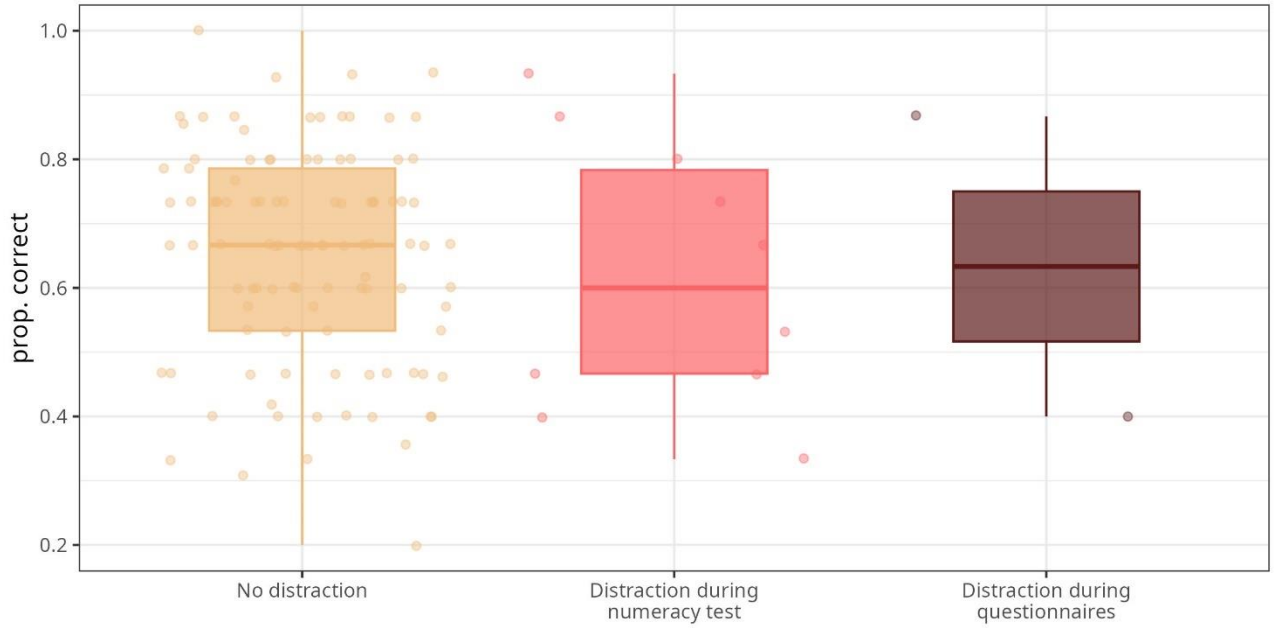


Supplementary material Study 3

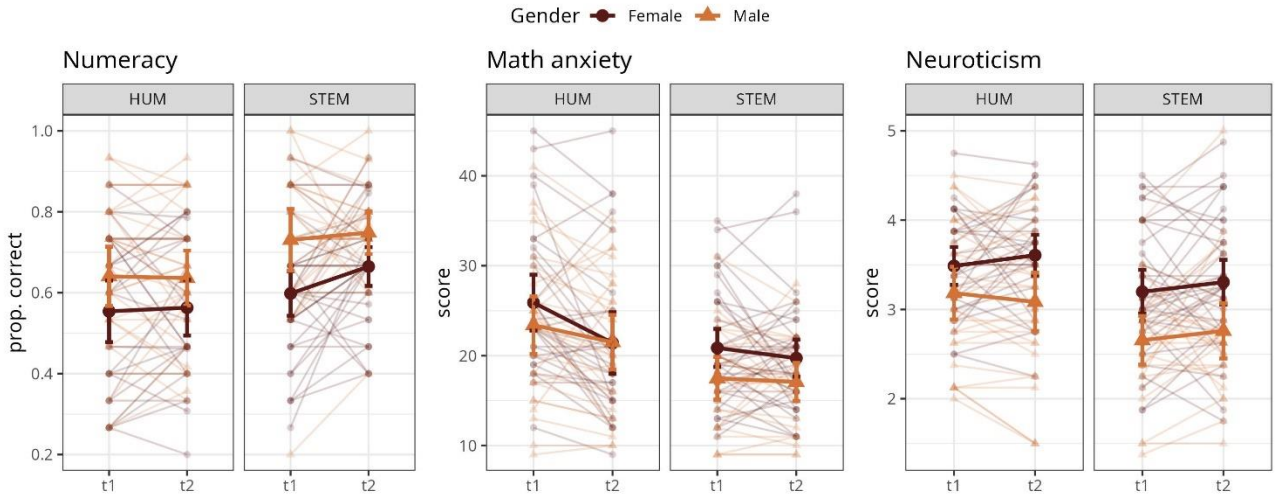
Supplementary Figure 6. Numeracy test performance and familiarity with its questions and answers. Transparent dots in the background represent individual scores.



Supplementary Figure 7. Numeracy test performance and distractions. Transparent dots in the background represent individual scores.



Supplementary Figure 8. Scores in numeracy, math anxiety and neuroticism in T1 and T2 separately for fields of study and gender. Transparent dots represent individual scores. Larger dots represent the mean. The error represent 95% confidence interval.



Supplementary Table 6. Results of simple mediation and moderated mediations with math anxiety as predictor. Indirect effect 1 = numeracy at T1 as mediator; Indirect effect 2 = math anxiety at T2 as mediator; Indirect effect 3 = numeracy at T1 and math anxiety at T2 as mediators.

