The role of working memory and inhibition efficiency in mathematics anxiety.

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Abstract

Mathematics anxiety is a feeling of apprehension and, sometimes, fear, that arises in people when they engage in mathematical tasks and has a negative relationship with mathematical performance. A possible reason for this relationship could be that mathematics anxiety might have a detrimental effect on working memory, which then could cause a drop in performance during mathematical tasks. I first assessed the relationship of mathematics anxiety with working memory and inhibition efficiency in university students during mathematical and neutral situations (Chapter 2). Participants with high mathematics anxiety had lower working memory spans and lower inhibition efficiency but being in a mathematical situation or not had no effect on working memory. I then developed a new working memory capacity task and reassessed the relationship between mathematics anxiety and inhibition efficiency using an extreme group design in university students (Chapter 3). Here, participants with high mathematics anxiety tended to have lower inhibition efficiency. Moreover, I carried out a longitudinal study in secondary school students assessing concurrent and longitudinal relationships of mathematics anxiety with mathematical performance, working memory, inhibition efficiency, and mathematics self-belief. In Chapter 4 I describe the significant concurrent relationships between mathematics anxiety, mathematical performance, mathematics self-belief, and working memory. In the longitudinal analysis in Chapter 5 mathematics self-belief did not show a significant longitudinal relationship with mathematics anxiety despite a strong concurrent relationship. This suggests that although mathematics self-belief is a relevant factor to assess when studying mathematics anxiety, it might play a smaller role in the development of mathematics anxiety. In contrast, inhibition efficiency and mathematical performance were significant longitudinal predictors of the development of mathematics anxiety. Overall, my results highlight that poor inhibition efficiency is related to mathematics anxiety in adults and might contribute directly and indirectly to the increase of mathematics anxiety during secondary school.

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Author's Declaration

I declare that this thesis is a presentation of original work and I am the sole author. This work has not previously been presented for an award at this, or any other, University. All sources are acknowledged as References.

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Chapter 1 - Literature Review

1.1 Introduction

Underachievement in mathematics is a very common problem (Cragg & Gilmore, 2014), both during development (Gross, 2007) and in adults (Williams et al., 2003; in Cragg & Gilmore, 2014). Additionally, mathematical competence is a key aspect for successful and high earning jobs (Ancker & Kaufman, 2007; S. L. Beilock & Maloney, 2015; Rubinsten et al., 2015; Vukovic et al., 2013). These findings suggest the study of numerical cognition is an important area of research as it might lead to insights on how to develop evidence-based approaches to improve the quality of mathematical teaching in schools. However, although deficits in mathematical abilities have a more negative effect on employability than reading deficits (Bynner, 2002), research on mathematical difficulties is much less developed than research on reading difficulties (Bishop, 2010).

Understanding how numerical skills are acquired and mathematical concepts develop is an important goal for educational psychology. A better understanding will hopefully provide a foundation for success for many of the students that currently struggle with mathematics.

1.2 Mathematics anxiety

Learning mathematics is a complex process that requires the acquisition of competences over many years, relies on many different skills and is affected by many components such as cognitive components (e.g., working memory; Passolunghi et al., 2008), motivational components (e.g., self-efficacy and self-concept; Pajares & Kranzler, 1995; Pietsch et al., 2003), and affective components (e.g., anxiety; Hembree, 1990). In a longitudinal study, Passolunghi and colleagues (2008) assessed working memory and mathematical performance in students during Year 1 and Year 2 (Italian students start Year 1 at the age of 6, so the participants were 6- and 7-years olds). The authors observed that working memory in Year 1 had a significant positive direct effect on mathematical performance in Year 2 ($\beta = 0.44$). Pajares and Kranzler (1995) assessed mathematics self-efficacy and mathematics achievement concurrently in high school students (from Year 9 to Year 12 students) and found that the participants' confidence in solving mathematical tasks influenced the participants' performance in that task. Similarly, Pietsch and colleagues (2003) found that in high school students (from Year 9 to Year 10 students) mathematics self-efficacy and mathematics self-concept were significant predictors of concurrent performance in mathematical tasks. Finally, Hembree (1990) produced a meta-analysis highlighting how mathematics anxiety consistently shows a moderate negative relationship with mathematical performance. This last factor, mathematics anxiety, is currently the most studied affective component affecting mathematical performance (Dowker et al., 2016).

Mathematics anxiety is a personal experience of apprehension that arises in people that have to deal with mathematics. Since Hembree's (1990) meta-analysis most of the research in mathematics anxiety found a negative relationship between mathematics anxiety and mathematical performance (e.g., Dowker et al., 2016; Hembree, 1990; Ma, 1999; Passolunghi et al., 2016). In fact, the relationship is so common that some teachers might view mathematics anxiety as a synonym of "being bad at math" (Beilock & Willingham, 2014). However, mathematics anxiety is not a mere synonym for "being bad at math". For example, there are individuals with high performance in mathematics who still suffer from mathematics anxiety (Lee, 2009). Because mathematics anxiety is not a synonym of being bad at math, it is important to study how mathematics anxiety develops and why it shows a negative relationship with mathematical performance.

Mathematics anxiety can have physical repercussions and long term effects (Lyons & Beilock, 2012b; Suaŕez-Pellicioni et al., 2013). Suaŕez-Pellicioni and colleagues (2013) found that participants with high levels of mathematics anxiety perceived numerical errors (i.e., in this case responding to the bigger in font size than in magnitude) as more salient than regular errors in a classical (i.e., non-numerical) Stroop task compared to participants with low mathematics anxiety. The authors proposed that this abnormal error monitoring can be perceived as a painful experience. Accordingly, Lyons and Beilock (2012) assessed brain activation before and during mathematical tasks and found that anticipation of mathematical tasks activates the pain network in participants with high levels of mathematics anxiety.

Multiple models (Ashcraft & Moore, 2009; Carey et al., 2016; Rubinsten et al., 2018) have been developed trying to explain the genesis and development of mathematics anxiety. For the current set of studies, it is useful to briefly introduce the model developed by Maloney and colleagues (Maloney, 2020, May). The model can be seen in Figure 1.1.

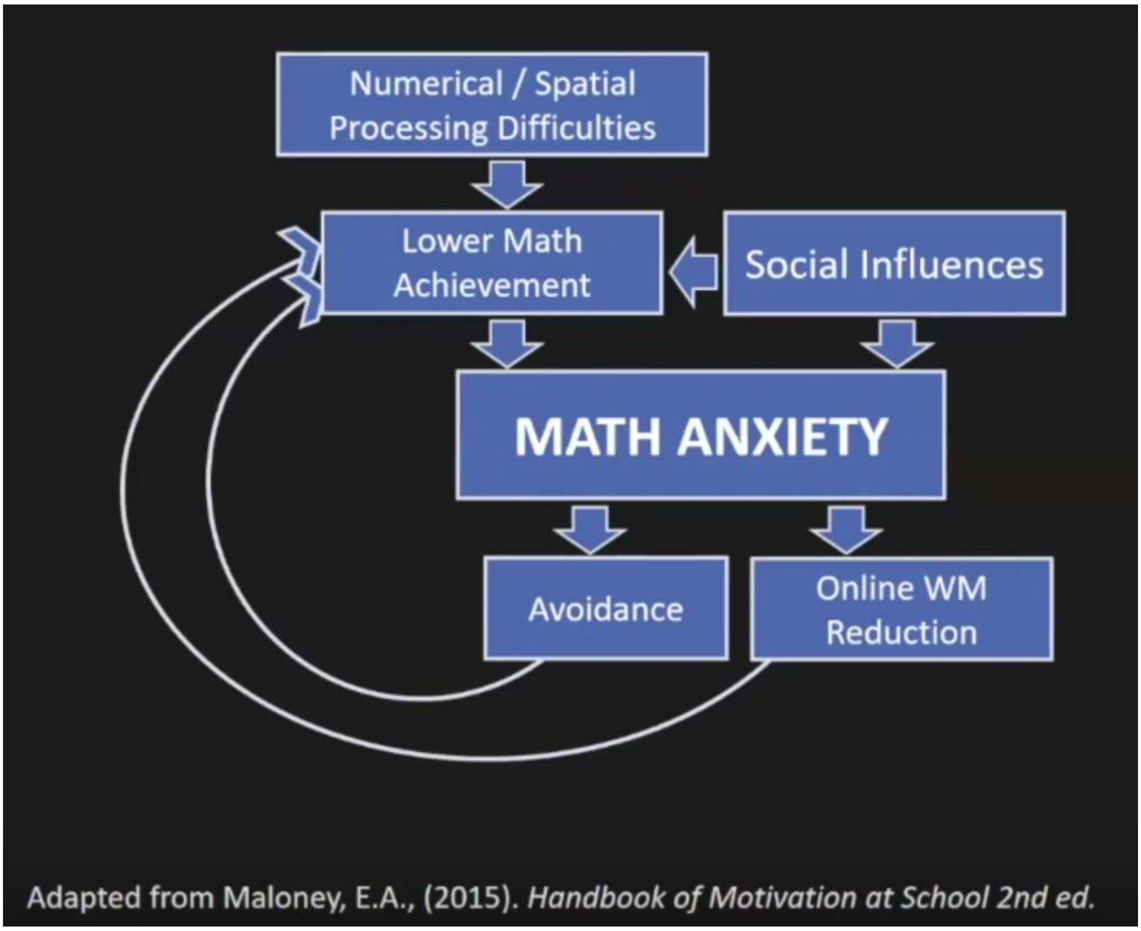

Figure 1.1. Maloney's model of mathematics anxiety (Maloney, 2020, May)

Maloney's model suggests that the first step is the presence of either numerical or spatial processing difficulties. Because spatial and numerical processing are important factors in mathematical processing, these difficulties can cause lower mathematical performance. The lower mathematical performance then is a risk factor for the genesis and the development of mathematics anxiety. The development of mathematics anxiety can lead to avoidance behaviours and an online reduction of working memory capacity. The avoidance behaviours mean that the person will avoid mathematical situations and thus lose learning opportunities and show less improvement than their peers, which will also cause further growth of their mathematics anxiety. Online working memory reduction is due to the presence of anxious thoughts and rumination during the processing of mathematical information (Maloney, 2020, May). These thoughts and ruminations work as a second task putting extra load on the cognitive resources, making it more difficult for the person to process the mathematical material. The added difficulty means that the person will be more likely to fail the task, causing further growth of the mathematics anxiety.

Maloney's model includes another factor that influences both mathematics achievement and mathematics anxiety: social influences, such as the role that parents and teachers have on the development of mathematics anxiety. For example, if parents or teachers feel insecure about their own mathematical skills, they might influence the person to feel insecure in front of mathematical material. Another interesting model that has been developed to explain mathematics anxiety was developed by Rubinsten and colleagues (2018). This model has some points in common with the model presented above, such as the importance of social factors and numerical skills but includes a more detailed and complete list of factors that influence mathematics anxiety, such as genetic risk factors and brain functions. However, the main purpose of Rubinsten's model is to offer a wide all-encompassing framework to study mathematics anxiety and much of it is beyond the scope of the current thesis which focuses on the role of working memory for mathematics anxiety. For these reasons it will not be discussed further here.

Of the factors proposed in Maloney's model, this thesis will focus on the cognitive factors such as mathematical performance and working memory, and the affective factors, such as mathematics anxiety. The current work will include some affective factors not included in Maloney's model: trait (or general) anxiety, test anxiety, and mathematics self-belief.

1.2.1 Measurements of mathematics anxiety

Given the importance of understanding how mathematics anxiety works, researchers have been developing different measures to assess this complex factor. Most research uses self-report questionnaires, but there are also examples of behavioural measures (physiological measures and implicit measures) of mathematics anxiety. I will now present an overview of these measures.

Questionnaires: The most common method to assess mathematics anxiety is through the use of questionnaires. Questionnaires used in mathematics anxiety research are usually self-report scales, meaning that the participant needs to assess how they feel during specific situations. The descriptions involve situations in which the participant needs to deal with mathematical information (e.g., calculating the tip at a restaurant, or having to sit a mathematical test). The self-assessment is usually through the use of a Likert scale that should help the participant to anchor the amount of anxiety perceived in the specific situation. The scale usually goes from one extreme (no anxiety) to the other extreme (highest level of anxiety experienced in their own life).

The first questionnaire developed to assess mathematics anxiety was the Mathematics Anxiety Rating Scale (MARS; Richardson & Suinn, 1972). This questionnaire is comprised of 98 items and the participants can answer on a 5-point Likert scale how anxious they feel in specific situations. For each item, the scale goes from 1 (not anxious) to 5 (very anxious). An example of situations can be 'to solve 976 + 777 in their own head'. The scale is supposed to be used only in adults. To overcome this limitation, in 1982 the MARS items were simplified and items involving secondary school situations were added. This process allowed the creation of the MARS-A (Suinn & Edwards, 1982; in Gilmore et al., 2018). Moreover, in 1988 the MARS was adapted to be used with primary school students from Year 4 through Year 6 (MARS-E, Suinn et al., 1988; in Wu et al., 2012). Furthermore, because MARS is a lengthy and complex questionnaire with 98 items, more recent versions tried to make it shorter and easier to use. Alexander and Martray developed the shortened MARS (sMARS, Alexander & Martray, 1989) with 25 items. Another short version was created by Suinn and Winston (2003). The instructions are the same as the MARS and involve expressing how anxious the participants feel during various situations. Examples of the questions are: "Studying for a mathematic test", "Getting ready to study for a mathematic test", "Figuring the sales tax on a purchase that costs more than $1.00" (Suinn & Winston, 2003, p. 169). Finally, it can be interesting to mention the Revised Mathematics Anxiety Rating Scale (MARS-R; Plake & Parker, 1982), which is a shorter version of the MARS that consists of 24 items to be used with adults.

Another questionnaire that is widely used in mathematics anxiety research is the Abbreviated Math Anxiety Scale (AMAS; Hopko et al., 2003). The AMAS is a shortened version of the MARS-R. With only 9 items it is a very quick and slim questionnaire with high test-retest reliability (r = .85) and good reliability (Cronbach's α of .90). Given its shortness and its reliability, it is widely used as a fast and efficient way to measure mathematics anxiety. Although it is developed to be used with adults, some researchers use it also with secondary school students (Passolunghi et al., 2016), and even with primary school students (Hill et al., 2016).

Most of the questionnaires that were presented up to this point were developed to be used with adult participants or older students. Because the language used and the situations depicted are not always appropriate for younger samples, some researchers decided to develop questionnaires specifically for younger participants. An example is the Scale for Early Mathematics Anxiety (SEMA; Wu et al., 2012), which is based on the MARS and the MARS-E, but it was developed to be used with children in Year 2 and Year 3. It is composed of 10 items based on the typical US mathematical curriculum of Year 2 and Year 3, and 10 items based on math-related social and testing situations that are common for children in Year 2 and Year 3. The questionnaire showed high internal consistency (Cronbach's α of .87) and good reliability (split-half reliability of .774; Wu et al., 2012).

Another questionnaire for younger participants is the Math Anxiety Questionnaire (MAQ; Thomas & Dowker, 2000; in Dowker et al., 2016), which is used to assess mathematics anxiety in children from 6 to 9 years old and has 28 items. Some researchers suggest that mathematics anxiety can be divided into two aspects: cognitive and affective mathematics anxiety (Dowker et al., 2016). This division in cognitive and affective mathematics anxiety was first observed by Wigfield and Meece (1988) with exploratory and then with confirmatory factor analysis. The cognitive dimension refers to the cognitive consequences, for example, the worrisome thoughts that accompany the experience. The affective dimension instead refers to the emotions that accompany the anxious experience. Dowker suggests that MARS and its derivations tap more on the affective aspects, whereas MAQ "places more emphasis on the cognitive ("worry") aspect of mathematics" (Dowker et al., 2016, p.9).

Physiological measures: Self-report measures are not always accurate, as our own perceptions might be biased (Gilmore et al., 2018). Moreover, answers to self-report questionnaires can be controlled, hence participants can lie to conform to norms, or to give a specific idea of themselves (Mammarella et al., 2019). To overcome this obstacle, some authors developed new measures that do not rely on self-report and memory. One type of these newly developed measures are the implicit measures that we will discuss later on, and another type are the physiological measures. One example of a physiological measure is measuring cortisol secretion, which is believed to be a response to stress (e.g., Mattarella-Micke et al., 2011). Mattarella-Micke et al. (2011) observed that mathematical performance in participants with high mathematics anxiety and high working memory was dependent on the increase of cortisol secretion during the task. Other physiological measures are reported in a review by Dowker and colleagues (2016). The authors reported heart rate, skin conductance, and brain imaging as physiological measures. Heart rate is considered a measure of arousal, hence the higher is the heart rate of a person in a given moment, the higher their arousal will be. If we measure heart rate during the execution of mathematical tasks and compare it to heart rate during a baseline task, any change in heart rate between the baseline task and the mathematical task might be partly due to mathematics anxiety. Skin conductance is also a measure of arousal level, with higher skin conductance associated with higher levels of arousal (Hopko et al., 2003). Regarding brain imaging, there are studies using EEG (Electroencephalogram), and fMRI (functional Magnetic Resonance Imaging) (for a review, see Dowker et al., 2016). For example, fMRI studies recorded different brain activation patterns between participants with high and low mathematics anxiety (Lyons & Beilock, 2012b; Young et al., 2012).

While results from brain imaging techniques such as EEG and fMRI do not seem appropriate for the independent measure of mathematics anxiety, other physiological measures, such as pupillometry (Caviola & Szűcs, 2018), heart rate variability, and skin conductance, might emerge in the future as useful independent measures of mathematics anxiety. For example, heart rate variability is the measure of the variation of the interval between two heartbeats (Laborde et al., 2017), and is a measure that can be used to assess stress levels. The reduction of the variability is associated with higher levels of stress (Dishman et al., 2000), and it has been found to correlate with different types of anxiety. Kawachi and colleagues (1995), for example, observed that reduced heart rate variability has been found in participants with specific phobias. Accordingly, Miu, Heilman, and Miclea (2009) found reduced heart rate variability in participants with high test anxiety. These results seem to suggest that heightened arousal could be associated with reduced heart rate variability. For this reason, it could be an interesting future area to investigate in the quest to find more appropriate physiological measures for mathematics anxiety.