	β	*p*	CI	R^2
Mediation				
Outcome: Numeracy T1				0.15
Math anxiety T1	-0.38	< .001	-0.55; -0.21	
Outcome: Math anxiety T2				0.48
Math anxiety T1	0.6	< .001	0.46; 0.75	
Numeracy T1	-0.18	0.013	-0.33; -0.04	
Outcome: Numeracy T2				0.65
Math anxiety T1	-0.1	0.032 3	-0.29; 0.10	
Numeracy T1	0.56	< .001	0.40; 0.72	
Math anxiety T2	-0.08	0.42	-0.27; 0.12	
Total effect	-0.37	< .001	-0.54: -0.19	
Indirect effect 1	-0.21		-0.42; -0.13	
Indirect effect 2	-0.05		-0.18; 0.06	
Indirect effect 3	-0.01		-0.03; 0.01	
Moderated mediation: Field				
Outcome: Numeracy T1				0.15
Math anxiety T1	-0.35	0.022	-0.64; -0.05	
Field (HUM = 1)	-0.04	0.82	-0.41; 0.32	
Math anxiety T1 x Field	-0.05	0.795	-0.42; 0.33	
Outcome: Math anxiety T2				0.49
Math anxiety T1	0.53	< .001	0.28; 0.77	
Numeracy T1	-0.2	0.057	-0.40; 0.01	
Field (HUM = 1)	-0.07	0.615	-0.36; 0.21	
Math anxiety T1 x Field	0.15	0.339	-0.16; 0.46	
Numeracy T1 x Field	0.03	0.831	-0.26; 0.32	
Outcome: Numeracy T2				0.53
Math anxiety T1	0.24	0.094	-0.04; 0.52	
Numeracy T1	0.31	0.003	0.11; 0.62	
Math anxiety T2	-0.48	0.002	-0.77; -0.18	
Field (HUM = 1)	-0.38	0.007	-0.66; -0.11	
Math anxiety T1 x Field	0.44	0.021	-0.81; -0.0	
Numeracy T1 x Field	0.44	0.003	0.14; 0.73	
Math anxiety T2 x Field	0.63	0.001	0.25; 1.00	
Conditional indirect effect 1				
STEM	-0.11		-0.24; -0.01	
HUM	-0.29		-0.46; -0.14	
Index of moderated mediation	-0.19		-0.38; 0.01	
Conditional indirect effect 2				

STEM	-0.25		-0.49; -0.07	
HUM	0.1		-0.03; 0.024	
Index of moderated mediation	0.35		0.13; 0.62	
Conditional indirect effect 3				
STEM	-0.03		-0.09; 0.003	
HUM	0.01		-0.01; 0.03	
Index of moderated mediation	0.04		-0.00; 0.10	
Moderated mediation: Gender				
Outcome: Numeracy T1				0.2
Math anxiety T1	-0.45	< .001	-0.70; -0.20	
Gender (Women = 1)	-0.43	0.013	-0.76; -0.09	
Math anxiety T1 x Gender	0.19	0.265	-0.15; 0.53	
Outcome: Math anxiety T2				0.49
Math anxiety T1	0.62	< .001	0.39-0.84	
Numeracy T1	-0.19	0.098	-0.42; 0.04	
Gender (Women = 1)	-0.16	0.252	-0.44; 0.12	
Math anxiety T1 x Gender	-0.01	0.921	-0.31; 0.28	
Numeracy T1 x Gender	-0.02	0.879	-0.33; 0.29	
Outcome: Numeracy T2				0.42
Math anxiety T1	-0.03	0.855	-0.35; 0.29	
Numeracy T1	0.52	< .001	0.27; 0.77	
Math anxiety T2	-0.17	0.315	-0.52; 0.17	
Gender (Women = 1)	-0.08	0.611	-0.38; 0.22	
Math anxiety T1 x Gender	-0.1	0.636	-0.51; 0.31	
Numeracy T1 x Gender	0.05	0.758	-0.28; 0.39	
Math anxiety T2 x Gender	0.14	0.527	-0.29; 0.56	
Conditional indirect effect 1				
Men	-0.23		-0.41; -0.8	
Women	-0.15		-0.29; -0.03	
Index of moderated mediation	0.09		-0.13; 0.31	
Conditional indirect effect 2				
Men	-0.11		-0.35; 0.10	
Women	-0.02		-0.21; 0.11	
Index of moderated mediation	0.08		-0.21; 0.35	
Conditional indirect effect 3				
Men	-0.02		-0.06; 0.02	
Women	-0.002		-0.03; 0.01	
Index of moderated mediation	0.01		-0.03; 0.05	

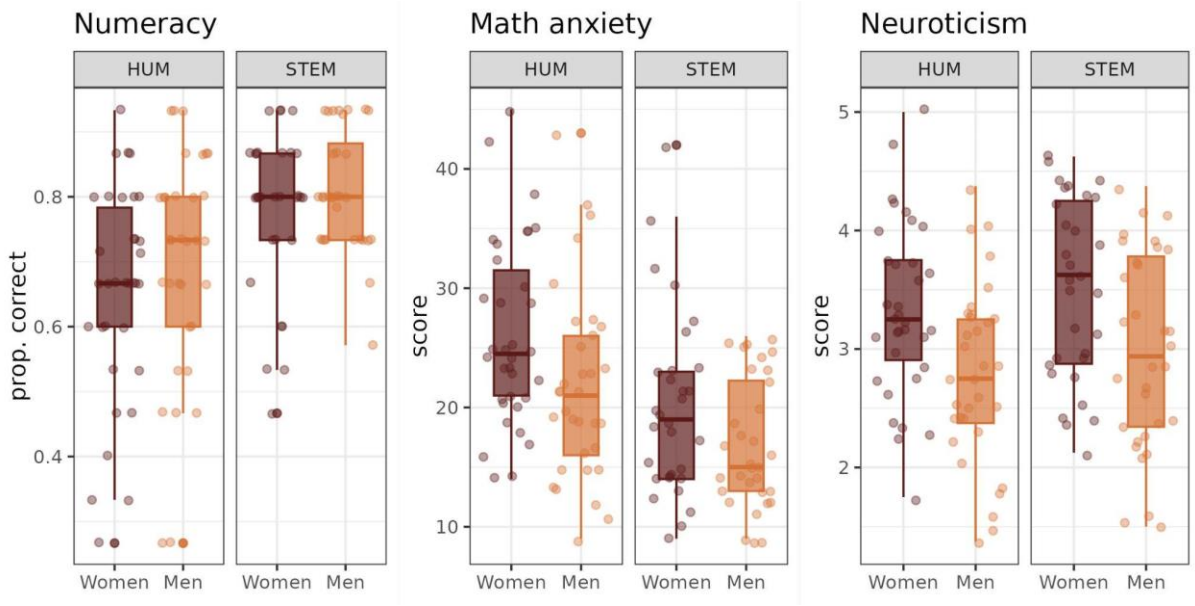
Supplementary Table 7. Results of simple mediation and moderated mediations with neuroticism as predictor. Indirect effect 1 = numeracy at T1 as mediator; Indirect effect 2 = neuroticism at T2 as mediator; Indirect effect 3 = numeracy at T1 and neuroticism at T2 as mediators.

	β	*p*	CI	R^2
Mediation				
Outcome: Numeracy T1				0.02
Neuroticism T1	-0.16	0.088	-0.33; 0.02	
Outcome: Neuroticism T2				0.49
Neuroticism T1	0.69	< .001	0.55; 0.82	
Numeracy T1	-0.06	0.387	-0.19; 0.08	
Outcome: Numeracy T2				0.41
Neuroticism T1	-0.06	0.535	-0.26; 0.14	
Numeracy T1	0.61	< .001	0.47; 0.76	
Neuroticism T2	-0.05	0.626	-0.25; 0.15	
Total effect	-0.19	0.036	-0.37; -0.01	
Indirect effect 1	-0.1		-0.21; 0.01	
Indirect effect 2	-0.03		-0.19; 0.10	
Indirect effect 3	-0.001		-0.005; 0.003	
Moderated mediation: Field				
Outcome: Numeracy T1				0.04
Neuroticism T1	-0.12	0.331	-0.37; 0.13	
Field (HUM = 1)	-0.23	0.231	-0.60; 0.15	
Neuroticism T1 x Field	-0.01	0.944	-0.39; 0.37	
Outcome: Neuroticism T2				0.5
Neuroticism T1	0.64	< .001	0.45; 0.82	
Numeracy T1	0.03	0.749	-0.16; 0.23	
Field (HUM = 1)	-0.02	0.874	-0.3; 0.25	
Neuroticism T1 x Field	0.13	0.366	-0.15; 0.4	
Numeracy T1 x Field	-0.17	0.205	-0.44; 0.1	
Outcome: Numeracy T2				0.48
Neuroticism T1	-0.09	0.486	-0.33; 0.16	
Numeracy T1	0.4	< .001	0.20; 0.60	
Neuroticism T2	0.05	0.691	-0.20; 0.3	
Field (HUM = 1)	-0.4	0.006	-0.68; -0.12	
Neuroticism T1 x Field	0.13	0.512	-0.27; 0.53	
Numeracy T1 x Field	0.34	0.017	0.06; 0.63	
Neuroticism T2 x Field	-0.18	0.374	-0.57; 0.22	
Conditional indirect effect 1				
STEM	-0.05		-0.16; 0.04	
HUM	-0.1		-0.31; 0.12	
Index of moderated mediation	-0.05		-0.27; 0.19	
Conditional indirect effect 2				
STEM	0.03		-0.17; 0.18	