Implicit measures: implicit measures are used to assess automatic cognitive processes. Given the automatic nature of these processes, the participants are not aware of them, so self-report measures would not be able to assess them. One example of an implicit measure is affective priming. Affective priming can be used, for example, to evaluate the implicit valence of mathematics by assessing the effect of an attentional prime on the target stimulus. A prime is a stimulus that should be ignored, but that is supposed to actually influence the response to a succeeding stimulus (Rubinsten & Tannock, 2010). Similarly, Rubinsten and Tannock (2010) described the affective priming. Affective priming involves an emotionally charged stimulus that can help the processing of future stimuli if they are affectively related. For example, words that are associated with positive emotions will allow faster processing of other words that are associated with positive emotions. At the same time, they will render the processing of words that are associated with negative emotions more difficult. In participants with high mathematics anxiety, for example, arithmetical primes could work as affective primes and should facilitate the processing of negative words, meaning that for individuals with high mathematics anxiety words related to mathematics are words associated to negative emotion. Rubinsten and colleagues (2012) suggested that the negativity effect of arithmetical primes can be used as an implicit measure of mathematics anxiety. Another way to implicitly measure mathematics anxiety is through the use of emotional Stroop tasks. Using either neutral stimuli or math-related words we can assess the difference in processing time between the two conditions to assess the cognitive effects of mathematics anxiety. Suárez-Pellicioni and colleagues (2015) observed that participants with high mathematics anxiety are slower than the participants with low mathematics anxiety when the words are math-related. Importantly, implicit and explicit measures of mathematics anxiety are not significantly related to each other (Daches Cohen & Rubinsten, 2017), hence it can be suggested that future studies might want to assess implicit and explicit measures separately to better understand the specific relationships with other constructs. Although the implicit measures of mathematics anxiety do not seem to be significantly related to explicit measures of mathematics anxiety (i.e., self-report questionnaires), the further development of these measures can be useful because implicit measures of mathematics anxiety are related to other environmental factors and might show novel relationships with relevant factors giving new insights in the mechanisms that underlie the development of mathematics anxiety.

In conclusion, at the moment most research in mathematics anxiety still use self-report questionnaires. One reason why questionnaires are still used is that they show good reliability (e.g., SEMA Cronbach's α = .87; MARS Cronbach's α = .94; for a review, see Dowker et al., 2016). Questionnaire results are typically summarised as a single total score, although factor analyses suggest that the questionnaires usually assess multiple factors (Lukowski et al., 2016; Rounds & Hendel, 1980). For example, Rounds and Hendel (1980) analysed the factor composition of the MARS and found two different factors, test anxiety and numerical anxiety. Based on that analysis the authors constructed two different scales each with 15 items from the MARS. The two scales showed a moderate relationship (r = .34). More recently, Lukowski and colleagues (2016) assessed the MARS-E and concluded that it was measuring three different factors; calculation anxiety, test anxiety, and classroom anxiety. Because each questionnaire is different from the others, different questionnaires might measure different factors, hence it is always important to choose carefully which measure to use.

In the behavioural studies with adult participants, I will use the AMAS. I decided on the AMAS because it is a reliable and fast method to assess mathematics anxiety, and this has been particularly useful in collecting big samples, such as the screening phase of the second behavioural study. The AMAS is reported in Appendix A.3. A typical item asks the participant, for example, to rate from 1 to 5 how anxious they would feel while listening to a lecture in a math class. In the longitudinal study with secondary school students, I will adapt the Revised Mathematics Anxiety Rating scale (RMARS; Taylor & Fraser, 2013) to be used with students in Year 7. I decided on this questionnaire because it showed good reliability (Cronbach's alpha > .90) and is supposed to allow a more sensitive measure given that with 27 items there is more chance for variability. Further information on the RMARS can be found in the methods section of the Time 1 analysis (please see chapter 4.2.2.1, page 135).

1.2.2 Mathematics anxiety and its relationship with other types of anxiety

Fear is a part of the human's emotional nature and usually is a "healthy adaptive response to a perceived threat or danger to one's physical safety and security" (Clark & Beck, 2011, p.4). Normally fear is useful since it prepares the body to respond to a threat, but it can be maladaptive when it occurs in non-threatening situations. Fear in non-threatening situations is called anxiety (Clark & Beck, 2011). Anxiety is defined as a future-oriented emotion, with feelings of uncontrollability and unpredictability over only potentially aversive events (instead of actually dangerous events) and is accompanied by a rapid shift of the attentional focus to threat-related events and/or the personal response to these events. Another distinction between fear and anxiety is that while fear is a response of contact with a stimulus (therefore is transitive), anxiety is a more stable and longer state of perceived threat (Clark & Beck, 2011).

The studies presented in this thesis focus on one type of anxiety: mathematics anxiety. Mathematics anxiety, according to Zettle (2003), should be seen as a specific 'phobia' since mathematics anxiety is characterized by fear toward very specific objects or situations. Zettle's view is supported by Young and colleagues' (2012) work, in which they suggest that mathematics anxiety is stimulus- and situation-specific. Mathematics anxiety overlaps with other types of anxiety; more specifically it has been suggested that mathematics anxiety shares variance with test anxiety and general anxiety. Test anxiety is anxiety about testing situations. Hembree (1990) reported a strong and positive relationship between mathematics anxiety and test anxiety (r = .52). General anxiety, also called trait anxiety, instead is a more stable tendency of the person to experience anxiety. Mathematics anxiety is also significantly related to trait anxiety. For example, Hembree (1990) reported a significant positive correlation between trait anxiety and mathematics anxiety (r = .35). These findings suggest that trait and test anxiety are relevant factors that should be considered when addressing the development and the effects of mathematics anxiety.

1.2.3 Prevalence of mathematics anxiety

Generally speaking, anxiety is a very common problem with roughly 25~30% prevalence of at least one anxiety disorder in the general population at a certain point in the life-time (Clark & Beck, 2011). However, assessing the prevalence of mathematics anxiety is a more complex task. Mathematics anxiety is not a recognized disorder and there are no specific recommended cut-off values of the self-report questionnaires that would pinpoint where it starts being problematic, and where it is not. Thus, it is important to report the chosen cut-off values. Nevertheless, some researchers give estimates of the prevalence of mathematics anxiety. For example, Cornoldi (1999) reported that 38% of students in primary school felt uneasy during mathematical tests, and 62% showed fear of mathematics. The 2003 PISA report showed that more than 50% of the 15-year-old students that participated reported feelings of anxiety when asked to solve mathematical problems (Suaŕez-Pellicioni et al., 2013). Even though there is not a specific definition for a mathematics anxiety disorder, the data presented here suggest that mathematics anxiety is very common.

1.2.4 Mathematics anxiety and gender

Studies suggest that females tend to experience higher levels of mathematics anxiety (Goetz et al., 2013; Hill et al., 2016; Jain & Dowson, 2009). For example, Goetz and colleagues (2013) assessed mathematics anxiety in two different studies, examining students from Year 5 to Year 11. The authors observed a significant difference between the scores reported by males and females in mathematics anxiety in both studies. Accordingly, Hill and colleagues (2016) found that in their study female participants scored higher on the AMAS questionnaire than male participants. Jain and Dowson (2009) assessed mathematics anxiety in Indian Year 8 students and observed that female students reported higher levels of mathematics anxiety than their male schoolmates. But does that mean there is a difference in mathematics anxiety between males and females, or is it due to a difference in the tendency to self-report difficulties? Rubinsten's study using affective priming tried to assess this (Rubinsten et al., 2012). Rubinsten's findings suggest that -while there might be a higher tendency to report anxiety issues in females (Egloff & Schmukle, 2004), there is also evidence from implicit measures of mathematics anxiety that there seems to be higher mathematics anxiety in female participants. This suggests that the higher levels of mathematics anxiety recorded by most researchers is due to actual differences in mathematics anxiety and not to self-report bias. However, not all research agrees in finding higher levels of mathematics anxiety in females. In fact, some researchers failed to find significant gender differences between males and females (Ramirez et al., 2013). Ramirez and colleagues (2013) assessed mathematics anxiety in students in Year 1 and Year 2. The authors did not observe a significant difference in the levels of mathematics anxiety in female and male students. Given the differences in the age of the participants between those studies, the gender differences may be age-dependent. There may be no gender difference in the first two years of primary school, but gender differences might emerge over later school years.

Moreover, as discussed in more detail later in this literature review, most available literature suggests a relationship between mathematics anxiety and mathematical performance.

The strength of this relationship might also be different between males and females; although how gender interacts with this relationship is still under debate. For example, some studies suggest that mathematics anxiety has stronger effects on males' mathematical performance than on females' one (Hembree, 1990; Miller & Bichsel, 2004). In contrast, Devine and colleagues (2012) assessed mathematics anxiety and mathematical performance in secondary school students and found that the relationship was significantly stronger for female than for males students. Finally, Ma's (1999) meta-analysis failed to find any significant gender differences in the relationship between mathematics anxiety and mathematical performance. Accordingly, also Meece and colleagues (1990) did not observe a significant difference in this relationship between female and males students. This argument will be further discussed in Chapter 4, to attempt to shed more light into the effect of gender in the mathematics anxiety – mathematical performance relationship. At the moment, however, it can be argued that there are reasons to believe that the relationship between mathematics anxiety and mathematical performance might be different between females and males and that for this reason, it is important to investigate gender effects in any study of mathematics anxiety.

One of the reasons why it is so important to study the gender differences in mathematics anxiety and mathematical performance is that researchers suggest that the gender gap in mathematics anxiety is one of the main reasons for the underrepresentation of women in STEM areas (e.g., Wu et al., 2012).

1.2.5 Mathematics anxiety and mathematics self-belief

Mathematics anxiety has also shown strong relationships with other self-measures that are important when studying mathematical performance. Between the self-measures, the most relevant for the current work are two measures of mathematics self-belief: mathematics self-efficacy and mathematics self-concept.

Mathematics self-efficacy is based on Bandura's (1997) self-efficacy construct. Self-efficacy is the self-assessment of our own competence, i.e., how effective we think we are in tackling different tasks. Bandura's theory suggests that behaviour changes in response to one's self-efficacy expectations, and these expectations can be either strengthened or weakened by the feedbacks that the individuals receive. Mathematics self-efficacy is how competent and effective a person perceives themselves to be in solving mathematical tasks. Participants with higher levels of self-efficacy are more confident in their ability, and this confidence will likely result in better performances compared to people with a lower level of self-efficacy. Past research found indeed that mathematics self-efficacy is an important predictor of mathematical performance, with standardized β-values that vary between .27 (Pajares & Graham, 1999) to .55 (Pajares & Miller, 1994). Moreover, zero-order correlations also suggest a significant positive relationship between mathematical performance and mathematics self-efficacy (r = .59; Pajares & Graham, 1999). Mostly, self-efficacy has been studied in adults, but as Jain and Dowson (2009) point out, the developmental differences between adults and children may result in differences in the relationship between self-efficacy and performance, thus suggesting that studying self-efficacy developmentally and in younger participants might lead to deeper insights about the aforementioned relationship.

Available evidence suggests that mathematics self-efficacy and mathematics anxiety are inversely related (Jain & Dowson, 2009; Mcmullan et al., 2012; Pajares & Graham, 1999; Pajares & Miller, 1994), i.e., typically for higher levels of mathematics self-efficacy people show lower levels of mathematics anxiety. McMullan and colleagues (2012) reported a strong and negative relationship between mathematics anxiety and mathematics self-efficacy (r = -.63). Jain and Dowson (2009) assessed the concurrent relationship between mathematics anxiety and self-efficacy in Year 8 students and found that self-efficacy was a significant predictor of mathematics anxiety (β = -.43). In line with these results, Pajares and Miller (1994) and Pajares and Graham (1999) also reported a strong and significant negative relationship between mathematics anxiety and mathematics self-efficacy (r = -.56 & r = -.61 respectively). These findings suggest that mathematics self-efficacy is an important factor to consider when studying mathematics anxiety.

Mathematics self-concept is similar to self-efficacy because it is also related to a person's perception of their own mathematical ability. However, it differs from self-efficacy by being measured at a broader level, whereas self-efficacy is measured at a specific level (Pajares & Miller, 1994). Whereas self-efficacy is supposed to assess one's own perceived capabilities in a specific situation (e.g., performing an addition), self-concept assesses the perceived competence of oneself in a general area of behaviour (e.g., mathematics in general). Similarly to what we observed for mathematics self-efficacy, mathematics self-concept is also inversely related to mathematics anxiety. Pajares and Miller (1994) observed that there was a strong negative relationship between mathematics self-concept and mathematics anxiety (r = -.87). In line with these results, a strong negative relationship between mathematics anxiety and mathematics self-concept was also found in Pajares and Graham's (1999) study (r = -.68) and in Lee's (2009) study (r = -.67).

Mathematics self-concept and mathematics self-efficacy assess similar and related concepts. Accordingly, research has suggested a strong positive relationship between these factors. Pajares and Graham (1999) observed a significant positive relationship between mathematics self-efficacy and mathematics self-belief (r = .66) as did Pajares and Miller (r = .61; 1994) and Lee (r = .52; 2009). Moreover, mathematics self-concept is also positively related to mathematical performance. For example, Kung (2009) observed concurrent (γ = .69) and longitudinal (β = .37) paths from mathematics self-concept to mathematical performance.

Given the strength of the relationships between mathematics anxiety, mathematics self-efficacy, and mathematics self-concept, it is worth to assess whether the three constructs are separate factors, or whether they are different sides of the same coin. Lee (2009) used the data from the 2003 PISA study to assess the factor composition of the three concepts. Results from an exploratory factor analysis as well as from a confirmatory factor analysis suggested a three-factor solution with separate factors for mathematics anxiety, for mathematics self-belief, and for mathematics self-efficacy.

1.2.6 The development and potential causes of mathematics anxiety

Mathematics anxiety is not a stable and immutable factor, but research has suggested that it develops during the primary and secondary school years, plateauing and stabilising in late adolescence (Hembree, 1990; Ramirez et al., 2013; Young et al., 2012). An influential work on the development of mathematics anxiety is the meta-analysis by Hembree (1990). Hembree suggested that mathematics anxiety tends to increase during development, reaching its peak during high school years (Year 9 to Year 10) and levels off after that. However, this meta-analysis offered little insight into when mathematics anxiety starts to develop. In fact, Ramirez and colleagues (2013) suggested that "although math anxiety has been extensively studied, little is known about the emergence of math anxiety in young children." (Ramirez et al., 2013, p.188). It is however becoming clearer and clearer that mathematics anxiety is already present in primary school students, and that students as early as in Year 1 and Year 2 of primary school already report experiencing mathematics anxiety (Ramirez et al., 2013; Young et al., 2012). It is still unclear and important to understand, however, what causes the emergence and development of mathematics anxiety. One factor that seems important is mathematical performance. Literature has suggested that better mathematical performance might work as a longitudinal protective factor against the development of mathematics anxiety as early as during the first and second years of primary school (Gunderson et al., 2018). Similar findings have been found for Year 6 to Year 7 students (Geary et al., 2019) and secondary school students (Wang et al., 2020). These results suggest that mathematical performance is an important factor to consider when investigating the development of mathematics anxiety. Other factors that have been suggested as relevant in the development of mathematics anxiety are the teachers' teaching methods, parents' attitudes toward mathematics, and fear of failure (for a review, see Mammarella et al., 2019). These factors can be considered part of the social factors in Maloney's model of mathematics anxiety (Maloney, 2020, May). As discussed in Maloney's model, these social factors might have direct effects on mathematics anxiety, and at the same time indirect effects as they might influence mathematical performance which then influences mathematics anxiety.

There might also be neurodevelopmental risk factors for the development of mathematics anxiety. For example, Young and colleagues (2012) assessed mathematics anxiety and brain activation pattern in children aged 7 to 9 years while they were performing mathematical tasks (i.e., additions and subtractions). Children with high mathematics anxiety showed different patterns of brain activation. The high mathematics anxiety children presented higher activation in, and abnormal effective connectivity of, the amygdala compared with their low mathematics anxiety peers. This finding is not surprising as the amygdala is a brain region involved in the processing of fearful stimuli and negative emotions (such as anxiety). However, the authors observed also an abnormal activation in areas involved in cognitive processes in children with high mathematics anxiety when compared with children with low mathematics anxiety. In fact, high mathematics anxiety children showed lower activation of the IPS (Intraparietal Sulcus), an area that has been implicated in the processing of numerical stimuli (Dehaene et al., 2003; in Young et al., 2012). The authors also observed lower activation of the right dorsolateral prefrontal cortex. The right dorsolateral prefrontal cortex is an area implicated in the ability to make choices while situations are changing, specifically through inhibition mechanisms (Konishi et al., 1999). This suggests that the observed brain activation pattern could be an expression of lower inhibition in the participants. Moreover, abnormal patterns of brain activation were also observed in the premotor cortex, in the bilateral caudate, in the putamen, and in the ventromedial prefrontal cortex (Young et al., 2012). The premotor cortex is an area involved in space perception, action understanding, and imitation (Rizzolatti et al., 2002). The bilateral caudate is an area that has been implied in decision making and in supporting the planning and execution of strategies and behaviours that are required for achieving complex goals (Grahn et al., 2008). The putamen has been suggested as the area where stimulus-response functions are processed (Grahn et al., 2008) and the ventromedial prefrontal cortex is an area that has been implied to be involved in the regulation of negative emotions (Etkin et al., 2010; in Young et al., 2012). However, these differences in brain activation could be causes or consequences of having mathematics anxiety, the results are purely correlational and cannot inform the questions about causality regarding the development of mathematics anxiety. Still, these results suggest that specific neural pathways show abnormal activation in children with mathematics anxiety.

Some authors also propose that there might be genetic causes for mathematics anxiety, such as Wang and colleagues (2014). Wang and colleagues suggested that genetic risk factors related to general anxiety and mathematical problem solving might play a significant role in the development of mathematics anxiety. In line with Wang and colleagues, other large scale studies with twins (e.g., Malanchini et al., 2017) found estimates of heritability of mathematics anxiety. Wang and colleagues (2014) observed that 9% of the variance in mathematics anxiety is associated with genetic influences shared with general anxiety. Moreover, the author observed that 12% of the variance in mathematics anxiety is associated with genetic influences shared with mathematical problem-solving. In addition to these findings, Malanchini and colleagues (2017) observed that 58% of the shared variance between mathematics and general anxiety is due to shared genetic factors, and 42% is due to environmental factors.

Finally, mathematics anxiety has troubling long-term effects. One consequence of mathematics anxiety that has been observed is global avoidance (Hembree, 1990; Hopko et al., 2003), i.e., people with high mathematics anxiety are more likely to avoid mathematical tasks. For example, students with high mathematics anxiety might avoid doing mathematics homework and thus may miss many mathematical learning opportunities (Passolunghi, 2011). Support for the global avoidance comes, for example, from studies showing that mathematics anxiety is negatively related to intrinsic motivation to study mathematics (*r* = -.33; Daches Cohen & Rubinsten, 2017). Global avoidance can also drive people away from math-related university courses and, eventually, careers (Hembree, 1990). Because mathematics anxiety does not disappear in adulthood, it is important to study mathematics anxiety and to find effective ways to reduce the impact of mathematics anxiety in both children and adults.

1.3 Mathematics anxiety and mathematical performance

Another reason why it is important to study mathematics anxiety is that mathematics anxiety has consistently been found to show a moderate negative relationship with mathematical performance (e.g., Ashcraft & Kirk, 2001; Hembree, 1990; Mammarella et al., 2019; Passolunghi et al., 2016). Most research in mathematics anxiety investigates the relationship between mathematics anxiety and a wide range of mathematical tasks (Ashcraft & Faust, 1994; Ashcraft & Kirk, 2001; Hembree, 1990; Maloney et al., 2010). For example, Ashcraft and Faust (1994) reported that participants with low mathematics anxiety were significantly faster and more precise in answering complex mathematical problems. Hembree's (1990) meta-analysis reported a significant moderate negative relationship between mathematics anxiety and performance on different mathematical tasks [from mathematics anxiety and mathematical computation (*r* = -.25; Hembree, 1990) to mathematics anxiety and abstract reasoning (*r* = -.40; Hembree, 1990)]. On the other hand, some authors focused on the relationship between mathematics anxiety and specific types of mathematical tasks(Miller & Bichsel, 2004; Passolunghi et al., 2016; Vukovic et al., 2013). For example, Miller and Bichsel (2004) assessed the relationship between mathematics anxiety and two different types of mathematical performance. The first task assessed basic mathematical performance by asking participants to process mathematical problems from simple additions to complex geometry and trigonometry. The second task assessed applied mathematical performance by requiring the participants to answer to an applied mathematical problem presented orally (e.g., calculate how many miles a car has travelled given a certain amount of speed and time). The authors found that mathematics anxiety was negatively related to both applied mathematical performance (r = -.32) and basic mathematical performance (r = -.41). Similarly, Passolunghi and colleagues (2016) assessed the difference between secondary students with high mathematics anxiety and secondary students with low mathematics anxiety using different types of mathematical tasks. Students with high mathematics anxiety showed lower performance in tasks that required complex calculations (i.e., written calculation and fact retrieval sub-tests), but neither in tasks with approximate calculations nor in their ability to process syntactical number information (i.e., place-value comprehension). Vukovic and colleagues (2013) assessed mathematical and geometrical reasoning and found a relationship between mathematics anxiety and mathematical reasoning (r = -.36), but not between mathematics anxiety and geometrical reasoning (r = -.12).

While it is clear that mathematics anxiety and mathematical performance are typically correlated in secondary school students and adults (e.g., Hembree, 1990; Hill et al., 2016; Passolunghi et al., 2016), it is currently still unclear when that relationship emerges. In fact, although it is becoming evident that mathematics anxiety can already be present in primary school, whether mathematics anxiety is already negatively related to mathematical performance in primary school is still under debate. On one hand, some studies (e.g., Hill et al., 2016; Krinzinger et al., 2009) did not find a significant relationship between mathematics anxiety and mathematical performance in primary school students. On the other hand, other authors did find a relationship between mathematics anxiety and mathematical performance in primary school students (e.g., Harari et al., 2013; Wu et al., 2012). Hill and colleagues (2016) assessed mathematics anxiety and mathematical performance in primary and secondary school students. The authors found that in female primary school students there was already a significant negative relationship between mathematics anxiety and mathematical performance. However, this relationship was no longer significant once the effect of general anxiety was partialled out. Moreover, zero-order correlations between mathematics anxiety and mathematical performance in male primary school students showed no significant relationship. These results suggest that the relationship between mathematics anxiety and mathematical performance was not present in primary school students. Additionally, Krinzinger and colleagues (2009) assessed mathematics anxiety and mathematical performance from Year 1 through Year 3. The authors did not observe concurrent significant relationships between mathematics anxiety and mathematical performance in Year 1 students. On the other hand, Harari and colleagues (2013) found a significant negative relationship between mathematics anxiety and mathematical performance. More specifically, mathematics anxiety had a significant negative relationship with students' counting skills (β = -.23) and mathematical concepts (β = -.34). Finally, Wu and colleagues (2012) also suggested that mathematics anxiety is already present in primary school students and that it already shows a relationship between mathematics anxiety and mathematical performance, even after partialling out trait anxiety and IQ (β = -.26).

To sum up, overall, higher mathematics anxiety is often related to lower mathematical performance even after other types of anxiety have been controlled for. However, it is still an area of active debate whether lower mathematical performance causes higher mathematics anxiety or whether higher mathematics anxiety leads to lower mathematical performance or both. The current debate can be categorised into three different approaches: the Deficit Theory, the Debilitating Anxiety Model, and the Reciprocal Theory (Carey et al., 2016).

1.3.1 The Deficit Theory

According to the deficit theory (Carey et al., 2016) mathematics anxiety is the result of a basic mathematical deficit and consequent common experiences of failures in mathematical tasks. Experiencing repeated failure in mathematical tasks is proposed to lead to the development of mathematics anxiety. According to this theory, people with high mathematics anxiety show also poor mathematical performance simply because they are bad at mathematics. This framework can be considered as a skill development approach (Abu-Hilal, 2000); meaning that according to this approach, affective variables (in this case mathematics anxiety) are the consequences of differences in achievement. Support for the deficit theory comes from some longitudinal studies of typically developing children and studies on children with mathematical learning disabilities (e.g., Ma & Xu, 2004; Passolunghi, 2011; Rubinsten & Tannock, 2010). For example, Ma and Xu (2004) assessed mathematics in students in Year 7 and followed them until Year 12. The authors observed that mathematics achievement had a consistent negative longitudinal effect on the development of mathematics anxiety; i.e., lower mathematical performance at Time 1 was associated with higher mathematics anxiety at Time 2; and lower mathematical performance at Time 2 was associated with higher mathematics anxiety at Time 3, and so forth. On the other hand, the authors observed that mathematics anxiety had no longitudinal effects on the development of mathematical performance. In line with these results, Rubinsten and Tannock (2010) suggested that in students with developmental dyscalculia mathematics anxiety might stem from unpleasant memories of previous failures during mathematical tasks in the class. In line with these suggestions, Passolunghi (2011) observed that children with developmental dyscalculia had higher levels of mathematics anxiety compared to normally developing children, but normal levels of anxiety for other school participants. The results of these studies are interpreted as meaning that the deficit in processing numerical information (i.e., Developmental Dyscalculia) causes poor mathematical abilities that cause mathematics anxiety, as it is unlikely that mathematics anxiety is a cause of developmental dyscalculia.

1.3.2 The Debilitating Anxiety Model

The second approach proposes that mathematics anxiety has a direct causal effect on mathematical performance. This framework can be considered as a self-enhancement approach (Abu-Hilal, 2000), in which the affective variable, in this case mathematics anxiety, has a causal effect on achievement. This model does not focus on explaining the development of mathematics anxiety. Instead, it concentrates on the consequences of mathematics anxiety and proposes that mathematics anxiety reduces mathematical performance on three different levels: the pre-processing, the processing, and the retrieval of information.

The pre-processing level refers to the events happening before the processing of mathematical material. There is evidence that students avoid math-related situations when they have high levels of mathematics anxiety (Hembree, 1990), thus learning less mathematics. Because these students avoid situations leading to the learning of mathematics, they show lower performance on mathematical tasks (i.e., global avoidance).

The second level, the processing level, refers to the processes that happens during the processing of mathematical information. And the third level refers to the retrieval of mnesic information. A processing mechanism is, for example, local avoidance. Local avoidance is the tendency of individuals with high mathematics anxiety to try to "hurry" when doing mathematical tasks to finish them as soon as possible so to not having to deal with mathematics anymore. For example, Ashcraft and Faust (1994) found that adults with high mathematics anxiety were faster in answering mathematical questions than adults with low mathematics anxiety. In addition, Morsanyi and colleagues (2014) observed that in secondary school students and university students mathematics anxiety was associated with reduced cognitive reflection and that university students with higher mathematics anxiety showed a tendency to rush through problems. These results suggest that participants with high mathematics anxiety try to hurry through mathematical tasks to reduce the time they are experiencing the unpleasant effects of mathematics anxiety. Another possible way in which mathematics anxiety affects mathematical performance at the processing level is the fact that there are reasons to believe that mathematics anxiety causes interference during the processing of mathematical information and during the retrieval of memories during mathematical tasks (Faust et al., 1996; Maloney et al., 2011); together they can be referred to as the online effect of mathematics anxiety on mathematical performance. Faust and colleagues (1996) assessed mathematical performance in participants with high and low mathematics anxiety. The authors observed that the highly anxious participants showed slower reaction times than the participants with low mathematics anxiety. The more difficult the task was, the more pronounced the difference was. The authors concluded that there were online effects of mathematics anxiety that interfered with mathematical performance. Although this seems in contradiction to local avoidance, these are two different arguments. Local avoidance refers to the fact that individuals with high mathematics anxiety tend to rush through mathematical tasks, meaning that participants tend to try to avoid answering the questions and rush through the task. In contrast, interference refers to the finding that when participants with high mathematics anxiety engage in mathematical tasks, they need more time to perform them than their colleagues with low mathematics anxiety because they need cognitive resources to deal with their negative feelings. Regarding reaction times, in line with the findings from Faust and colleagues, Maloney and colleagues (2011) observed a similar relationship. The authors assessed the relationship between mathematics anxiety and performance on a numerical comparison task and observed that mathematics anxiety was positively related to reaction times. This suggests that the higher the participant's mathematics anxiety was, the longer it took them to compare two magnitudes. This possible mechanism will be further discussed later on (please see chapter 1.4.3, page 49). For now, it is useful to understand that researchers interpret these findings as providing evidence that mathematics anxiety causes an interference in working memory, and this interference makes it harder to process numerical information and to retrieve information from memory.

Support for a causal effect of mathematics anxiety on mathematical performance comes also from longitudinal studies. For example, Ching (2017) assessed primary school students in Hong Kong and observed a significant longitudinal effect of mathematics anxiety on mathematical performance. The author concluded that mathematics anxiety has a causal relationship in the development of mathematical performance.

Further evidence of a causal effect of mathematics anxiety on mathematical performance comes also from studies that manipulate mathematics anxiety. For example, mathematics anxiety can be manipulated through the use of the stereotype threat, which is when a negative stereotype about the participant's ingroup is made salient and the participant feels at risk of confirming the negative stereotype. For example, some people believe that females are not good at mathematics. While testing female participants, they can be made aware of the stereotype about them by presenting it as a fact. This would make the stereotype salient and cause anxiety in the participants because they will worry about confirming the stereotype (Dowker et al., 2016). Galdi and colleagues (2014) observed that 6- to 7- years-old girls showed poorer mathematical performance under stereotype threat compared to the stereotype-inconsistent condition (this condition was achieved by activating the idea that girls can be good in math). These results suggest that raising mathematics anxiety levels has a negative effect on mathematical performance. However, because the authors did not assess mathematics anxiety it is possible that the manipulation did not actually influence mathematics anxiety but other related concepts (e.g., the manipulation might have reduced the participants' mathematics self-belief). Park and colleagues (2014) used the opposite manipulation. They used "Expressive Writing", a technique that requires participants to freely write about their deepest thoughts and feelings (Clark & Beck, 2011), to lower mathematics anxiety and investigated its effect on mathematical performance. Existing research suggested that expressive writing is effective in reducing anxiety (Klein & Boals, 2001). In Park and colleagues' (2014) study students were allocated to an expressive writing group or a control group before a mathematical test. Students in the expressive writing group were instructed to write for 7 minutes openly about their feelings about the mathematical test, students in the control group were asked to wait quietly for 7 minutes. The authors found that during mathematical tasks with high working memory demand, participants with high mathematics anxiety in the expressive writing group performed better (faster reaction times and lower error rates) compared to the participants with high mathematics anxiety in the control group.

1.3.3 The Reciprocal Theory

There seems to be evidence for both, a possible causal effect from mathematical performance to the development of mathematics anxiety and that mathematics anxiety influences the performance on mathematical tasks. The reciprocal theory combines both previous approaches by proposing a reciprocal relationship between mathematics anxiety and mathematical performance (e.g., Pekrun, 2006). Pekrun (2006) discussed the control-value theory in regard to anxiety in general. According to this theory, academic achievement and appraisal emotions are linked in a reciprocal relationship feeding into each other. This theory proposes that appraisals of the performance and of the value of the task influence the arousal of achievement emotions, such as enjoyment and frustration, and of outcome emotions, such as joy, pride, and anxiety. Anxiety, in turn, can affect academic performance, which in turn will influence the appraisal of the performance, creating a loop. Support for this hypothesis comes from studies that find a reciprocal relationship between mathematics anxiety and mathematical performance. For example, Gunderson and colleagues (2018) observed a significant longitudinal reciprocal relationship between mathematics anxiety and mathematical performance in primary school students. The fact that Year 1 mathematics anxiety had a significant effect on Year 2 mathematical performance while controlling for Year 1 mathematical performance suggests that, at least at the beginning of formal schooling, mathematics anxiety affects the development of mathematical performance.

Carey and colleagues (2016) in their review argue that the current research on the topic is not able to answer the question about the causal relationship. In fact, although some research has started to consider the possibility of a reciprocal theory (Gunderson et al., 2018), most researchers try to prove one theory or the other, without considering both alternatives at the same time (Carey et al., 2016). This situation is probably due to the difficulty of controlling for a reciprocal theory due to methodological constraints. In fact, the deficit theory might work through long-term mechanisms, i.e., the influence of poor mathematical performance on the development of mathematics anxiety might not be immediate, but it might require the repetition of failures that cause an additive effect on mathematics anxiety. On the other hand, the debilitating anxiety model could be supported by short-term mechanisms, for example, the online effect of mathematics anxiety on mathematical performance might have no long-term repercussions, so it can only be observed by concurrent analysis. This is even more evident if we consider that most longitudinal studies tend to support the deficit theory, and that experimental studies (e.g., studies that manipulate mathematics anxiety) support the debilitating anxiety model (Galdi et al., 2014; Hembree, 1990; Park et al., 2014). In light of this, a model in which both mechanisms are at work will likely be able to best express the nature of the mathematics anxiety – mathematical performance relationship. On the other hand, another possible explanation of the discrepancy between the findings is that different age groups might show different relationships. Future research might try to use mixed designs to try to capture longitudinal effects and short-term effects and try to see if the data fits this model and include different age groups to assess if the relationships observed are stable across development or not. For this reason, this thesis will investigate the relationship between mathematics anxiety and mathematical performance in adults and secondary school students. Moreover, I will attempt at addressing directionality by manipulating mathematics anxiety and by studying the longitudinal relationships between the two factors.

1.4 Working memory, mathematics anxiety, and mathematical performance

Maloney (2020, May) in her model proposed that mathematics anxiety influences working memory and that the influence on working memory indirectly affects mathematical performance. The reason why influence on working memory can affect mathematical performance is that it is widely agreed that there is a significant positive relationship between mathematical performance and working memory (Friso-van Den Bos et al., 2013; Hawes et al., 2019; Hawes & Ansari, 2020). Given the possibility of this relationship between mathematics anxiety and working memory and given that this relationship might play a detrimental role in mathematical performance, we need to investigate these relationships.

1.4.1 Working memory

Working memory is a system that allows the temporary retention and manipulation of information. Moreover, this system allows the performance of complex tasks by allowing the storing and the processing of information (Baddeley et al., 2015).

The three most important components of working memory are the phonological loop, the visuo-spatial sketchpad, and the central executive. The phonological loop is used for verbal and probably acoustic information. The visuo-spatial sketchpad is used for visual and spatial information. The central executive is the system that takes care of attentional control and the processing of information. Recently one more system was added to the model, the episodic buffer (Baddeley et al., 2015), but the research on this construct is still unclear, and for the scope of the current thesis we will concentrate on the central executive, the phonological loop, and the visuo-spatial sketchpad.

1.4.2 Working memory and mathematical performance

Working memory has a relevant role in the processing of numerical and mathematical information. For example, Hoard and colleagues (2008, in Meyer et al., 2010) and Passolunghi and colleagues (2008) found that the children who excel in mathematics are the ones with higher working memory.

Although evidence suggests that working memory is a relevant factor in mathematical performance, exactly which system is relevant and how they support mathematical performance is still under debate. Indeed, there is evidence that visuo-spatial working memory is a predictor of mathematical performance (De Smedt et al., 2009; Hawes et al., 2019; Hawes & Ansari, 2020; Miller & Bichsel, 2004; Passolunghi & Mammarella, 2012; Szucs et al., 2013). Miller and Bichsel (2004) found that in adults' high visuo-spatial working memory was associated with better basic and applied mathematical performance ($\beta = 0.28$ & $\beta = 0.23$ respectively). Accordingly, Passolunghi and Mammarella (2012) found that children with either a calculation deficit or a problem-solving deficit showed also a deficit in spatial processing, suggesting that the visuo-spatial sketchpad is involved in mathematical performance. Moreover, Szucs and colleagues (2013) found that children with Developmental Dyscalculia had lower performance in the visuo-spatial sketchpad and inhibition processes. Accordingly, De Smedt and colleagues (2009) also found that the visuo-spatial sketchpad was significantly related to mathematical achievement. Interestingly, however, this relationship was significant for Year 1 students, but not for Year 2 students. This result suggests that the involvement of the visuo-spatial sketchpad might change with age and might be more relevant during some developmental timepoints and less during some others. Moreover, Hawes and colleagues (2019) assessed children from the age of 4 to the age of 11 concurrently in visuo-spatial working memory and mathematical performance. The visuo-spatial working memory included two different tasks. The authors observed that mathematical performance was significantly positively related to both the forward visuo-spatial working memory span (r = .57), and the backward visuo-spatial working memory span (r = .63). Finally, Hawes and Ansari's (2020) review suggested that visuo-spatial working memory may play a role in numerical tasks where the participants need to maintain and recall the information, whereas other tasks might involve different systems.

Verbal working memory also appears to have a significant relationship with mathematical performance (Friso-van Den Bos et al., 2013; Miller & Bichsel, 2004). In Miller and Bichsel (2004)'s study, verbal working memory was also a significant predictor of basic and applied mathematical performance (β = 0.26 & β = 0.19 respectively). In line with these results, Friso-van Den Bos and colleagues (2013) carried out a meta-analysis and found an overall medium positive relationship between verbal working memory and mathematical performance (r = .31).