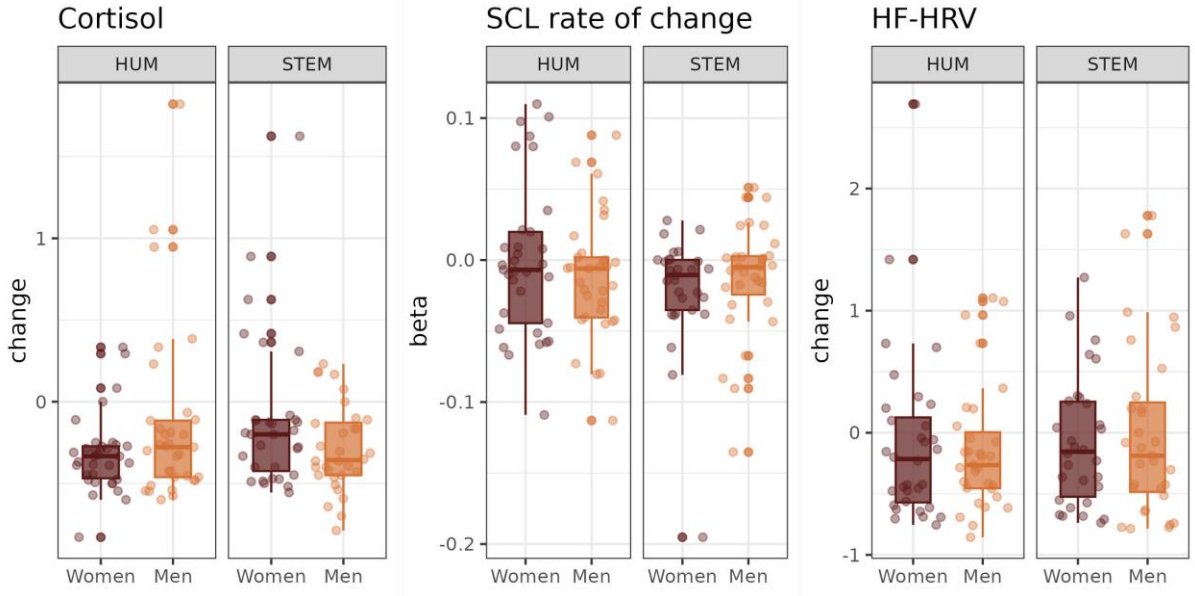
HUM	-0.1		-0.35; 0.16	
Index of moderated mediation	-0.13		-0.42; 0.19	
Conditional indirect effect 3				
STEM	-0.0002		-0.005; 0.005	
HUM	-0.003		-0.02; 0.01	
Index of moderated mediation	-0.002		-0.02; 0.01	
Moderated mediation: Gender				
Outcome: Numeracy T1				0.09
Neuroticism T1	-0.18	0.178	-0.43; 0.08	
Gender (Women = 1)	-0.49	0.009	-0.86; -0.13	
Neuroticism T1 x Gender	0.17	0.352	-0.19; 0.54	
Outcome: Neuroticism T2				0.52
Neuroticism T1	0.73	< .001	0.54; 0.92	
Numeracy T1	-0.1	0.319	-0.3; 0.1	
Gender (Women = 1)	0.29	0.05	0.0005; 0.56	
Neuroticism T1 x Gender	-0.17	0.21	-0.44; 0.1	
Numeracy T1 x Gender	0.16	0.259	-0.12; 0.43	
Outcome: Numeracy T2				0.42
Neuroticism T1	-0.26	0.107	-0.57; 0.06	
Numeracy T1	0.58	< .001	0.36; 0.84	
Neuroticism T2	0.07	0.688	-0.26; 0.39	
Gender (Women = 1)	-0.02	0.887	-0.34; 0.29	
Neuroticism T1 x Gender	0.34	0.103	-0.07; 0.75	
Numeracy T1 x Gender	0.05	0.762	-0.26; 0.35	
Neuroticism T2 x Gender	-0.16	0.438	-0.58; 0.26	
Conditional indirect effect 1				
Men	-0.1		-0.24; 0.03	
Women	-0.002		-0.17; 0.15	
Index of moderated mediation	0.1		-0.12; 0.31	
Conditional indirect effect 2				
Men	0.05		-0.24; 0.27	
Women	-0.06		-0.22; 0.09	
Index of moderated mediation	-0.1		-0.39; 0.22	
Conditional indirect effect 3				
Men	0.001		-0.006; 0.02	
Women	0		-0.005; 0.006	
Index of moderated mediation	-0.001		-0.02; 0.008	

Supplementary material Study 4

Supplementary Figure 9. Boxplots for numeracy, math anxiety and neuroticism for female and male students in HUM and STEM. Transparent points represent individual scores.



Supplementary Figure 10. Boxplots for physiological indexes for female and male students in HUM and STEM. Transparent points represent individual scores.



Note. The value of a man in HUM was removed to improve visualization, as it was extremely high compared to the others (HF-HRV change = 56.12).

Supplementary Table 8. Spearman's rank correlations in HUM and STEM students. Values in gray refer to the HUM group.

	1.	2.	3.	4.	5.	6.	7.	8.
1. Numeracy	1	-0.555***	-0.355**	0.087	0.193	0.062	0.393***	0.456***
2. Math anxiety	-0.321*	1	0.377**	-0.051	0.012	0.055	-0.323**	-0.277*
3. Neuroticism	-0.184	0.332**	1	-0.124	0.057	0.074	-0.141	-0.100
4. Cortisol change	0.060	0.148	-0.019	1	0.104	0.036	-0.140	0.078
5. SCL rate of change	-0.257*	0.102	-0.019	-0.093	1	-0.195	0.018	0.167
6. HF-HRV change	0.076	-0.214	-0.085	-0.104	-0.010	1	0.091	-0.147
7. IQ	0.447***	-0.056	0.015	-0.080	-0.015	0.200	1	0.255*
8. Basic arithmetic skills	0.417***	-0.330**	-0.118	-0.032	-0.107	0.215	0.070	1

Note. * indicates $p < .05$. ** indicates $p < .01$. *** indicates $p < .001$.

Supplementary Table 9. Spearman's rank correlations in men and womens. Values in gray refer to women.

	1.	2.	3.	4.	5.	6.	7.	8.
1. Numeracy	1	-0.633***	-0.256*	0.184	0.017	-0.010	0.447***	0.482***
2. Math anxiety	-0.397**	1	0.278*	-0.065	0.022	-0.079	-0.359**	-0.311*
3. Neuroticism	-0.102	0.214	1	-0.067	-0.141	0.031	-0.150	-0.157
4. Cortisol change	0.075	0.058	-0.091	1	0.193	-0.163	-0.011	0.294*
5. SCL rate of change	0.008	0.113	0.155	-0.174	1	-0.196	-0.193	0.005
6. HF-HRV change	0.130	-0.135	-0.029	0.122	-0.017	1	0.149	-0.078
7. IQ	0.419***	-0.047	0.043	-0.159	0.186	0.128	1	0.129
8. Basic arithmetic skills	0.499***	-0.354**	0.090	-0.108	0.034	0.094	0.310*	1

Note. * indicates $p < .05$. ** indicates $p < .01$. *** indicates $p < .001$.

Supplementary Table 10. Linear regression models testing the association of physiological indexes and their interactions with field and gender with math anxiety and neuroticism.

	DV: Math anxiety				DV: Neuroticism			
Predictors	*β*	CI	*t*	*p*	*β*	CI	*t*	*p*
(Intercept)	0.50	0.08 – 0.91	2.38	**.019**	0.11	-0.33 – 0.56	0.50	.617
Cortisol	-0.36	-0.96 – 0.23	-1.21	.228	-0.41	-1.05 – 0.22	-1.29	.200
Field	-0.89	-1.49 – -0.28	-2.91	**.004**	0.26	-0.38 – 0.91	0.8	.425
Gender	-0.39	-0.91 – 0.14	-1.46	.146	-0.55	-1.11 – 0.01	-1.95	.054
SCL	0.05	-0.26 – 0.37	0.35	.730	<0.01	-0.34 – 0.33	-0.03	.979
HRV	-0.09	-2.53 – 2.36	-0.07	.945	-0.13	-2.75 – 2.48	-0.10	.919
Cortisol × Field	0.45	-0.21 – 1.11	1.36	.177	0.45	-0.25 – 1.16	1.28	.205
Cortisol × Gender	0.23	-0.41 – 0.88	0.71	.478	0.38	-0.31 – 1.06	1.08	.283
Field × Gender	0.22	-0.56 – 1.00	0.55	.583	-0.10	-0.93 – 0.74	-0.23	.820
Field × imputed scl	0.25	-0.24 – 0.74	1.02	.311	0.02	-0.50 – 0.55	0.09	.926
Gender × imputed scl	-0.05	-0.51 – 0.42	-0.20	.844	0.02	-0.48 – 0.52	0.08	.938
Field × imputed hrv	-2.67	-6.67 – 1.32	-1.33	.188	-0.45	-4.72 – 3.82	-0.21	.836
Gender × imputed hrv	<.0.01	-2.45 – 2.45	<0.01	.998	0.12	-2.50 – 2.74	0.09	.929
(Cortisol × Field) × Gender	-0.10	-0.96 – 0.76	-0.23	.819	-0.44	-1.36 – 0.48	-0.95	.344
(Field × Gender) × SCL	-0.19	-0.89 – 0.52	-0.52	.602	0.01	-0.75 – 0.76	0.01	.989
(Field × Gender) × HRV	2.09	-2.57 – 6.74	0.89	.377	-0.51	-5.48 – 4.47	-0.20	.841
Observations	130				130			
R2 adjusted	0.153				0.031			

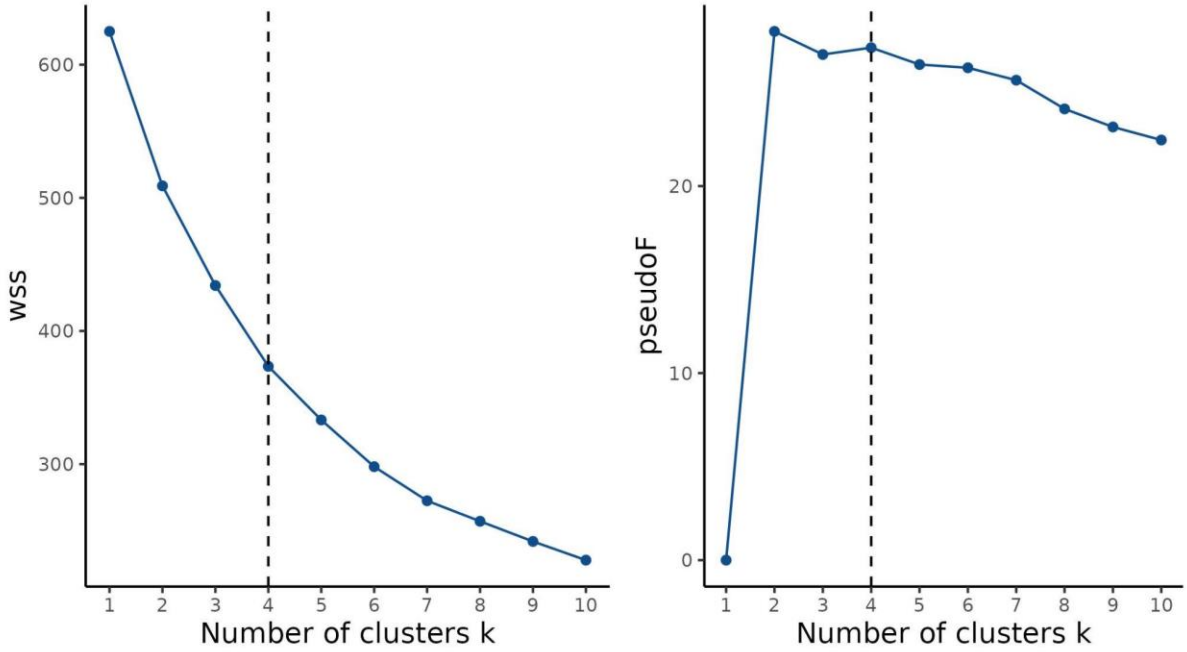
Note. Cotisol = cortisol change; SCL = SCL rate of change; HRV = HF-HRV change. Field code: HUM = 0; STEM = 1. Gender code: Woman = 0; Man = 1.

Supplementary Table 11. Spearman-s rank correlations between numeracy test completion time and the main study variables.