Finally, the central executive seems to be a relevant factor to consider when assessing mathematical performance. For example, Purpura and colleagues (2017) assessed inhibition efficiency, which is one of the processes of the central executive. The author observed that inhibition efficiency was significantly positively related to the performance in basic (r = .50 between inhibition and subitizing) and more complex mathematical tasks (r = .51 between inhibition and solving of story problems). Findings in a study by Passolunghi and Cornoldi (2008) also suggest that the central executive is important for mathematical performance. The authors observed that students with developmental dyscalculia showed lower performance on active working memory tasks and lower efficiency in inhibition processes than normally developing peers. Also, Friso-van Den Bos and colleagues (2013) observed a significant positive relationship between inhibition efficiency and mathematical performance (r = .27). The importance of central executive processes, and especially the inhibition of irrelevant information, for mathematical success, has been found by several other authors. For example, Blair and Razza (2007) found that in 5- to 7-year-old children inhibition and shifting efficiency were significant predictors of mathematical performance. Finally, De Smedt et al. (2009) also found that the central executive was a significant unique predictor of mathematics achievement of students in Year 1 and Year 2 (r = .52 & r = .53 respectively). Moreover, when all three systems (i.e., verbal and visuo-spatial working memory and central executive) were included in a multiple regression model, only visuo-spatial working memory (β = .38) and central executive (β = .35) were significant predictors of mathematical performance, suggesting that these two systems are the most relevant for mathematical performance.

A possible explanation for the plethora of different findings existing in literature is that different mathematical tasks require different cognitive systems. For example, Lee and Kang (2002) argued that different operations are carried out in different parts of the working memory. The authors asked the participants to perform three mathematical tasks, one where they had only to perform the mathematical task, one where at the same time the participants needed to perform a phonological suppression task (continuously repeat a non-word), and finally, one where at the same time the participants needed to perform a visuo-spatial suppression task (needed to keep in mind the shape and spatial location of an abstract shape). The mathematical tasks required the participants to perform multiplications and subtractions. For multiplications, the authors observed that the participants were significantly slower while performing a multiplication concurrently with the phonological task than in the other two situations. For subtraction, the authors observed that the participants were significantly slower while performing a subtraction concurrently with the visuo-spatial task than in the other two situations. In sum, the phonological dual tasks disrupted the performance on multiplications but not subtractions, and the visual dual task disrupted the performance on subtractions but not multiplications. These results suggest that multiplications take place in the phonological loop, whereas subtractions use the visuo-spatial sketchpad. This might explain some discrepancies found in the literature. Another possibility is that the involvement of each system changes with development. For example, the involvement of the visuo-spatial working memory changed from Year 1 to Year 2 students in De Smedt and colleagues study (2009). While the focus of this thesis is not on the relationship of working memory and mathematical performance per se, but on the relationship between working memory and mathematics anxiety, it is clearly important to keep in mind that working memory is an important factor for mathematical performance which is associated with mathematics anxiety.

1.4.3 Working memory and mathematics anxiety

The literature suggests that there is a significant relationship between mathematics anxiety and working memory. In fact, as discussed above, some researchers suggest that mathematics anxiety causes interference in working memory during the processing and the retrieval of mathematical information. For example, Faust and colleagues (1996) observed that participants with high levels of mathematics anxiety had a higher deficit in mathematical performance when the problems were more difficult compared to when the problems were easier. However, when the participants had to complete the same problems without time limitation, the performance difference between the high mathematics anxiety group and the low mathematics anxiety group in easier and more difficult problems was no longer significant, i.e., the participants with high mathematics anxiety performed similarly to the participants with low mathematics anxiety. Subsequently, Ashcraft & Kirk (2001) assessed mathematical performance and working memory in participants with high, medium, and low levels of mathematics anxiety with multiple experiments. In the first experiment, the authors found that participants with high mathematics anxiety showed lower performance in verbal working memory tasks. In the second experiment, the researchers assessed the relationship between mathematics anxiety and working memory by including a mathematical task. The design required the participants to perform simple and complex additions while maintaining a letter in memory. The results suggested that the participants with high mathematics anxiety were outperformed by the participants with low mathematics anxiety in complex additions. In easier tasks, the difference in performance between the participants with high mathematics anxiety and the participants with low mathematics anxiety was markedly smaller. The results of these two studies were explained in light of the processing efficiency theory. The processing efficiency theory (Eysenck & Calvo, 1992) suggests that anxiety causes interference in working memory leading to an efficiency deficit, but not necessarily to a performance deficit, i.e., people with higher anxiety need longer to perform a task, but perform at the same level as people with low anxiety when they have enough time. In line with the processing efficiency theory, participants with high mathematics anxiety showed longer reaction times (meaning that it took them longer to perform a mathematical task), but not a significantly different performance when time restraints were lifted. These findings are in line with the debilitating anxiety model and predict an interference in the processing of mathematical information. However, it is unclear which working memory system is affected by mathematics anxiety. For example, Ashcraft and Kirk's study assessed verbal working memory and found a significant relationship between complex verbal working memory and mathematics anxiety ($r = -.40$). Moreover, Passolunghi and colleagues (2016) found that secondary school students with high mathematics anxiety had significantly lower scores in the Word Span Forward task, which measures verbal working memory. In addition, Mammarella and colleagues (2015) tested primary students with developmental dyscalculia, with high mathematics anxiety, and typically developing students. The three groups were matched in reading comprehension, general anxiety, and IQ. The authors found that students with high mathematics anxiety showed worse verbal working memory than typically developing participants. However, the authors assessed also visuo-spatial working memory and observed that high mathematics anxiety students had also lower visuo-spatial working memory than the typically developing students. In contrast, Miller and Bichsel (2004) found that mathematics anxiety was inversely related with visuo-spatial working memory (*r* = -.25) but the relationship with verbal working memory was non-significant (*r* = -.11). It is possible that depending on the mathematical task and the age of the participants, mathematics anxiety has different relationships with different aspects of working memory.

Whichever working memory system we are talking about, a possible relationship between working memory and mathematics anxiety could be one of the reasons why there is a relationship between mathematics anxiety and mathematical performance. In fact, according to Ashcraft and Moore's 'affective drop in performance' (Ashcraft & Moore, 2009), mathematics anxiety causes a working memory deficit, which then is the cause for the mathematical deficit. The authors state that the drop in performance in individuals with high mathematics anxiety can be termed as an affective drop, as it can be attributed to the growth in arousal due to mathematics when the individuals are in high stakes mathematical situations and it is not due to numerical or other general cognitive difficulties. Essentially, it has been suggested that the working memory deficit leaves the person with fewer cognitive resources to deal with the mathematical task. Fewer resources then mean that the person with high mathematics anxiety is more likely to fail, or that in any case, they will take longer to process the mathematical information. This can be referred to as the 'online effect' of mathematics anxiety (Devine et al., 2012). Overall, the 'affective drop in performance' approach provides an interesting framework for studying and interpreting the results of studies of mathematics anxiety. However, this approach relies on the processing efficiency theory to explain the anxiety – performance relationship, but new evidence suggests a slightly different story.

1.4.4 Attentional control theory, inhibition and mathematics anxiety

The processing efficiency theory was further updated to reflect new findings, and Eysenck and colleagues (2007) proposed the attentional control theory. According to this theory, anxiety causes a deficit specifically in the inhibition and shifting processes which then causes the processing efficiency deficit. According to this theory, we should find significant effects of mathematics anxiety on measures that involve the central executive and, more importantly, in measures that assess the efficiency of the inhibition and the shifting processes, but not on other working memory components.

Indeed, it is possible that a reduced efficiency of inhibition processes could account for the relationship between mathematics anxiety and mathematical performance. This idea is based on the inhibition theory (Hasher & Zack, 1988; in Hopko et al., 1998) suggesting that during the execution of tasks, inhibition processes are put in place to control and inhibit distracters, which would otherwise use cognitive resources and that this leaves less free resources for the task at hand. When these processes are working properly, participants show adequate performance. However, when inhibition processes are less efficient, working memory resources will be drained by task-irrelevant data, and participants perform worse. Hence, the fact that participants with high levels of mathematics anxiety find themselves with worrisome intrusive thoughts (Hunt et al., 2014) might be a result of faulty inhibition mechanisms. In line with this prediction, Hopko and colleagues (1998) found that participants with high mathematics anxiety were slower to read and showed worse text comprehension when there were distracters in the text compared to participants with low mathematics anxiety. Hopko and colleagues (1998) gave people with low, medium, or high levels of mathematics anxiety a text to read. Part of the text was italicized, and another part of the text was not italicized. Participants were instructed to only read the italicized text and to ignore any text that was not italicized. Participants with medium and high levels of mathematics anxiety had significantly longer reading times than participants with low levels of mathematics anxiety. This extra time was not used to gain a better understanding and memory of the text. The authors suggested that the participants took longer to read the italicized text because they could not inhibit the irrelevant text and actually had to read it. Interestingly, this effect was found for both texts with and without mathematical content suggesting this effect was not specific for the mathematical content. The authors suggested that the presence of intrusive worrisome thoughts in individuals with high mathematics anxiety are the consequence of a more general impairment in the inhibition processes. This deficit of the inhibition processes in individuals with high mathematics anxiety could overload the working memory with irrelevant information as they are not able to successfully inhibit environmental distracters. The saturation of the working memory capacity could then lead to more difficulties during mathematical tasks. Hopko and colleagues do not explain why this deficit in inhibition specifically causes mathematics anxiety. However, an explanation why this deficit is more likely to cause mathematics anxiety resides in the very nature of mathematics. The inhibition deficit and its consequent waste of cognitive resource with irrelevant information is likely to cause lower performances in different aspects of everyday and academic life, such as mathematical tasks (Passolunghi et al., 2016), but also in reading comprehension tasks (Hannon, 2012). The reason why the deficit is more likely to cause the development of mathematics anxiety than reading anxiety is that an error in mathematics is very evident, whereas an error in the comprehension of written text is less evident and sometimes open to different interpretations (Cornoldi, 1999). Moreover, there is the commonly held belief that being good at mathematics is a synonym of being smart, a belief that is not held for other academic material (Cornoldi, 1999). A history of repeated difficulties and mistakes in mathematics might cause the individual to develop mathematics anxiety as they fear more of failing mathematical tasks than they fear to fail in other tasks. Recently, Passolunghi and colleagues (2016) found that, in accordance with the 'affective drop in performance' approach, secondary school children with high levels of mathematics anxiety indeed had worse mathematical performance, and worse measures of verbal working memory and working memory capacity. More interestingly though, children with high mathematics anxiety made more intrusion errors during active working memory task than children with lower mathematics anxiety. Intrusions during active working memory tasks are believed to be a measure of the efficiency of the inhibition processes (Passolunghi & Siegel, 2001, 2004). More intrusions would indicate lower efficiency of the inhibition processes. In line with Passolunghi and colleagues' results, Georges and colleagues (2016) also found that mathematics anxiety was associated with weaker inhibitory control in University students. These results, in line with the inhibition theory, suggest the need to update the framework as the deficit is not only in the passive storage, but there appears to be a deficit in the central executive, which could also explain the deficits observed in the verbal and in the visuo-spatial systems.

More support for the involvement of inhibitory processes in mathematics anxiety comes from neurophysiological studies. Lyons and Beilock (2012a), for example, investigated participants with high mathematics anxiety who performed well on mathematical tasks. The authors observed that the participants with high mathematics anxiety who managed to perform well on the mathematical tasks showed higher activation of frontal regions of the brain, such as the inferior frontal junction, an area that has been suggested as involved in cognitive control (Derrfuss et al., 2005, 2009; in Lyons & Beilock, 2012a). The authors suggested that the participants with high mathematics anxiety who performed well on mathematical tasks were able to recruit extra cognitive resources to perform the mathematical task. If it is true that mathematics anxiety causes the presence of irrelevant information in the working memory due to lower inhibition efficiency, the recruitment of extra resources could have allowed the participants to overcome the system overflow.

In conclusion, the data presented in this review suggest that there is a significant and negative relationship between mathematics anxiety and mathematical performance in secondary school students and adults. This relationship could be explained by a self-enhancement approach, a skill development approach, or a reciprocal relationship approach. Interestingly, the role of cognitive resources in this relationship has received little attention. This will be a key question for the studies presented in this thesis.

1.5 Brief overview of the studies

In this thesis, I will present three different studies. The first two studies are with adult participants, and the last study is a longitudinal study with secondary school students. The first study is a within-participant experiment involving the assessment of working memory in mathematical and in non-mathematical situations. I expected to find that the participants with high mathematics anxiety would show a significant deficit in the performance in the working memory tasks compared with the participants with low mathematics anxiety. Moreover, I expected that this deficit would be found only in mathematical situations, whereas it should be absent in non-mathematical situations. In the second study, I aimed to replicate the findings of the first study, using an extreme group design (high versus low mathematics anxiety) and a more sensitive measure for inhibition efficiency. The last study is a longitudinal study in secondary school students that aimed at assessing the reciprocal concurrent and longitudinal relationships between mathematics anxiety, mathematical performance, and mathematics self-belief over one school year. In chapter 4 I will present the concurrent relationships for the first time-point of this study, whereas in chapter 5 I will focus on the longitudinal relationships.

Chapter 2 - Is the relationship between working memory and mathematics anxiety context-dependent?

2.1 Introduction

In this chapter, I am presenting a study with adults investigating whether being in a mathematical situation affects different working memory systems (phonological loop, visuo-spatial sketchpad, and central executive) and whether the size of these effects is related to mathematics anxiety.

2.1.1 Anxiety and cognitive resources

Working memory was introduced in the literature review (please see chapter 1.4.1, page 45) as a system that allows the temporary storage and manipulation of information. Literature suggests a significant negative relationship between anxiety and performance (Eysenck et al., 2007; Eysenck & Calvo, 1992). Eysenck and Calvo's (1992) review suggested that this negative relationship is due to working memory interferences of anxious origin. Based on these findings, the authors proposed the processing efficiency theory (PET) that theorized that worrisome thoughts reduce working memory's processing efficiency and storage capacity. Processing efficiency is defined as the relationship between performance effectiveness (the quality of the performance; e.g., the accuracy on the task) and the amount of cognitive resources used to attain that level of performance (Derakshan & Eysenck, 2009); the higher the efficiency, the lower the amount of cognitive resources that are needed to achieve the same performance. A key distinction presented in the processing efficiency theory is between effectiveness and efficiency. Effectiveness is the quality of the performance in the task (e.g., response accuracy on the task), whereas efficiency refers to the relationship between the performance and the resources used to reach the performance. The same performance might need different amounts of resources from two people. For example, accuracy in a task might be the same for two people, but one person needed significantly more time than the other to complete the task. The person that needed more time used more cognitive resources to reach the same performance, hence showed lower efficiency (Eysenck & Calvo, 1992). Lower efficiency is not associated with lower accuracy performance in normal situations. The problem arises in high stake and high working memory demanding tasks, in which the available resources are not enough to overcome the system's reduced capacity (Berggren et al., 2012). Berggren and colleagues (2012) observed that cognitive demands influenced anxious participants' performance as in a visual search task, the introduction of a counting task did not affect the reaction times of low anxiety participants, but reaction times of anxious individuals were significantly longer.

Building on the processing efficiency theory, Eysenck and colleagues (2007) developed the attentional control theory intending to explain which processes of the central executive are involved in the relationship between anxiety and performance. The attentional control theory (ACT) stated that the cognitive deficit that is found in highly anxious participants is due to the effects of deficits in two processes of the central executive: the inhibition of the irrelevant information and the attentional shifting. Inhibition is the ability to inhibit irrelevant information and has two components: the inhibition of prepotent responses which is defined as motor or response inhibition, and the resistance to the interference from distractors which is defined as semantic or attentional inhibition (Friedman & Miyake, 2004; Tiego et al., 2018). The attentional control theory proposes that anxiety is involved in the reduction of both types of inhibitory control (Eysenck et al., 2007). For example, Calvo and Eysenck (1996) found that highly anxious participants showed poorer text comprehension, when compared with participants low in anxiety, when the text was heard in concurrence with articulatory suppression or irrelevant speech, but not when there was no interference. The authors suggested that the drop in performance observed when the participants were hearing additional information was due to the participants' inability to inhibit the irrelevant additional information. The second process of the central executive that is affected by anxiety is shifting. Shifting consists of the function of the central executive that is responsible for shifting the attentional focus between multiple tasks (Miyake et al., 2000). In the literature it is also referred to as "task switching" or "attention switching", and it is required when we need to shift our attentional focus from one aspect of the world (e.g., the screen in front of yourself) to a different aspect (e.g., the words coming out of the mouth of a colleague). Santos and colleagues (2006) found that highly anxious participants are slower in switching tasks compared with participants with low anxiety.

These results suggest that anxiety, in general, seems to have a detrimental effect on the efficiency of the processing of information and that individuals with high levels of anxiety might struggle more in tasks that require the intensive use of cognitive resources.

2.1.1.1 Working memory and performance on mathematical tasks

Literature suggests the presence of a positive relationship between working memory and mathematical performance (please see chapter 1.4.2, page 46). However, researchers are still arguing about the specific involvement of the different working memory systems.

For example, some researchers argued that in adults the retrieval of strategies to solve problems require limited cognitive resources. In fact, for example, Imbo and Vandierendonck (2007) found that the use of retrieval strategies require progressively less working memory resources with the development of mathematical skills. Moreover, the phonological loop is probably simply involved in the encoding and maintaining of arithmetical operands, but not in the calculation as such (Fürst & Hitch, 2000). Fürst and Hitch (2000) found that suppression of articulation (repeating continuously the word "the") did not impair the addition of two numbers when these were visible. On the other hand, articulatory suppression significantly impaired the performance when the numbers were presented only briefly and then needed to be remembered. Other authors found a significant positive relationship between visuo-spatial working memory and mathematical performance (*r* = .63; Hawes et al., 2019).

On the other hand, other researchers (e.g., Hubber et al., 2014) showed that in adults central executive processes are critical for mathematical performance, more so than visuo-spatial manipulation. In their study, Hubber and colleagues (2014) used an addition task that involved three different strategies to solve the mathematical problem: a retrieval strategy, a decomposition strategy, and a counting strategy. The retrieval strategy required participants simply to remember the correct solution. The decomposition strategy required participants to decompose the addition in two parts. For example, to solve 7+6=?, the instructions were to add 3 onto 7 and then add the remaining units to get the answer. Finally, the counting strategy required to count up the units from the first number on the second number to reach the answer. In the 7+6=? example, this would mean to count six times starting from 7. The authors found that loading the central executive (i.e., asking participants to generate random letters) produced slower and less accurate responses in concurrent mathematical tasks than simply loading the visuo-spatial sketchpad (i.e., asking participants to remember where 4 dots were on a 4 by 4 grid). Moreover, they found that counting was the strategy most affected by the load on the central executive and that the more demanding the operation was (i.e., double-digit addition versus single-digit addition), the more the load affected the performance. The finding that also retrieval of the solution was influenced by the central executive is in contrast to the findings of Imbo and Vandierendonck (2007) in which the involvement of working memory in retrieval decreased with the development of mathematical abilities. These findings also are in contrast with previous literature (Lee & Kang, 2002) showing that the visuo-spatial sketchpad is involved in arithmetical operations. However, Lee and Kang (2002) used multiplications and subtractions, and not additions. Moreover, the authors found that the phonological loop was involved in the performance on multiplications, whereas the visuo-spatial sketchpad was more involved in subtractions.

Overall, these findings suggest that the phonological loop is involved in the maintenance of the operands of the problems and multiplications. The visuo-spatial sketchpad appears to be involved in subtractions, and the central executive in additions and counting. However, Lee and Kang (2002) did not control for the effect of the central executive in multiplications and subtractions, so the central executive may be also involved in those operations.

2.1.2 Mathematics anxiety and mathematical performance

Mathematics anxiety is negatively related to mathematical performance, i.e., individuals with high mathematics anxiety tend to perform poorly in mathematical tests (Hembree, 1990; Justicia-Galiano et al., 2017). Hembree's influential meta-analysis (1990) reported a significant negative correlation between mathematics anxiety and mathematical performance in High school students ($r = -.30$). Accordingly, Justicia-Galiano and colleagues (2017) observed a significant negative correlation between mathematics anxiety and mathematical problem solving ($r = -.27$) and between mathematics anxiety and teacher's assessment of mathematical performance ($r = -.27$).

However, the mechanisms underlying this relationship are still unclear. As discussed in the literature review (please see chapter 1.3, page 36), there are currently three proposed explanations for this relationship in the literature; 1) the deficit theory, 2) the debilitating anxiety model, and 3) the reciprocal theory (Carey et al., 2016). The deficit theory proposes that poor mathematical performance causes the development of mathematics anxiety and is supported by longitudinal studies (Ma & Xu, 2004) and from studies on students with developmental dyscalculia (Passolunghi, 2011). In contrast, the debilitating anxiety model states that mathematics anxiety causes a drop-in performance in mathematical performance. This theory is supported by studies that observed global and local avoidance in individuals with high mathematics anxiety (Faust et al., 1996; Hembree, 1990; Morsanyi et al., 2014). Moreover, support for this thesis comes from studies that suggested the presence of an online effect of mathematics anxiety on mathematical performance (Ashcraft & Kirk, 2001; Ashcraft & Krause, 2007). Finally, the reciprocal theory combines both previous hypotheses and proposes that mathematics anxiety and poor mathematical performance are in a vicious cycle of a reciprocal relationship (Carey et al., 2016). The model proposes that on one hand poor mathematical performance is involved in the development of mathematics anxiety and on the other hand that mathematics anxiety is involved in lower mathematical performance in the participants who suffer from it (Carey et al., 2016). Support for the reciprocal theory comes from the finding that there is strong evidence for both other models and that they are not mutually exclusive. Hence, in early years poor mathematical performance may be one of the causes of the development of mathematics anxiety. But this does not exclude that once established, mathematics anxiety causes more deficits in the mathematical performance.

2.1.3 Mathematics anxiety, working memory, and mathematical performance

The online effect of mathematics anxiety on mathematical performance can work through different methods (please see chapter 1.3.2, page 40). Of relevance for the current work is the proposed mechanism by which the online effect is caused by interference from anxiogenic thoughts in the working memory. This interference supposedly diminishes cognitive resources for the mathematical task, working as a dual-task (Ashcraft & Moore, 2009; Ashcraft & Kirk, 2001; Ashcraft & Krause, 2007; Faust et al., 1996). This mechanism was, for example, suggested by Ashcraft and Kirk (2001; for a description, please see chapter 1.4.3, page 49).

On the other hand, recent research questioned the online effect previously described, by finding deficits in basic numerical processing and proposing that the mathematics anxiety –

mathematical performance relationship cannot be explained by a deficit in working memory (Maloney et al., 2010). The authors found that participants with high mathematics anxiety showed a deficit in counting but not in subitizing tasks compared to participants with low mathematics anxiety. Counting and subitizing are two different processes involved in the enumeration. Subitizing happens when the numerosity is between 1 and 4. The authors observed a small increase in Reaction Times (RTs) and no difference in accuracy when the participants needed to enumerate the number of 1-4 objects in a group. Counting happens when the numerosity is 5 or more, and RTs becomes greater as the number of objects increase and at the same time accuracy decreases. The authors observed that participants with high mathematics anxiety were slower than participants with low mathematics anxiety in the counting range. Moreover, the difference between the two groups grew with the increase of the target number. According to Maloney and colleagues (2010), the fact that a basic process like counting is affected by mathematics anxiety shows that individuals with high mathematics anxiety have a basic numerical processing deficit, not just a specific deficit for difficult tasks. However, as discussed earlier (Hubber et al., 2014), working memory might be involved in the process of counting, hence it is not surprising that counting performance was affected by mathematics anxiety.

Finally, it has been hypothesised that in accordance to the attentional control theory, mathematics anxiety research should focus on the central executive processes instead of passive working memory systems (Passolunghi et al., 2016). Indeed, Passolunghi and colleagues found that in secondary school students, participants with higher mathematics anxiety had lower performance in verbal working memory tasks (in both passive and active working memory measures) and lower efficiency of the inhibition processes of the central executive. These findings suggest the involvement of the central executive processes (in this case inhibition processes).

So far, to the best of my knowledge, no study investigated all three main working memory systems together (phonological loop, visuo-spatial sketchpad, and central executive) in the same study to understand the effect of mathematics anxiety on each system. In addition, no study measured these working memory systems in mathematical and non-mathematical situations to allow for comparisons between these measures and evaluate the effect that being in a math-related situation might have on working memory. For this reason, I designed a study in which participants participated in two different sessions. One was a mathematical session in which the participants were informed that they would be tested on mathematics and before the mathematical tasks they were tested on working memory and mathematics anxiety. The second session was a non-mathematical session in which participants were informed that it was simply about trait anxiety and working memory and were tested only on trait anxiety and working memory.

Based on Passolunghi and colleagues (2016) findings, I expected to find lower efficiency in the inhibition processes and a lower span of active working memory measure (i.e., Listening Span) for participants with high levels of mathematics anxiety. Moreover, I expect to find this pattern specifically in mathematically related situations.

2.2 Methods

2.2.1 Participants

A total of 44 students of a University in the North Yorkshire participated in this study. Of these, 36 (12 males, mean age 20.53 years, age range 18 – 32 years) completed both sessions and were included in the analysis. Of the remaining 8, 7 did not come to one of the sessions and 1 was excluded because their age was significantly different from the age range of the sample (55 years old).

Ethical approval was obtained from the ethics committee of the Psychology Department of the University of York. Participants could choose between receiving payment (6£ per hour) or receiving participation hours (1 hour per hour of participation).

2.2.2 Materials

The following tasks were designed to assess working memory and were administered to all participants in both sessions:

Verbal working memory

To assess verbal working memory, I decided to use a passive measure of verbal short-term memory that would not involve the presence of numbers. To achieve this goal, I developed a Letter Span task. The task requires participants to repeat a series of letters after hearing them spoken aloud, in the same order as they heard them. The span starts with 2 letters and ends with 8 letters. For each level of the span, there are two series. The presentation ends either when the participant reaches the end, or when the participant cannot recollect both series of a span level. The span measure recorded is the number of trials correctly recollected (Min = 0; Max = 14).

The choice of letters used was driven by the need to avoid phonological similarities between letters (e.g., "m" and "n"). To avoid phonological similarity between letters, I used Conrad's table (Conrad, 1964) and chose the letters with the lowest phonological similarity between them. I chose the following letters: F, R, H, J, Y, Z, M W, Q (for the task, see Appendix A.1).

The score showed good a correlation between the two sessions (correlation letter span scores in mathematical and non-mathematical sessions: $r = .62$).

Visuo-spatial working memory

To assess visuo-spatial working memory, I used the Corsi Span task forward (subtest of the Wechsler Memory Scale, WMS-3) (Wechsler, 1997). In this task participants are asked to touch a series of blocks in the same order as they were touched by the examiner before them. The span starts with 2 blocks and ends with 9 blocks. For each level of the span, there are two series. The presentation ends either when the participants reach the end, or when the participants cannot recollect both series of a span level. The score is the number of series correctly recollected (Min = 0; Max = 16). The Corsi Span task was adopted from the Wechsler Memory Scale III (WMS-III), which report a good overall test-retest reliability (r = .71) in the test manual.

Working memory capacity

Working memory capacity can be considered a complex measure that includes the passive storage of information and the cognitive control aspects that can influence this passive storage (Shipstead et al., 2016). I decided to use a Listening Span task (Daneman & Carpenter, 1980) as an active measure of working memory that can assess working memory capacity. The task required the participants to listen to a set of sentences (for example: "Chocolate is eaten on spaghetti"; see Appendix A.2 for the full list). For each sentence participants need to decide if the statement is true or false and remember the last word of the sentence. At the end of the set of sentences participants are asked to repeat the last words of each sentence in the same order as they were presented. Hence the participant is engaged in a dual task. The set of sentences starts with 2 sentences and ends with 6 sentences per set. Each level has two different sets of sentences. The presentation is concluded after all sets of sentences have been presented, meaning that there is no discontinuation rule.

This task allows two different measures: *Words*, indicating the number of last words correctly remembered during the whole presentation (Min = 0; Max = 40) which refers to the working memory capacity; and *Intrusions,* indicating the number of non-target words erroneously recollected (e.g.: from the sentence "Chocolate is eaten on spaghetti" the participant remember chocolate or tomato sauce) (Min = 0; Max = 40). The intrusions measure is believed to assess the inverse of the efficiency of inhibition processes (Passolunghi et al., 2016) since an intrusion is the effect of the failure to inhibit a word that should have been inhibited.

The span score showed good correlation between the two sessions (correlation listening span scores in mathematical and non-mathematical sessions: $r = .65$).

The following tasks were administered only during the Mathematical session:

Mathematics anxiety

To assess mathematics anxiety, I used the Abbreviated Math Anxiety Scale (AMAS; Hopko et al., 2003). AMAS is a self-report questionnaire (see Appendix A.3) that is composed of 9 items associated with different math-related situations (in school and everyday life; an example of a situation: "Watching a teacher work an algebraic equation on the blackboard"). In the AMAS, the participant needs to rate the feelings during those situations using a 5-point Likert scale from 1 – No bad feelings to 5 – Worst feelings (Min AMAS score = 9; Max = 45). The AMAS shows good internal consistency ($\alpha = .90$) and good two-week test-retest reliability ($r = .85$) in adults (Hopko, Mahadevan, et al., 2003). I used the scores on the AMAS to divide participants into two groups; a high mathematics anxiety group and a low mathematics anxiety group. The design involved the creation of the groups based on a median split design. To divide the participants, I used a median split based on the median in the current sample (*Mdn* = 18). Participants with an AMAS score below the median were allocated to the low mathematics anxiety group (N = 17); participants with an AMAS score above the median were allocated to the high mathematics anxiety group (N = 15). Participants with an AMAS score equal to the median (N = 4) were excluded from the analysis.

Mathematical performance

To assess the participants' mathematical proficiency I used the mathematical subtest of the Wide Range Achievement Test (WRAT-4; Wilkinson & Robertson, 2006) blue form. The math computation subtest includes 30 mathematical problems of increasing difficulty. It measures participants' ability to perform basic mathematical computations through the solving of problems with additions, subtractions, multiplications, divisions, fractions, use of decimals, and algebra. In adults, the math computation subtest scores 1 point for each correct operation and 0 for each empty or wrong operation. There are 40 operations, and the final score is reached by adding 15 points if there are at least 5 correct responses in the task (Min = 0; Max = 55). The blue form of the math computation subtest of the WRAT-4 shows good overall reliability (α = .89) and a good average immediate retest reliability with the alternate form (green form; *r* = .88) (Wilkinson & Robertson, 2006).

Arithmetical fluency

To assess participants' fluency in arithmetic I used the Simple Calculations task. The task requires the participant to solve as many calculations as possible within a specific time limit. The task includes three subtests, addition, subtraction, and multiplication. For each type of operation, there are two subtests: 1) an easy page with 25 items (15 seconds to complete as many items as possible for addition and subtraction, 20 seconds for the multiplications); 2) a difficult page with 25 items (45 seconds to complete as many items as possible for addition and subtraction, 2 minutes for the multiplications) which has more difficult operations (see Appendix A.4). Operations use single-digit operands for the easy task and single- and double-digit operands for the difficult task. Each page has 25 items, but the easy page of each operation has two examples. Consequently, the maximum score for each of the easy tasks is 23, whereas the maximum score for each difficult tasks is 25. The final score is a sum of all tasks to get a measure of arithmetical fluency (Max = 144). The test was adapted from the simple addition and subtraction test from Westwood and colleagues (Westwood et al., 1974).

The following tasks were administered only during the Non-mathematical session:

Trait anxiety

To assess participants' trait anxiety, I used the GAD-7 (General Anxiety Disorder – 7; see Appendix A.5) questionnaire (Spitzer et al., 2006). The GAD-7 is a short questionnaire composed of 7 items (e.g., "Over the last 2 weeks, how often have you been bothered by not being able to stop or control worrying?") that assess general anxiety levels and proved valid and efficient in screening and assessing the severity of the general anxiety disorder (Spitzer et al., 2006). Items are rated on a 4-point Likert scale from "Not at all" (score of 1) to "Nearly every day" (score of 4). The minimum score is 7, the maximum score is 28. GAD-7 shows good convergent validity with the Beck Anxiety Inventory (r = .72) and with the anxiety subscale of the Symptom Checklist-90 (r = .74) in adults (Spitzer et al., 2006).

2.2.3 Design and Procedure

A repeated measures design involved two different sessions; a Mathematical session and a Non-mathematical session. Sessions took place on different days with 48 – 1007 (Mean = 184.26) hours between the two sessions. The order of the two sessions was counterbalanced between participants.

Mathematical session

In the mathematical session, participants were told beforehand that the study investigated the involvement of working memory in the relationship between mathematics anxiety and mathematical performance. The tasks were given in the following order: 1. AMAS; 2. Letter span task; 3. Corsi span task; 4. Listening span task; 5. WRAT-4 mathematical computation subtest; 6. Simple calculations.

Non-mathematical session

In the non-mathematical session, participants were told that the study investigated the relationship between trait anxiety and working memory. The tasks were given in the following order: 1. Letter Span task; 2. Corsi Span task; 3. Listening Span task; 4. GAD-7.

2.3 Results

2.3.1 Descriptive Statistics

Table 2.1 reports the descriptive statistics divided by session (i.e., mathematical session versus non-mathematical session) for the full sample (N = 36).

Table 2.1. Descriptive statistics divided by session

		Non-Mathematical Session		Mathematical Session		
Factor	Measure	M *(SD)*	*Min - Max*	M *(SD)*	*Min - Max*	N
WM	Verbal working memory	9.11 *(1.89)*	6 - 14	9.03 *(1.68)*	6 - 12	36
	Visuospatial working memory	10.56 *(1.99)*	6 - 14	10.19 *(1.75)*	5 - 14	36
	Working memory capacity	32.11 *(4.85)*	20 - 40	31.36 *(5.99)*	18 - 40	36
	Intrusions	1.44 *(1.46)*	0 - 6	1.61 *(1.66)*	0 - 6	36
Mathematics	Mathematical performance			30.36 *(4.49)*	35 - 53	36
	Arithmetical Fluency			65.36 *(14.57)*	31 - 88	36
Anxiety	Mathematics anxiety			19.22 *(5.19)*	11 - 33	36
	Trait anxiety	7.11 *(4.8)*	0 - 17			36

In this sample, mathematics anxiety ranged from 11 to 33 with a median of 18 (N = 36). I divided the participants into two groups, low and high mathematical anxiety. Table 2.2 reports the descriptive statistics for the two groups (N = 32). Analysis of mean mathematics anxiety in the two groups showed that the average difference between the low mathematics anxiety group (LMA; M = 15.18; N = 17) and the high mathematics anxiety group (HMA; M = 24.13; N = 15) was low compared with the range of the questionnaire scores (Range = 9 - 45), although independent t-test showed that the difference was significant, t (30) = 8.02, $p < .001$.

Table 2.2. Descriptive statistics and group differences of anxiety and mathematics measures.

	LMA (N = 17)			HMA (N = 15)			
Measure	Min	Max	Mean *(SD)*	Min	Max	Mean *(SD)*	T(30)
Mathematics Anxiety	11	17	15.17 *(1.74)*	20	33	24.13 *(4.22)*	8.02***
Trait Anxiety	0	17	5.00 *(4.02)*	4	16	10.20 *(4.48)*	3.62**
Mathematical Performance	24	38	32.00 *(4.44)*	20	36	28.67 *(4.52)*	2.10*
Arithmetical Fluency	44	88	70.29 *(13.95)*	31	87	58.93 *(14.31)*	2.27*

Legend:
*: $p < .05$
**: $p < .01$
***: $p < .001$

2.3.2 Group Differences

Table 2.2 reports the results of the independent samples t-tests of the differences between the low mathematics anxiety and the high mathematics anxiety groups on the background measures. Mathematical performance was significantly different between the two groups and descriptive statistics show that participants with high mathematics anxiety had lower mathematical performance compared with participants with low mathematics anxiety. The independent samples t-test for arithmetical fluency show that participants with high mathematics anxiety performed significantly worse than participants with low mathematics anxiety. Interestingly trait anxiety was also significantly different between the two groups, with the low mathematics anxiety group also showing lower levels of trait anxiety.

In particular, I wanted to assess the differences between the groups in the working memory measures. Specifically, I wanted to assess if there were significant differences in working memory spans between the two groups and between the two sessions (for the descriptive statistics see Table A.1 in Appendix A.6). To answer this question, I carried out 3 separate 2-way mixed ANOVAs, one for each working memory span measure, with the within-subject factor session (mathematical and non-mathematical) and the between-subject factor group (low mathematics anxiety and high mathematics anxiety). The results can be seen in Table 2.3.