Variable	*r*	*p*
Numeracy	0.105	0.233
Neuroticism	-0.097	0.270
Math anxiety	-0.108	0.220
SCL rate of change	0.105	0.241
HF-HRV change	0.069	0.443
Cortisol change	-0.232	0.008

Note. The only significant correlation is the one with cortisol change. Therefore, individual numeracy test completion time was entered as covariate in the hierarchical models with cortisol change.

Supplementary Figure 11. Within-cluster sum of squares and Calinski-Harabasz index (also called pseudo F, Giordani et al., 2020) for 2 to 10-cluster solutions.



Supplementary Table 12. Hierarchical regression models testing the role of cortisol change and its interactions with math anxiety, neuroticism, field of study and gender in predicting numeracy.

	Step 0		**Step 1**		**Step 2-MA**		**Step 3-MA-F**		**Step 3-MA-G**		**Step 2-N**		**Step 3-N-F**		**Step 3 N-G**	
Predictors	*β* [CI]	*t (p)*	*β* [CI]	*t (p)*	*β* [CI]	*t (p)*	*β* [CI]	*t (p)*	*β* [CI]	*t (p)*	*β* [CI]	*t (p)*	*β* [CI]	*t (p)*	*β* [CI]	*t (p)*
IQ	0.29 [0.14 – 0.45]	**3.71 (<0.001)**	0.3 [0.15 – 0.46]	**3.94 (<0.001)**	0.18 [0.03 – 0.33]	**2.39 (0.018)**	0.15 [-0.00 – 0.30]	1.94 (0.054)	0.17 [0.02 – 0.32]	**2.26 (0.026)**	0.29 [0.14 – 0.45]	**3.87 (<0.001)**	0.24 [0.09 – 0.38]	**3.19 (0.002)**	0.29 [0.14 – 0.45]	**3.76 (<0.001)**
Basic arithmetic skills	0.4 [0.24 – 0.55]	**5.13 (<0.001)**	0.41 [0.26 – 0.56]	**5.36 (<0.001)**	0.3 [0.15 – 0.44]	**3.98 (<0.001)**	0.25 [0.10 – 0.40]	**3.25 (0.001)**	0.32 [0.16 – 0.47]	**4 (<0.001)**	0.39 [0.24 – 0.54]	**5.18 (<0.001)**	0.31 [0.17 – 0.46]	**4.2 (<0.001)**	0.4 [0.24 – 0.56]	**5 (<0.001)**
Time numeracy	0.05 [-0.10 – 0.20]	0.64 (0.526)	0.08 [-0.07 – 0.22]	1.01 (0.314)	0.05 [-0.09 – 0.18]	0.69 (0.494)	0.05 [-0.09 – 0.19]	0.74 (0.462)	0.04 [-0.10 – 0.19]	0.63 (0.532)	0.06 [-0.09 – 0.21]	0.82 (0.414)	0.02 [-0.12 – 0.16]	0.31 (0.756)	0.07 [-0.08 – 0.22]	0.87 (0.383)
Cortisol change			0.2 [0.05 – 0.34]	**2.7 (0.008)**	0.18 [0.05 – 0.31]	**2.68 (0.008)**	0.14 [-0.04 – 0.32]	1.52 (0.131)	0.12 [-0.08 – 0.33]	1.18 (0.24)	0.18 [0.03 – 0.32]	**2.44 (0.016)**	0.23 [0.02 – 0.44]	**2.19 (0.031)**	0.08 [-0.16 – 0.31]	0.63 (0.528)
Math anxiety					-0.38 [-0.52 – -0.23]	**-5 (<0.001)**	-0.39 [-0.59 – -0.18]	**-3.59 (<0.001)**	-0.48 [-0.67 – -0.29]	**-4.84 (<0.001)**						
Cortisol change × Math anxiety					0.1 [-0.03 – 0.23]	1.52 (0.131)	0.17 [-0.01 – 0.35]	1.89 (0.061)	0.11 [-0.06 – 0.29]	1.27 (0.205)						
Field							0.33 [0.03 – 0.63]	**2.22 (0.028)**					0.49 [0.19 – 0.78]	**3.19 (0.002)**		
Cortisol change × Field							0.01 [-0.26 – 0.28]	0.07 (0.947)					-0.09 [-0.40 – 0.21]	-0.61 (0.545)		
Math anxiety × Field							0.17 [-0.15 – 0.49]	0.95 (0.345)								
(Cortisol change × Math anxiety) × Field							-0.23 [-0.50 – 0.05]	-1.63 (0.105)								
Gender									-0.07 [-0.34 – 0.20]	-0.47 (0.642)					-0.04 [-0.35 – 0.27]	-0.16 (0.87)
Cortisol change ×									0.09 [-0.19 – 0.37]	0.62 (0.536)					0.14 [-0.18 – 0.46]	0.85 (0.394)

Gender												
Math anxiety × Gender (Cortisol change × Math anxiety) × Gender					0.22 [-0.05 – 0.50]	1.58 (0.116)						
Neuroticism					-0.02 [-0.30 – 0.26]	-0.11 (0.911)						
Cortisol change × Neuroticism							-0.16 [-0.30 – -0.01]	**-2.08 (0.04)**	-0.28 [-0.49 – -0.08]	**-2.47 (0.015)**	-0.2 [-0.43 – 0.03]	-1.61 (0.109)
Neuroticism × Field (Cortisol change × Neuroticism) × Field							0.08 [-0.06 – 0.22]	1.08 (0.28)	0.22 [-0.02 – 0.47]	1.81 (0.073)	0.17 [-0.04 – 0.37]	1.6 (0.113)
Neuroticism × Gender (Cortisol change × Neuroticism) × Gender									0.19 [-0.09 – 0.47]	1.18 (0.239)		
									-0.25 [-0.57 – 0.06]	-1.58 (0.116)		
											0.05 [-0.26 – 0.37]	0.24 (0.815)
											-0.15 [-0.46 – 0.17]	-0.94 (0.35)
Observations	128	128	128	128	128		128		128		128	
R2 / R2 adjusted	0.318 / 0.302	0.356 / 0.335	0.474 / 0.448	0.503 / 0.461	0.488 / 0.445		0.385 / 0.354		0.462 / 0.416		0.462 / 0.416	

Note. Field code: HUM = 0; STEM = 1. Gender code: Woman = 0; Man = 1.