Table 2.3. Mixed ANOVA for working memory and session

Working memory		Sum of Squares	df	Meas Square	F	p-value	η_p^2
Verbal working memory	Session	0.48	1	0.48	0.40	.532	.013
	Error	35.53	30	1.18			
	Group	22.35	1	22.35	4.52	**.042**	.131
	Error	148.40	30	4.95			
	Session * Group	0.91	1	0.91	0.77	.387	.025
	Error	35.53	30	1.18			
Visuospatial working memory	Session	2.43	1	2.43	1.93	.175	.060
	Error	37.81	30	1.26			
	Group	19.15	1	19.15	4.18	**.050**	.122
	Session * Group	1.05	1	1.05	0.83	.368	.027
	Error	37.81	30	1.26			
Working memory capacity	Session	13.19	1	13.19	1.17	.288	.037
	Error	338.81	30	11.29			
	Group	272.80	1	272.80	6.40	**.017**	.176
	Error	1279.14	30	42.64			
	Session * Group	4.94	1	4.94	0.44	.513	.014
	Error	338.81	30	11.29			

There was no main effect of session in any of the ANOVAs, i.e., working memory spans did not differ between being in a mathematical or in a non-mathematical situation. However, there were significant main effects of group for the verbal working memory and for the working memory capacity. There was also a marginally significant effect of group on the visuo-spatial working memory. Participants with high mathematics anxiety performed worse than the participants with low mathematics anxiety on all working memory span tasks (see Figure 2.1). None of the interactions were significant, suggesting that session did not influence the differences between groups. The means and standard errors of the span measures by group and session can be seen in Figure 2.1.

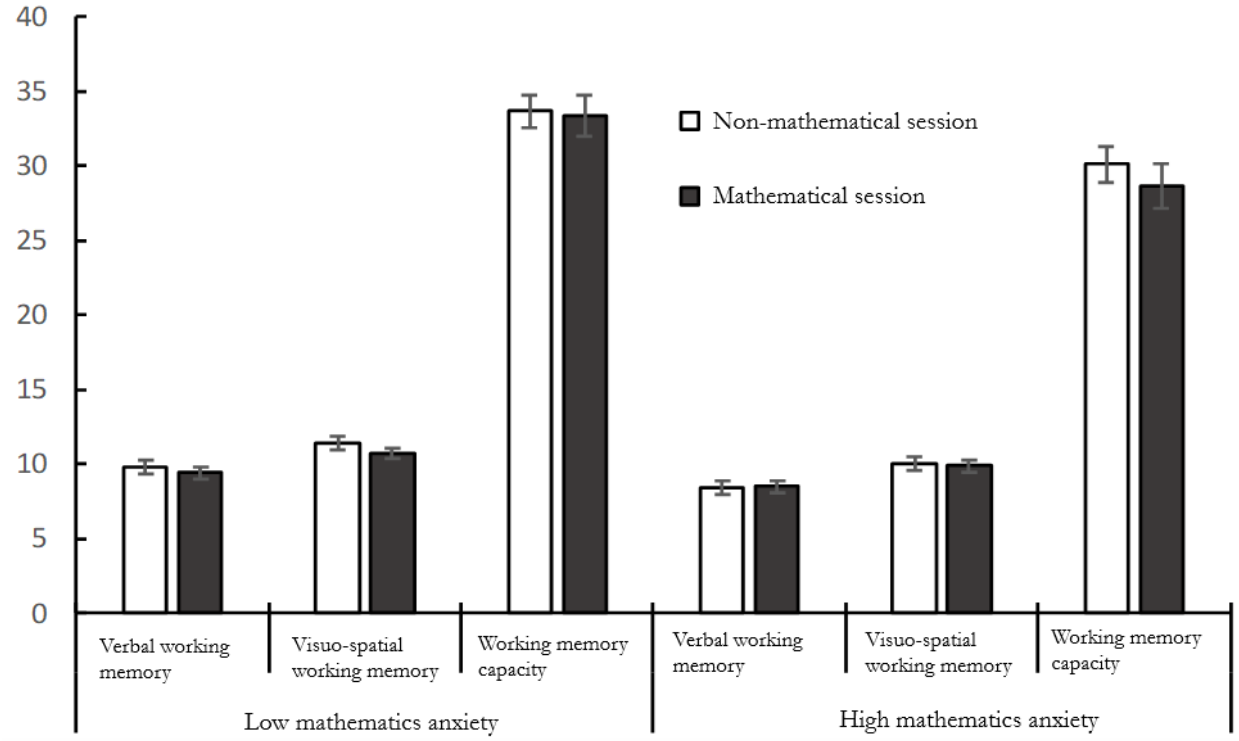

Figure 2.1. Working memory measures in the two sessions divided by mathematics anxiety group (low versus high).

Because Intrusion scores showed flooring effect (please see Table A.1, Appendix A.6), I decided to not include this measure in the ANOVA but ran separate non-adjusted non-parametric tests. Wilcoxon signed-rank test for intrusion showed no significant differences between the non-mathematical session (Mdn = 1.00) and the mathematical session (Mdn = 1.00) for the low mathematics anxiety group, $U = 26.00$, $p = .527$. Moreover, Wilcoxon signed-rank test for intrusion showed no significant differences between the non-mathematical session (Mdn = 1.00) and the mathematical session (Mdn = 1.00) for the high mathematics anxiety group, $U = 36.00$, $p = .383$. A Mann-Whitney U-test for intrusions in the non-mathematical session found no significant difference between the low mathematics anxiety group (Mdn = 1.00) and the high mathematics anxiety group (Mdn = 1.00), $U = 131.00$, $p = .911$. Moreover, in the Mathematical session, the median number of intrusions for the low mathematics anxiety group (Mdn = 1.00) was not significantly different from the high mathematics anxiety group (Mdn = 1.00), U = 158.50, p = .246. The boxplots of the intrusions for the different groups can be seen in Figure 2.2. Although the non-parametric analysis was not significant, the boxplots suggest that there might be some differences in the efficiency of the inhibition processes between the groups.

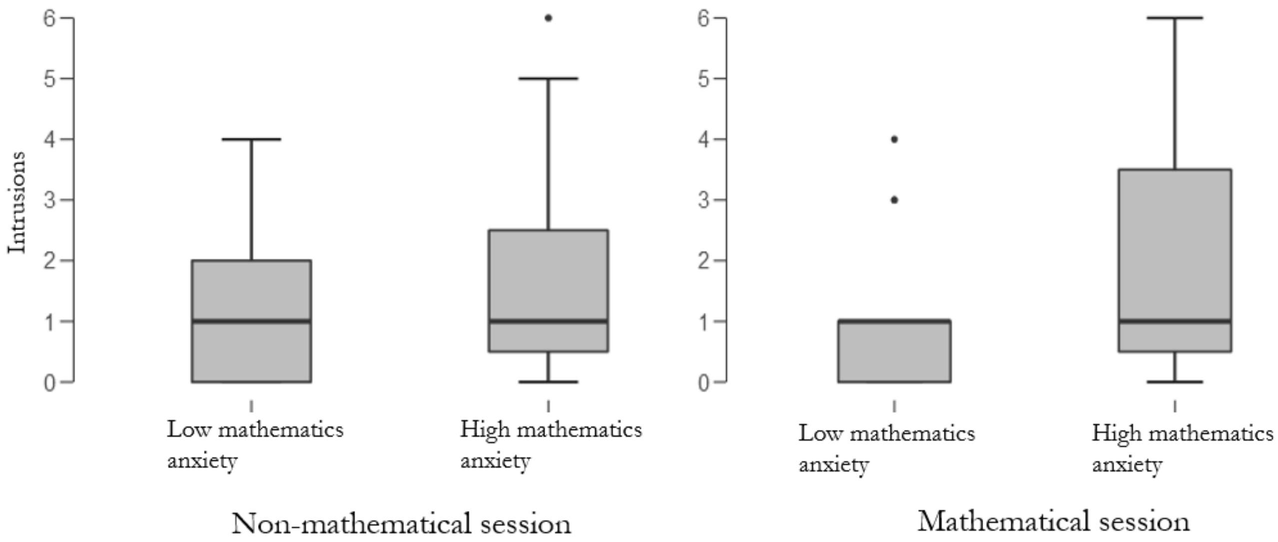

Figure 2.2. Intrusion boxplots divided by session and group.

2.3.3 Predicting mathematical performance

I wanted to investigate the differences between the high and low mathematics anxiety groups. However, because the differences in mathematics anxiety between the two groups were small compared to the range of the questionnaire, I decided to include the whole sample and ran a correlational analysis (please see Table 2.4 for the whole correlational matrix).

Table 2.4. Whole correlation matrix

Measure	1	2	3	4	5	6	7	8	9	10	11	12
1. Trait anxiety	-	.56 **	-.06	-.15	-.12	-.08	.17	-.07	-.19	-.19	-.11	-.07
2. Mathematics anxiety		-	-.43 **	-.29	-.28	-.28	-.51 **	.22	-.28	-.30	-.52 **	.42
3. Mathematical performance			-	.63 **	.17	.11	.24	-.16	.28	.28	.39 *	-.31
4. Arithmetical fluency				-	-.03	.08	.03	.02	.14	.08	.24	-.08
5. Verbal working memory - Non-mathematical					-	.24	.05	-.08	.62 **	.24	.04	.10
6. Visuospatial working memory - Non-mathematical						-	.19	-.36 *	-.07	.67 **	< .01	-.18
7. Working memory capacity - Non-mathematical							-	-.49 **	-.05	.12	.65 **	-.31
8. Intrusions - Non-mathematical								-	.18	-.36 *	-.18	.25
9. Verbal working memory - Mathematical									-	.13	.24	-.01
10. Visuospatial working memory - Mathematical										-	.03	-.18
11. Working memory capacity - Mathematical											-	-.60 **
12. Instrusions - Mathematical												-

Legend:

Non-mathematical: non-mathematical session

Mathematical: mathematical session

*: $p < .05$;

**: $p < .01$;

***: $p < .001$.

The first goal was to assess which factors best predict mathematical performance. To do this, I ran regression analyses on the whole sample. Firstly, given the known relationship between mathematics anxiety and trait anxiety (please see chapter 1.2.2, page 27) I wanted to investigate the individual influences of mathematics anxiety and trait anxiety on mathematical performance. I computed a stepwise linear regression with mathematics anxiety and trait anxiety as predictors of mathematical performance. The analysis showed mathematics anxiety as the only significant predictor of mathematical performance (β = -.43, p = .009). The model explained 18% of the variance and was significant, F(1,34) = 7.67, p = .009.

After evaluating the relationship between mathematical performance and anxiety, I investigated working memory measures to assess which working memory components predicted mathematical performance. I ran a regression analysis with the three spans measures in the mathematical situation as predictors, and mathematical performance as outcome. Stepwise linear regression indicated that working memory capacity was the only significant predictor of mathematical performance (β = .39, p = .018). The model explained 15 % of the variance and was significant, F(1, 34) = 6.20, p = .018.

To compare the relative contributions of mathematics anxiety and working memory capacity, I ran a regression analysis to test whether the two variables are still significant predictors of mathematical performance when considered together in the same regression model. Stepwise linear regression showed mathematics anxiety as the main predictor of mathematical performance. Including working memory capacity did not significantly improve the fit of the model, hence the resulting model included only mathematics anxiety as a significant predictor of mathematical performance (β = -.43, p = .009). The resulting model explained 18% of the variance and proved significant, F(1, 34) = 7.67, p = .009.

Arithmetical fluency was excluded from the analysis because it did not show a significant relationship with mathematics anxiety (see Table 2.4).

2.3.4 Predicting working memory

In the next step I assessed which factors best predicted working memory by running regression analyses on the whole sample.

First, I ran a regression analysis to control the influence of mathematics anxiety and trait anxiety. Regarding the verbal and the visuo-spatial working memory, I did not run regression analysis because the measures, although significantly different between the two groups, did not show a significant relationship with mathematics anxiety (see Table 2.4).

Working memory capacity as assessed by the listening span task, on the other hand, showed significant relationships in both sessions. I computed a stepwise linear regression with mathematics anxiety and general anxiety as predictors of working memory capacity in the non-mathematical session. The analysis showed mathematics anxiety as a significant predictor (β = -.51, p = .001), but not trait anxiety. The resulting model showed that mathematics anxiety explained 26% of the variance and that the model was a significant predictor of working memory capacity, $F(1, 34) = 12.22$, $p = .001$.

I then computed a stepwise linear regression with mathematics anxiety and trait anxiety as predictors of working memory capacity in the mathematical session. The analysis showed mathematics anxiety as a significant predictor (β = -.52, p = .001), but not trait anxiety. The resulting model showed that mathematics anxiety explained 27% of the variance and that the model was a significant predictor of working memory capacity, $F(1, 34) = 12.51$, $p = .001$.

Given that I was comparing the same construct in two different situations (mathematical and non-mathematical), and the only significant predictor is the same construct in both models, I decided to compare the confidence intervals of the standardized coefficients in the two models. In this way, I can assess if the relationship between mathematics anxiety and working memory capacity is significantly different between the two sessions or not. The regression coefficients for the two models are presented in Table 2.5 with 95% confidence intervals.

Table 2.5. Regression coefficients with 95% confidence intervals

Model	B	S.E. B	95% C.I.
Working memory in non-mathematical session	-0.48	0.14	-0.76 ~ -0.201
Working memory in mathematical session	-0.60	0.17	-0.94 ~ 0.255

Legend:
C.I. : confidence intervals

As we can see from Table 2.5, the confidence intervals overlap by more than 50%; this suggests that the two models are not significantly different. Comparison between correlation coefficients also suggested that the relationship between mathematics anxiety and working memory capacity in the two sessions was not significantly different, $z = 0.06$, $p = .952$.

2.4 Discussion

Previous literature addressed the relationship between mathematics anxiety, mathematical performance, and working memory (e.g., Dowker, Sarkar, & Looi, 2016). However, to the best of my knowledge, the current study is the first study in which the three working memory systems have been investigated concurrently in the context of mathematics anxiety. The main aim of this study was to assess the differences in three working memory systems and in the inhibition efficiency between participants with high and low mathematics anxiety, and between mathematical and non-mathematical situations. Moreover, I investigated if being in a math-related situation affected participants' working memory spans.

2.4.1 Group Differences and Session

Replicating previous findings (e.g., (Ashcraft & Kirk, 2001; Faust et al., 1996; Hembree, 1990; Passolunghi et al., 2016), I found that participants with high mathematics anxiety compared to participants with low mathematics anxiety showed significantly lower mathematical performance and arithmetical fluency. Interestingly, both mathematical performance and arithmetical fluency were significantly different between the two groups. Indeed, the WRAT-4 mathematical subtest is a complex task; it is designed to allow the assessment of mathematical performance from young children to older adults without ceiling effects. Hence, the findings are in line with the idea that participants with high mathematics anxiety have trouble with difficult tasks (debilitating anxiety model; Carey et al., 2016). On the other hand, my data showed significant differences also for the arithmetical fluency task, that measures performance with simple calculations. According to most of the literature, participants with high mathematics anxiety should not show a significant deficit in simple mathematical tasks when compared with participants with low mathematics anxiety (e.g., Ashcraft & Kirk, 2001). However, this task is stressful for the participants and requires the processing of many operations in a limited time frame. Hence, the finding of group differences on this task in this study is in accordance with findings by Faust and colleagues (1996) that suggests a specific impairment on mathematical performance for time-restricted situations. The results on the group differences on mathematical performance and arithmetical fluency are in line with the literature and suggest that the participants with high mathematics anxiety perform worse than the participants with low mathematics anxiety in mathematical tasks.

Moreover, the participants with high mathematics anxiety showed significantly lower spans in verbal and visuospatial working memory and lower working memory capacity in comparison with participants with low mathematics anxiety. Results on the verbal working memory and working memory capacity tasks are in line with Passolunghi and colleagues (2016), although the researchers tested secondary school students. Moreover, in accordance with Ganley and Vasilyeva (2014), I found that mathematics anxiety was associated with lower visuo-spatial working memory. These results suggest that there might be a relationship between mathematics anxiety and working memory, and this relationship, at least for the verbal working memory and the working memory capacity, might be present across different ages.

In contrast to the significant group differences on the working memory span measures, there was no significant effect of group on the number of intrusions. This suggests that the efficiency of the inhibition processes might not have been affected by group. However, the measure showed a flooring effect with most participants showing no intrusion or just one intrusion. Visual inspection of the boxplots shows a hint of a possible difference between groups. It is possible that the measure was not sensitive enough to detect any possible differences. Hence, I suggest studying the efficiency of the inhibition processes using measures with higher sensitivity and that are better suited to use with adults.

Contrary to my predictions, I did not find an effect of session. I will discuss this further in the general discussion, once we take into consideration also the regression analyses. However, for the current discussion it can be interesting to point out that mathematics anxiety is supposed to refer to feelings that arise in the presence of mathematical material. For this reason, the fact that the working memory deficit is present in participants with high mathematics anxiety regardless of situation does not support the idea that mathematics anxiety causes the deficit, as it is present also when mathematics anxiety should not be present. The current data instead could suggest that a deficit in working memory might be a causal factor in the development of mathematics anxiety.

Finally, higher trait anxiety accompanied having higher levels of mathematics anxiety. Which is in accordance with previous literature that reports a positive relationship between mathematics anxiety and trait anxiety (Dowker et al., 2016).

These findings suggest that participants with high levels of mathematics anxiety show lower performance in mathematical tasks and that they have lower working memory spans. However, the lower working memory spans are not related to being in a mathematical situation or not.

2.4.2 Mathematics anxiety as a continuous predictor

As discussed in the previous section there was a significant negative correlation between mathematics anxiety scores and mathematical performance (r = -.43). The direction and size of this correlation are in line with previous findings (Hembree, 1990; Justicia-Galiano et al., 2017). If anything, my results show a slightly larger negative correlation between mathematics anxiety and mathematical performance than reported in the literature. Moreover, the regression analysis suggested that this relationship is significant after controlling for the effect of trait anxiety, which in itself was not a significant predictor of mathematical performance. This is in line with the idea that mathematics anxiety has a unique relationship with mathematical performance that is not due to trait anxiety (Dowker et al., 2016). On the other hand, the correlation between mathematics anxiety and mathematical fluency was non-significant, even though there were significant differences between the groups. This might be due to the lack of power in my sample, as correlation analysis tends to need bigger samples than group differences (Conway et al., 2005)[1].