Supplementary Table 13. Hierarchical regression models testing the role of SCL rate of change and its interactions with math anxiety, neuroticism, field of study and gender in predicting numeracy.

	Step 0		**Step 1**		**Step 2-MA**		**Step 3-MA-F**		**Step 3-MA-G**		**Step 2-N**		**Step 3-N-F**		**Step 3 N-G**	
Predictors	*β* [CI]	*t (p)*	*β* [CI]	*t (p)*	*β* [CI]	*t (p)*	*β* [CI]	*t (p)*	*β* [CI]	*t (p)*	*β* [CI]	*t (p)*	*β* [CI]	*t (p)*	*β* [CI]	*t (p)*
IQ	0.3 [0.15 – 0.45]	**3.94 (<0.001)**	0.3 [0.15 – 0.45]	**3.88 (<0.001)**	0.18 [0.03 – 0.33]	**2.37 (0.019)**	0.13 [-0.02 – 0.28]	1.77 (0.079)	0.19 [0.04 – 0.34]	**2.48 (0.014)**	0.28 [0.13 – 0.43]	**3.64 (<0.001)**	0.23 [0.08 – 0.37]	**3.14 (0.002)**	0.3 [0.14 – 0.45]	**3.77 (<0.001)**
Basic arithmetic skills	0.4 [0.25 – 0.56]	**5.29 (<0.001)**	0.41 [0.26 – 0.56]	**5.32 (<0.001)**	0.33 [0.19 – 0.48]	**4.6 (<0.001)**	0.29 [0.14 – 0.44]	**3.93 (<0.001)**	0.35 [0.20 – 0.50]	**4.75 (<0.001)**	0.4 [0.25 – 0.54]	**5.24 (<0.001)**	0.33 [0.18 – 0.47]	**4.38 (<0.001)**	0.4 [0.24 – 0.55]	**5.14 (<0.001)**
SCL rate of change			-0.05 [-0.20 – 0.09]	-0.71 (0.481)	-0.02 [-0.16 – 0.12]	**-0.3 (0.765)**	0.05 [-0.11 – 0.21]	0.61 (0.546)	0.07 [-0.14 – 0.28]	0.63 (0.53)	-0.07 [-0.21 – 0.08]	-0.9 (0.368)	-0.03 [-0.21 – 0.14]	-0.37 (0.71)	0.04 [-0.17 – 0.24]	0.35 (0.724)
Math anxiety					-0.37 [-0.52 – -0.22]	**-4.91 (<0.001)**	-0.46 [-0.66 – -0.26]	**-4.64 (<0.001)**	-0.48 [-0.69 – -0.28]	**-4.61 (<0.001)**						
SCL rate of change × Math anxiety					0.02 [-0.12 – 0.16]	0.27 (0.789)	-0.04 [-0.18 – 0.11]	-0.46 (0.644)	0.01 [-0.18 – 0.21]	0.12 (0.905)						
Field							0.31 [0.02 – 0.60]	**2.14 (0.034)**					0.51 [0.23 – 0.80]	**3.58 (0.001)**		
SCL rate of change × Field							-0.13 [-0.45 – 0.18]	-0.86 (0.393)					-0.17 [-0.49 – 0.14]	-1.09 (0.278)		
Math anxiety × Field							0.29 [-0.01 – 0.59]	1.88 (0.062)								
(SCL rate of change × Math anxiety) × Field							0.18 [-0.21 – 0.57]	0.91 (0.366)								
Gender									-0.04 [-0.32 – 0.24]	-0.25 (0.805)					0.04 [-0.27 – 0.35]	0.28 (0.776)
SCL rate of change × Gender									-0.18 [-0.50 – 0.14]	-1.12 (0.266)					-0.2 [-0.50 – 0.09]	-1.35 (0.179)

Math anxiety × Gender					0.27 [-0.03 – 0.56]	1.79 (0.075)			
(SCL rate of change × Math anxiety) × Gender					0.02 [-0.34 – 0.37]	0.09 (0.93)			
Neuroticism							-0.16 [-0.30 – -0.01]	**-2.13 (0.035)**	-0.29 [-0.49 – -0.08]	**-2.63 (0.01)**	-0.12 [-0.36 – 0.11]	-0.97 (0.332)
SCL rate of change × Neuroticism							-0.09 [-0.23 – 0.05]	-1.29 (0.201)	-0.16 [-0.34 – 0.02]	-1.78 (0.077)	-0.12 [-0.35 – 0.10]	-1.08 (0.28)
Neuroticism × Field									0.22 [-0.06 – 0.50]	1.49 (0.139)		
(SCL rate of change × Neuroticism) × Field									0.34 [0.04 – 0.65]	**2.25 (0.026)**		
Neuroticism × Gender											-0.04 [-0.35 – 0.28]	-0.23 (0.82)
(SCL rate of change × Neuroticism) × Gender											0.04 [-0.25 – 0.34]	0.3 (0.768)
Observations	129	129	129	129	129	129	129	129				
R2 / R2 adjusted	.320 / 0.310	0.323 / 0.307	0.434 / 0.411	0.478 / 0.439	0.457 / 0.416	0.360 / 0.334	0.457 / 0.416	0.370 / 0.323				

Note. Field code: HUM = 0; STEM = 1. Gender code: Woman = 0; Man = 1.