The regression analysis also showed that working memory capacity was a significant predictor of mathematical performance. This is in line with the findings by Hubber and colleagues (2014), suggesting that the central executive is an important factor in mathematical

[1] Mathematics anxiety and arithmetical fluency showed a non-significant moderate negative relationship (r = -.29). Power analysis suggests that for an effect size of r = .29 to be correctly identified with α = .05 and β = .80 I would need a sample of 88 participants. My sample size was N = 36, i.e. , the results might have been not-significant due to lack of power.

performance. Moreover, the multiple regression on mathematical performance with the three working memory measures suggested that only the central executive was significantly involved in mathematical performance. However, as discussed earlier, it might be that my sample was not big enough to show all the significant relationships, hence I cannot conclude that the other two working memory systems are not involved. It would be interesting to design a similar study in which all three systems are compared, but with bigger sample size. In any case, my data suggests that once all three systems are considered together, only the central executive proves to be involved in the performance of mathematical tasks.

The final regression model showed, however, that once the variance explained by mathematics anxiety was controlled for, working memory capacity was no longer a significant predictor of mathematical performance. Given my small sample, this finding needs to be replicated in a bigger sample. However, this result points towards a relationship between mathematics anxiety and working memory and suggest that the relationship between working memory and mathematical performance might be largely driven by differences in mathematics anxiety. To the best of my knowledge this finding is new in the literature. However, it seems to suggest that working memory and mathematical performance are not related and that the relationship found in some studies, and in my data, might be driven by differences in mathematics anxiety, which in turn cause differences in mathematical performance and working memory measures.

2.4.3 Conclusions

One of the first findings of the current study was that although both mathematical performance and arithmetical fluency were significantly lower in the group with high mathematics anxiety, only mathematical performance was significantly related to mathematics anxiety in the whole sample, but not arithmetical fluency. Mathematical performance was related to working memory capacity, whereas arithmetical fluency was not. The finding that numerical processing in participants with high mathematics anxiety was lower only in tasks that are also related to working memory is in accordance with the majority of the literature (Faust, Ashcraft, & Fleck, 1996; Ashcraft & Kirk, 2001; Ashcraft & Krause, 2007), but in contrast with the findings of Maloney and colleagues (2010). However, the groups were significantly different in all three working memory spans and in both mathematical performance and arithmetical fluency. This suggests that although I found evidence for the involvement of working memory in the relationship between mathematics anxiety and mathematical performance, as suggested by Ashcraft and Krause (2007), my results might be the result of not enough power. It is possible that with a larger sample there would be significant relationships with the other two working memory systems (i.e., the phonological loop and the visuo-spatial sketchpad), and with arithmetical fluency. It would be interesting to investigate, eventually, whether there is a mediation effect of working memory measures on any of the two types of mathematical tasks and if the relationships between the two types of mathematical tasks and mathematics anxiety are significantly different.

Moreover, I found that the relationship between mathematical performance and working memory capacity is no longer significant once I control for the variance explained by mathematics anxiety. This suggests that, in my study, at least part of the relationship between working memory measures and mathematical performance (Hubber et al., 2014) is due to the relationship that both constructs have with mathematics anxiety; or that at the very least, that mathematics anxiety is a variable that needs to be considered every time we investigate the relationship between mathematical performance and working memory. Mediation analysis could be useful for understanding these findings, and to disentangle the nature of the relationship between mathematics anxiety, mathematical performance, and working memory.

In this study, I was also interested in assessing the effects that being in a math-related situation has on working memory spans. Contrary to my predictions, I did not find an effect of the session. On the other hand, I did find that all three subsystems (i.e., verbal and visuo-spatial working memory and working memory capacity) were significantly impaired in participants with high mathematics anxiety. This finding seems to suggest that participants with high mathematics anxiety suffer from a basic deficit in their working memory capacity. On the other hand, Eysenck and colleagues (2007) specified that one assumption of the attentional control theory is that anxiety impairs attentional control even when there are no threat-related stimuli. In this case, it might be that mathematics anxiety impairs attentional control even when there are no mathematical-related stimuli. No other studies found evidence of this in mathematics yet, hence more studies are needed to replicate the current findings. Moreover, if these findings are accurate, it could be interesting to evaluate if reducing mathematics anxiety also improves attentional control or not. As will be further discussed in the general discussion (please see chapter 6, page 225), future studies could investigate attentional control in participants with high mathematics anxiety before and after a session of expressive writing (Park et al., 2014), or before and after some sessions of systematic desensitization (Hembree, 1990), and see the effect that reducing mathematics anxiety has on attentional control.

On a different note, although significant, the difference in mathematics anxiety between the two groups was small compared to the range of the questionnaire and the studies presented in the literature. For example, in Maloney, Ansari, and Fugelsang (2011), participants in the low mathematics anxiety group had AMAS scores below 20, and in the high mathematics anxiety group, they had AMAS scores over 30. Often an extreme group design has been used in the literature (Maloney et al., 2011; Passolunghi et al., 2016), and a comparison with those studies suggests that the difference in mathematics anxiety between my groups was rather small and perhaps not large enough to detect subtle differences. It might be that future studies with an extreme group design might find different effects of group and session.

Conclusions: In conclusion, my study suggests that mathematics anxiety is negatively related to working memory capacity, but that this relationship is not limited to situations in which the participants need to deal with numerical material. More studies need to address this finding. However, possible reasons for this could be that poor working memory capacity is involved in the genesis of mathematics anxiety, or that anxiety impairs attentional control even when there are no threat-related stimuli (Eysenck et al., 2007).

Chapter 3 - Mathematics anxiety, working memory, and inhibition efficiency: extreme groups differences.

3.1 Introduction

Results from the previous chapter suggested that there could be a relationship between mathematics anxiety and inhibition processes, but the design had two main flaws; the task I used showed a floor effect for intrusions and thus was not sensitive enough to detect potential group differences and the design used a median split to form the two groups resulting in overall rather small group differences in mathematics anxiety. Additionally, it is reasonable to expect an indirect effect of mathematics anxiety on mathematical performance through working memory (Skagerlund et al., 2019). In fact, the authors, assessed working memory and mathematical performance in adult university students. Then they assessed direct and indirect effects of mathematics anxiety on mathematical performance (both numeracy and arithmetic) and found that mathematics anxiety showed a significant direct effect on both numeracy (β = -.15) and arithmetic (β = -.28). Moreover, the authors observed an indirect effect of mathematics anxiety on numeracy through working memory (β = -.14) and on arithmetic through working memory (β = -.15).

Regarding task sensitivity, visual inspection of the boxplots and the descriptive data showed that the number of intrusions showed a strong flooring effect, with many participants with either zero or one intrusion. Flooring and ceiling effects are known to attenuate cross-sectional effect estimation (Weuve et al., 2015) hence my pairwise comparisons were not reliable. The second limitation in my design was that I used a median split to form the two groups (high versus low mathematics anxiety). As we will see in the next section, it is possible that the overall differences in mathematics anxiety between the two groups in the previous study were not large enough to show clearer effects. These two factors together suggest that a follow-up study would be interesting to run to have stronger and clearer results to interpret. So, I decided to run a follow-up study with different design and a different measure for intrusions.

3.1.1 Study design

Based on previous research a better design for large group differences might be the creation of two extreme groups based on mathematics anxiety. Much of the available literature on mathematics anxiety either used an extreme groups design (Maloney et al., 2011; Passolunghi et al., 2016), or used three groups (i.e., low mathematics anxiety, medium mathematics anxiety, and high mathematics anxiety; Ashcraft & Kirk, 2001). For example, Maloney and colleagues (2011) administered the AMAS questionnaire during a mass testing session with undergraduate students. From the whole sample, the authors selected the participants whose AMAS score was either lower than 20 (24 participants), or higher than 30 (24 participants). The ones with an AMAS score below 20 were considered in the low mathematics anxiety group. The ones with a score over 30 were considered in the high mathematics anxiety group. More recently Passolunghi and colleagues (2016) used AMAS to measure mathematics anxiety in secondary school students. From 135 tested students, the authors selected two different groups of participants based on their AMAS score, trait anxiety (measured with RCMAS-2) and Primary Mental Abilities – Verbal subscale. Participants selected for the low mathematics anxiety group were the students that showed scores around the mean on all three measures. Participants selected for the high mathematics anxiety group were the students that showed scores of 1 standard deviation or more above the mean on the AMAS, and scores around the mean for the other tasks. Finally, Ashcraft and Kirk (2001) used sMARS (short Mathematics Anxiety Rating Scale) to measure mathematics anxiety in 66 college students. Participants were divided into three groups based on the score on the sMARS. Participants with scores at least 1 standard deviation below the mean were considered in the low math anxiety group. Participants with scores between -0.5 and +0.5 standard deviations from the mean were considered in the medium mathematics anxiety group. Participants with scores at least 1 standard deviation above the mean were considered in the high mathematics anxiety group.

Moreover, Conway and colleagues (2005) suggest that extreme group comparisons are efficient in detecting the presence of relationships between working memory and other constructs. The authors report a mathematical example of how an extreme group design tends to slightly overestimate the effect size of a relationship, with moderate effects being the ones with the highest overestimation. This means that although there is a slightly enhanced risk of type 1 error, the use of an extreme group design is cost-efficient because it allows the detection of effects with a lower number of participants.

My goal in designing the study was to detect differences if there were present. As we saw, an extreme group design would be more in line with the existing literature and it would allow easier detection of differences. Hence, I decided to use an extreme groups design (please see chapter 3.2.1, page 96 for a description of the grouping criterion).

3.1.2 Performance and Anxiety

In the previous study, I used the GAD-7 questionnaire to test trait anxiety. Trait anxiety is defined as a relatively stable tendency of being prone to anxiety (Spielberger, 1983). Since trait anxiety is a stable tendency, it might be better to add a measure of how anxious the participants are during the testing session. This decision was based on previous studies which suggest that when investigating task performance, other than trait anxiety, it is important to control for state anxiety. State anxiety refers to the current condition and feelings of apprehension, nervousness, and worry (Spielberger, 1983). In fact, Eysenck and Calvo's review (Eysenck & Calvo, 1992) concluded that individuals with high state anxiety showed poorer efficiency of attentional processing because much of their attentional resources are wasted on anxious thoughts. Their predictions were supported by Calvo and colleagues' (1994) findings that participants with high test anxiety took longer in reading tests than participants with low test anxiety. However, the two groups did not differ in text comprehension. Moreover, Zohar (1998) found that state anxiety was negatively correlated with test performance in academic situations. In his study, Zohar investigated the relationship between the performance in the SAT-I (which is an Israeli college entrance exam) and state anxiety. The SAT-I includes three different exams; quantitative skills, verbal skills, and an English test. They found significant negative relationships between state anxiety and all three subtests relationship (state anxiety: with the quantitative exam subtest $r = -.25$; with the verbal exam subtest $r = -.32$, with the English exam subtest $r = -.48$). Together, these results suggested a negative relationship between state anxiety and test performance. Finally, Seipp (1991) found that state anxiety can be used as an indicator of the participant's anxiety levels during test-taking. These reasons prompted me to add a measure of state anxiety (please see chapter 3.2.2.2 page 98) in the current study.

3.1.3 Reasoning Abilities

Extreme group designs are susceptible to bias (Field, 2013). Because the division in groups is not randomly assigned, but based on a characteristic, third variables may be causing the effect that is detected. This type of problem is hence a source of potential bias. For this reason, it is important to control for variables that are known to relate to the variables of interest. We saw in the previous paragraph that I measured trait and state anxiety because they are related to mathematics anxiety (please see Chapter 1.2.2 page 27). Another factor that needs to be considered is reasoning abilities. There are two different reasons why I decided to control for the effect of reasoning abilities.

The first reason is that available literature suggests a relationship between learning mathematics and IQ. McGrew and colleagues (1997) found a relationship between mathematics and fluid reasoning (the ability to reason and to solve problems using new information and procedures). More recently Taub and colleagues (2008) used a subsample of participants from the Woodcock Johnson III standardization sample. This subsample was composed of participants aged 5 to 19 years. The authors measured fluid reasoning with the subtests Numerical Reasoning, Concept Formation, and Analysis-Synthesis. They also measured mathematics achievement with the subtests Applied Problems and Calculation of the WJ III ACH. They found that fluid reasoning showed significant and large direct effects on mathematics achievement. These results are in line with longitudinal data from Primi and colleagues (2010). The authors used a multilevel growth curve to look at the relationship between fluid intelligence (measured with the Differential Reasoning Tests Battery) and math achievement (measured with the 3EMat). The authors found that in Year 7 students there are relationships between mathematics and reasoning abilities. Moreover, by using longitudinal data they found that at the end of the Year 8 mathematical rate of learning was positively correlated with scores on the fluid intelligence task (Primi et al., 2010).

The second reason is that there is evidence of a relationship between working memory capacity tasks and IQ measures. Baddeley's model of working memory (Baddeley et al., 2015) states that there are two slave systems called the phonological loop and the visuo-spatial sketchpad. These two systems are usually referred to as the short term memory, a simple storage component (Engle et al., 1999). On the other hand, working memory is that storage component with the addition of an attentional component (Engle et al., 1999). In Engle's review (2002) it was suggested that when we use working memory capacity measures we are measuring these two different constructs, the short term memory component and the attentional component. Engle's conclusion derived from previous work (Engle et al., 1999) where the authors used structural equation modelling to look at the relationships between short-term memory, working memory, and fluid intelligence. The latent variable analysis suggested that only working memory capacity tasks (namely operation span, reading span, and counting span) showed a relationship with fluid intelligence measures(Engle et al., 1999). Engle (2002) then suggested that intelligence is an important factor to control for when investigating working memory capacity differences.

3.1.4 Reading and Listening Span tasks

In the previous study intrusions in the listening span task showed a flooring effect. This prompted me to develop a more sensitive measure that would be able to detect individual and group differences if present. I decided to prepare a reading span task. This new task needed to be more sensitive to the efficiency of the inhibition processes.

First, I decided to make the task more challenging. To this end, I used different sentences in the reading span to make the co-occurring process of sentence comprehension even more cognitively demanding. The result was that I created new sentences with a more complex structure and that were based on concepts that require more attention to answer. For example, in the listening span, one sentence was: "Chocolate is eaten on spaghetti". Conversely, one sentences of the reading span was: "Lawyers are people that spend their lives studying the law, so that they can use their knowledge to work in courtrooms and orchards". The second sentences has a more complex structure compared with the first one. It is also important to note that both sentences can be answered with general knowledge, but that the second one requires more cognitive resources to understand its meaning.

A second factor that needs to be considered is the effect of subvocal rehearsing. Subvocalization refers to the speech, often internal, that is sometimes used to read (Reber & Reber, 2001). Listening span tasks can be aided by subvocal rehearsing (Baddeley et al., 2015). This means that in retaining the information, the participant can keep the memory trace active by subvocally repeating the words that he/she needs to remember. On the other hand, the reading process suppresses this possibility, as the subvocal rehearsing mechanism is used to read. For this reason, I decided to use a reading span task.

Thirdly, I considered semantic similarity. Semantic similarity refers to when two or more words have a similar meaning. In regular span measures, this is not a problem, because it shows interference effect only in delayed recall (Baddeley et al., 2015). However, the reading span task has a maximum of six sentences. When presented with a list of six sentences, there is some delay between the presentation of the first word that needs to be remembered and the cue for recall. For this reason, I decided that it was best to reduce this possible source of bias and eliminate the sentences where the last word was semantically similar to other words in the same series or adjacent series.

Finally, I considered proactive interference (PI). Proactive interference refers to a memory mechanism by which what is learned now will influence the performance on future tasks (Quinlan & Dyson, 2008). In this task, more proactive interference increases the chance of having intrusions. In fact, when we are processing and keeping active one list, the inhibition mechanism needs to inhibit previous irrelevant information to avoid intrusions. The higher the amount of previous information, the higher the chance of the presence of errors from the inhibitory mechanisms. For example, in Keppel and Underwood (1962) participants had to retain a syllable for either 3 or 18 seconds. Syllables from the earlier part of the task were remembered regardless of time. However, the further into the trial, the fewer syllables could be remembered after 18 seconds compared with 3 seconds delay, suggesting that previous trials caused proactive interference in the retention of the mnesic material. More recently, Lustig and colleagues (2001) found that reading span scores were affected by the order of presentation of the material. The authors prepared long (four sets of sentences), medium (three sets of sentences), and short (two sets of sentences) trials. The design required two different procedures for presenting the trials. The normal procedure starts with the short trials and progressively arrives in the long trials. The descending procedure presented the long (four set of sentences) trials first and ended with the short trials. When the participants deal with the long set trials, in the descending procedure there is no proactive interference from previous trials. In the normal procedure instead, participants deal with the long set after going through the short set ones. In the descending procedure, performance on the long sets was significantly better compared with performance on long sets in the normal procedure. This suggests that proactive interference can have a significant effect on the performance on long sets of trials. Hence, I decided to add more sentences to enhance the proactive interference effect of the task. However, the span of unrelated words is around five items (Baddeley, 2010), and a span task with more items starts to require the recruitment of long-term memory processes. Although the goal was to stress the working memory system, I should avoid bias from long-term memory. To avoid long-term memory bias in the measure, I used a maximum of six sentences per set. To have a higher number of trials without exceeding six sentences per set, I added more trials with six sets of sentences. The resulting task has two trials for each set of sentences from two sentences to five sentences. After these set of sentences, the task presents six sets with six sentences (please see chapter 3.2.2.2, page 99 for a more complete review on the construction of the reading span task).

The newly developed Reading span task was piloted together with the listening span task in 10 participants. I found that the listening span showed a ceiling effect (with 1 out of 10 participants at ceiling), whereas no participant managed to remember all words in the reading span. I also found that the intrusion measure showed a flooring effect for the listening span. The reading span instead showed no flooring effect in the intrusion measure. The reading and the listening span tasks were not significantly correlated (r_s = -.11, p = .762), prompting me to decide to include both measures in the study. Moreover, after we piloted the new Reading span task, we observed that nine items showed semantic similarity as they were referring to similar concepts and were removed and replaced. Finally, I found that seven sentences were too complex (e.g., "The Hawaiian Islands have formed thanks to a long series of eruptions from the earth and reached altitudes over 5000 meters above the sea level), and were simplified to reduce bias from reading comprehension (i.e., "The Hawaiian Islands have formed thanks to a long series of volcanic eruptions.").