Supplementary Table 14. Hierarchical regression models testing the role of HF-HRV change and its interactions with math anxiety, neuroticism, field of study and gender in predicting numeracy.

	Step 0		**Step 1**		**Step 2-MA**		**Step 3-MA-F**		**Step 3-MA-G**		**Step 2-N**		**Step 3-N-F**		**Step 3 N-G**	
Predictors	*β* [CI]	*t (p)*	*β* [CI]	*t (p)*	*β* [CI]	*t (p)*	*β* [CI]	*t (p)*	*β* [CI]	*t (p)*	*β* [CI]	*t (p)*	*β* [CI]	*t (p)*	*β* [CI]	*t (p)*
IQ	0.3 [0.15 – 0.45]	**3.96 (<0.001)**	0.28 [0.13 – 0.44]	**3.63 (<0.001)**	0.16 [0.02 – 0.31]	**2.2 (0.03)**	0.12 [-0.03 – 0.27]	1.62 (0.109)	0.16 [0.01 – 0.31]	**2.12 (0.036)**	0.26 [0.11 – 0.42]	**3.44 (0.001)**	0.21 [0.06 – 0.35]	**2.81 (0.006)**	0.25 [0.10 – 0.41]	**3.22 (0.002)**
Basic arithmetic skills	0.4 [0.25 – 0.55]	**5.28 (<0.001)**	0.41 [0.26 – 0.56]	**5.4 (<0.001)**	0.35 [0.21 – 0.50]	**4.83 (<0.001)**	0.34 [0.19 – 0.48]	**4.62 (<0.001)**	0.35 [0.21 – 0.50]	**4.78 (<0.001)**	0.42 [0.26 – 0.57]	**5.43 (<0.001)**	0.36 [0.21 – 0.51]	**4.76 (<0.001)**	0.42 [0.27 – 0.58]	**5.39 (<0.001)**
HF-HRV change			0.1 [-0.05 – 0.25]	1.33 (0.185)	0.08 [-0.06 – 0.22]	1.11 (0.27)	0.16 [-0.02 – 0.35]	1.75 (0.082)	0.04 [-0.15 – 0.24]	0.44 (0.664)	0.1 [-0.04 – 0.25]	1.38 (0.171)	0.21 [0.02 – 0.40]	**2.15 (0.033)**	0.02 [-0.20 – 0.24]	0.14 (0.89)
Math anxiety					-0.34 [-0.49 – -0.18]	**-2.29 (0.024)**	-0.4 [-0.61 – -0.19]	-1.94 (0.055)	-0.47 [-0.68 – -0.27]	**-2.77 (0.007)**						
HF-HRV change × Math anxiety					0.11 [-0.07 – 0.28]	1.22 (0.223)	0.12 [-0.13 – 0.37]	0.95 (0.344)	0.04 [-0.21 – 0.29]	0.32 (0.752)						
Field							0.34 [0.05 – 0.64]	1.2 (0.233)					0.54 [0.25 – 0.82]	**2.12 (0.036)**		
HF-HRV change × Field							-0.17 [-0.45 – 0.12]	-1.16 (0.25)					-0.23 [-0.50 – 0.05]	-1.64 (0.104)		
Math anxiety × Field							0.25 [-0.07 – 0.57]	0.93 (0.353)								
(HF-HRV change × Math anxiety) × Field							-0.04 [-0.39 – 0.32]	-0.2 (0.838)								
Gender									0 [-0.28 – 0.28]	0.62 (0.534)					-0.01 [-0.31 – 0.30]	0.15 (0.884)
HF-HRV change × Gender									0.17 [-0.14 – 0.49]	1.08 (0.283)					0.05 [-0.28 – 0.38]	0.32 (0.753)
Math anxiety ×									0.32 [0.02 –	1.95 (0.053)						

Gender					0.62]									
(HF-HRV change × Math anxiety) × Gender					0.21 [-0.18 – 0.61]	1.07 (0.286)								
Neuroticism							-0.15 [-0.30 – -0.01]	-1 (0.319)	-0.32 [-0.52 – -0.12]	-1.88 (0.063)	-0.1 [-0.34 – 0.13]	0.47 (0.639)		
HF-HRV change × Neuroticism							0.08 [-0.06 – 0.23]	1.12 (0.265)	0.07 [-0.15 – 0.30]	0.66 (0.51)	0.26 [0.01 – 0.51]	**2.1 (0.038)**		
Neuroticism × Field									0.24 [-0.04 – 0.51]	1.22 (0.223)				
(HF-HRV change × Neuroticism) × Field									-0.02 [-0.30 – 0.27]	-0.12 (0.902)				
Neuroticism × Gender											-0.06 [-0.37 – 0.26]	-1.23 (0.22)		
(HF-HRV change × Neuroticism) × Gender											-0.3 [-0.63 – 0.04]	-1.75 (0.083)		
Observations	129		129		129		129		129		129		129	
R2 / R2 adjusted	0.321 / 0.310		0.331 / 0.315		0.447 / 0.425		0.492 / 0.453		0.469 / 0.429		0.363 / 0.337		0.455 / 0.414	0.380 / 0.333

Note. Field code: HUM = 0; STEM = 1. Gender code: Woman = 0; Man = 1.