3.1.5 Hypotheses

In the previous study, I found a significant difference between participants with high mathematics anxiety and participants with low mathematics anxiety in simple verbal and visuo-spatial working memory tasks. Accordingly, I expected to find significantly higher simple working memory spans for the participants in the low mathematics anxiety group than for the participants in the high mathematics anxiety group. My previous study also showed that the participants with low mathematics anxiety showed a significantly higher complex working memory span compared with the participants with high mathematics anxiety. However, in the current study, I added the reading span task. I decided to replicate the finding with both measures, i.e., the listening and the reading span task. This also ensures that any potential differences in findings between this and the previous study cannot be due to using only a new measure of complex working memory. Consequently, I expect to find significantly higher span scores in the low mathematics anxiety group compared with the high mathematics anxiety group in the listening and the reading span tasks. Finally, the main reason for this follow-up study was to investigate the effect of mathematics anxiety on the efficiency of the inhibition processes. The previous study concluded that listening span task was not sensitive enough to detect high number of intrusions in adults. Moreover, visual inspection of the data suggested that there could be a difference in intrusions. I am now using the new reading span task developed to be more sensitive to detect intrusions. Accordingly, I expect to find a difference in the number of intrusions between the participants in the two groups in the reading span task.

3.2 Methods

3.2.1 Participants

Participant screening: I screened 192 first- and 77 second-year Psychology students at a University in the North Yorkshire using the Abbreviated Math Anxiety Scale (overall AMAS mean 20.10, AMAS range 9-43). The mean AMAS score for first-year students (mean age 18.83, age-range 18-32, 158 females) was 19.61(range 9-43) and for second-year students (mean age 20.19, age-range 19-51, 70 females) was 21.32 (range 11-35).

For the follow-up laboratory testing, I selected only female participants because gender might be an important factor in mathematics anxiety (Hill et al., 2016). Furthermore, 82.29% of participants in my screening sample were female, rendering it difficult to control for gender effects in other ways. Moreover, I selected only native English speakers, to avoid potential differences in the working memory tasks caused by fluency differences in English (in the screening sample there were overall 226 native English-speakers: 164 in Year 1 and 62 in Year 2).

I also excluded all participants whose age deviated by three or more standard deviations from the screening sample mean (N=6), because age is related to performance on working memory measures (Salthouse, 1992).

Laboratory testing: To select the participants for the laboratory testing, I invited screened participants based on their AMAS score in the screening.

1st Year students: For the first-year students, based on the distribution of their AMAS scores, I invited the 25 participants with the lowest AMAS scores (AMAS < 16) and the 25 participants with the highest AMAS scores (AMAS > 25) to take part in the laboratory testing. Of those students, 19 first-year students with low AMAS scores (mean age 18.37 years, age range

18 – 20 years) and 16 first-year students with high AMAS scores (mean age 18.50 years, age range 18 – 21 years) took part in the laboratory testing session.

2nd Year students: For the second-year students, I invited all participants with AMAS scores below 16 or above 25 to take part in the laboratory testing. I used the same AMAS cut off scores as for the first-year students. Of the 14 second-year students with low AMAS scores that were invited, seven (mean age 19.57 years, age range 19-21 years) took part in the laboratory testing session. Of the 23 second-year students with high AMAS scores that were invited 12 (mean age 19.75 years, age range 19-22 years) participated in the laboratory testing session.

Full Sample: A total of 54 participants engaged in both sessions of the study (mean age 18.87 years, age range 18 – 22). For the descriptive statistics of the full sample divided by group (LMA: low mathematics anxiety, HMA: high mathematics anxiety) see Table 3.1.

Ethical approval was obtained from the ethics committee of the Psychology Department of the University of York. The screening session lasted for approximately 10 minutes, and all participants were awarded course credit (0.25 hours). The testing session lasted for approximately 1.5 hours, and participants either received a monetary reward (8.5 £) or course credit (1.5 hours).

3.2.2 Materials

3.2.2.1 Screening

Mathematics anxiety

To assess the participants' mathematics anxiety, I used the Abbreviated Math Anxiety Scale (AMAS; Hopko, Mahadevan, Bare, & Hunt, 2003). AMAS is a self-report questionnaire (see Appendix A.3) that is composed of 9 items associated with different math-related situations related to school and in everyday life (e.g., "Watching a teacher work an algebraic equation on the blackboard"). Participants were asked to rate their feelings during those situations using a 5-point Likert scale, from 1 – No bad feelings; to 5 – Worst feelings (AMAS Min = 9; Max = 45). The AMAS showed good internal consistency in my sample ($\alpha = .88$), and good two-week test-retest reliability ($r = .85$) reported by Hopko et al. (2003) in undergraduate students.

First-year students were screened in the computer lab. I used the software Qualtrics to display the AMAS items on a computer. Second-year students were screened during a lecture using a paper-and-pencil version of the same questionnaire. Although in this case the AMAS was given with a different medium, I do not expect an effect of media. In fact, Jones and colleagues (2012) found that there was a strong correlation ($r = .91$) between a paper and pencil and an online version of the AMAS taken one week apart. Moreover, Cipora and colleagues (2017) compared an online study and a paper and pencil study and found only small differences between them (Cohen's $d = 0.15$).

3.2.2.2 Laboratory testing

Verbal working memory

To assess verbal working memory, I used a letter span task (Marcel, 1974) developed by myself. The task requires participants to repeat a series of letters after hearing them spoken, in the same order as they heard them. I used the same task as in the first study, so for the details please see chapter 2.2.2, page 64.

Visuo-spatial sketchpad

To assess visual working memory, I used the Corsi Span task forward (a subtest of the Wechsler Memory Scale, WMS-III) (Wechsler, 1997). In this task, participants are asked to touch a series of blocks in the same order as the examiner touched them. I used the same task as in the first study, so for the details please see chapter 2.2.2, page 64.

Central executive

As dual tasks, I decided to use a Listening Span task and a Reading Span task (Daneman & Carpenter, 1980). The tasks require the participants to listen to or read a set of sentences (for example: "Chocolate is eaten on spaghetti"; see Appendix A.2 for the full listening span). For each sentence, participants have to decide if the statement is true or false and remember the last word of the sentence. At the end of the set of sentences, the participant is asked to repeat the last word of each sentence, in the same order as they were presented. Because in this way the participant needs to actively process two types of information, namely the last words of each sentence and the sentence itself to decide whether it is true or false, the participant is engaged in a dual task.

A set of sentences details how many sentences the participant will listen to (or read) before prompted to recollect the last words. For example, a set of two sentences will require the participant to listen to two sentences (e.g., "Chocolate is eaten on spaghetti" and "Bees make honey") before being prompted to recollect the two last words (i.e., spaghetti and honey). A set of three sentences will require the participant to listen to three sentences before being prompted to recollect the three last words, and so forth. The set of sentences starts with two sentences and ends with six sentence per set. Each level has two different sets of sentences, i.e., the first level will present four sentences, two times a set of two sentences and the last levels (with six sentences per set) will present twelve sentences each level; six for each set. The presentation is concluded after all sets of sentence have been presented, i.e., there is no discontinuation rule.

This task allows two different measures: *Words*, indicating the number of last words correctly remembered during the whole presentation (for the listening span task, Min = 0; Max = 40; for the reading span task, Min = 0, Max = 64) and *Intrusions* indicating the number of non-target words erroneously recollected (e.g., from the sentence "Chocolate is eaten on spaghetti" the participant remember chocolate or tomato sauce) (for the listening span task, Min = 0; Max = 40; for the reading span task, Min = 0; Max = 64). In the current study, performance in the listening span and the reading span showed a good correlation.[2] I will report the measures of number of correct trials as working memory capacity, whereas the number of intrusions can be considered the inverse of inhibition efficiency (i.e., more intrusions, lower efficiency).

Reasoning ability

To assess participants' reasoning skills, I used the Matrix Reasoning subtest of the Wechsler Abbreviated Scale of Intelligence – Second Edition (WASI-II, Wechsler, 2011). The matrix reasoning subtest includes 30 incomplete matrixes or series of increasing difficulty. For each incomplete matrix, the participants need to find the option that completes it in the correct way. In adults, one point is given for each correct option identified. There are 30 matrixes, the administration is stopped after three consecutive errors (Max score= 30).

The internal consistency reliability coefficients show on average high reliability (17 to 19 years, $r = .85$; 20 to 24 years, $r = .87$, Wechsler, 2011). Moreover, the scale showed high test-retest reliability ($r = .82$, Wechsler, 2011). The matrix reasoning subtest also shows a strong

[2]In my study, the span scores showed a medium to large correlation ($r = .45$, $p = .001$). I expected the measures to not show a perfect correlation, because in the listening span task participants can use subvocal rehearsal techniques; whereas in the reading span task these techniques are not possible.

correlation with other intelligence measures (e.g., strong correlation with Wechsler Adult Intelligence Scale-Fourth Edition (WAIS-IV; $r = .70$; Wechsler, 2011).

Mathematical performance

To assess the participants' mathematical proficiency, I used the blue form of the mathematical subtest of the Wide Range Achievement Test (WRAT-4, Wilkinson & Robertson, 2006). The task was the same used in the first study, so for the details please see chapter 2.2.2, page 64.

Arithmetical fluency

To assess participants' fluency in arithmetic I used the Simple Calculations task. The task required the participant to solve as many calculations as possible within a specific time limit. The task included three operations: addition, subtraction, and multiplication. I used the same items as in the first study, so for the details please see chapter 2.2.2, page 64.

State anxiety

To assess participants' state anxiety, I used the State-Trait Anxiety Inventory Form Y-1 (Spielberger, 1983). The form Y-1 has 20 items that assess the current levels of anxiety of the participant. Each item requires the participant to refer to how they feel at the moment (e.g., at the moment "I feel secure") on a scale from "Not at all" to "Very much so". Items are rated on a 4-point Likert scale from 1 (not at all) to 4 (very much so); however, some items (e.g., items 8 and 10) are inverted, meaning that an answer as "very much so" is coded as 1, and a "not at all" answer would be coded as a 4. The minimum score is 20, the maximum score is 80. The alpha coefficient for female college students shows high reliability (α = .93) and high reliability for females in the 19 to 39 years range (α = .93; Spielberger, 1983).

Trait anxiety

To assess participants' trait anxiety, I used the GAD-7 (General Anxiety Disorder – 7; see Appendix A.5) questionnaire. The GAD-7 is a short questionnaire of 7 items. The same questionnaire was used in the first study, so for the details please see chapter 2.2.2 page 64.

3.2.3 Design and Procedure

A between-subjects design involved the creation of two different groups: one group that had low levels of mathematics anxiety (low mathematics anxiety, LMA), and one group with high levels of mathematics anxiety (high mathematics anxiety, HMA), as described in the participants' section. The selected participants were then called back to participate in the testing session. Testing took place in a quiet room within the Psychology department of the University of York. The tasks were given in the following order: 1. letter span task; 2. Corsi span task; 3. listening span task; 4. WASI matrix reasoning subtest; 5. reading span task; 6. WRAT-4 math computation subtest; 7. simple calculations; 8. State-Anxiety Inventory; 9. GAD-7. The administration order of the listening span task and the reading span task was counterbalanced between participants within each mathematics anxiety group separately, and the answers were audio-recorded to help to code the data. Because participants were divided into groups based on their AMAS score that was recorded during the screening session, participants were not given another math anxiety questionnaire during lab testing.

3.3 Results

3.3.1 Descriptive Statistics

For the full sample of the laboratory testing (N = 54), Table 3.1 reports the descriptive statistics divided by group (low mathematics anxiety vs high mathematics anxiety). See Appendix B.1 for a report on the correlations between the measures.

Table 3.1. Descriptive statistics divided by group and differentiated between background and anxiety measures.

	LMA		HMA				
Measure	M *(SD)*	Min-Max	M *(SD)*	Min-Max	T (52)	p-value	*d*
Age	18.69 *(0.84)*	18 - 21	19.01 *(1.07)*	18 - 22	1.31	.197	0.36
Reasoning Ability	22.04 *(2.78)*	17 - 27	22.18 *(2.53)*	17 - 26	0.19	.847	0.05
Mathematical Performance	45.92 *(4.61)*	37 - 55	42.89 *(8.06)*	10 - 55	1.68	**.050[a]**	0.46
Arithmetical Fluency	68.08 *(14.14)*	27 - 91	62.54 *(15.59)*	32 - 97	1.37	.178	0.37
Mathematics Anxiety	13.15 *(1.22)*	11 - 15	29.18 *(3.98)*	26 - 43	19.67	**< .001**	5.36
General Anxiety	12.15 *(3.57)*	7 - 24	15.11 *(4.28)*	8 - 25	2.74	**.008**	0.75
State Anxiety	37.77 *(13.13)*	21 - 76	43.93 *(9.25)*	27 - 63	2.00	**.050**	0.55

Legend:

*a: one-tailed t-test

HMA: high mathematics anxiety group

LMA: low mathematics anxiety group

There were no significant group differences in reasoning ability between the low mathematics anxiety and the high mathematics anxiety groups. In contrast, mathematical performance was significantly lower in the high mathematics anxiety than in the low mathematics anxiety group when using a one-tailed test. In the literature there is evidence for a negative relationship between mathematical performance and mathematics anxiety, justifying the use of a one-tailed test here. It is important to note that the effect size is in the medium range (Cohen, 1988), which is in line with literature. Performance in simple arithmetical calculations, however, is not significantly different between the two groups.

On the other hand, not only mathematics anxiety (which was the group selection criterion) but also the two other anxiety measures (general and trait anxiety) showed significantly higher levels of anxiety in the high mathematics anxiety group. Thus, in relevant analyses I will control for the effect of trait and state anxiety, otherwise, they could influence any group differences found.

3.3.2 Differences in simple working memory

At first I assessed the group differences in verbal and visuo-spatial working memory. The results can be seen in Figure 3.1.

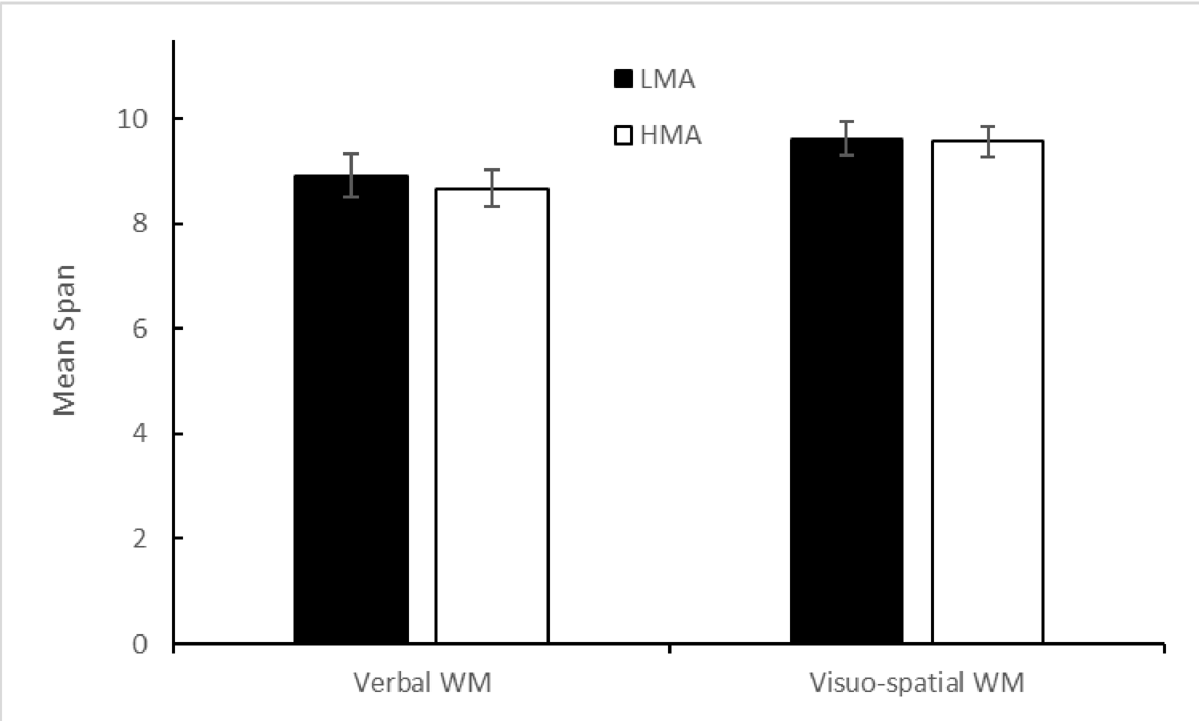

Figure 3.1. Number of correct trials on the two simple working memory span measures. The scores are divided between participants with low mathematics anxiety (LMA) and participants with high mathematics anxiety (HMA). Error bars show ± 1 standard error.

To control for the effect of trait and state anxiety on simple working memory measures I ran an ANCOVA on the number of correct trials. Previous literature suggests that the covariates should be independent from the factors (Field, 2013). However, there is no strictly statistical reason for this independence and the ANCOVA can be biased when there is no temporal additivity (Field, 2013; Senn, 2006). I have no reason to not assume temporal additivity in my sample neither for the simple nor the complex measures; hence, I do not expect this to be a source of bias.

The 2 (Type of simple working memory) X 2 (Group) mixed ANCOVA revealed a marginal main effect of working memory type $F(1, 50) = 3.84$, $p = .056$, $\eta_p^2 = .07$. This marginal result seems to suggest that there might be a difference between the scores in the two tasks, although the effect size is small. The analysis showed no main effect of Group, $F(1, 50) = 0.35$, $p = .555$ $\eta_p^2 = .01$, and no significant interaction between type of simple working memory task and mathematics anxiety group, $F(1, 50) = 0.77$, $p = .386$, $\eta_p^2 = .02$. These results indicate that despite their significant differences in mathematics anxiety, there are no significant differences between the groups on the simple working memory measures.

Moreover, the ANCOVA showed that trait anxiety was not a significant covariate, $F(1, 50) = 2.46$, $p = .123$, $\eta_p^2 = .05$, with no significant interaction with number of correct trials, $F(1, 50) = 2.07$, $p = .157$, $\eta_p^2 = .04$. Finally, also state anxiety was not significant as covariate, $F(1, 50) = 2.41$, $p = .127$, $\eta_p^2 = .05$, with no significant interaction with number of correct trials, $F(1, 50) = 0.1$, $p = .909$, $\eta_p^2 < .01$.

3.3.3 Differences in complex working memory

Next, I decided to assess the group differences in working memory capacity using the number of recalled words in the listening span and in the reading span task. The results can be seen in Figure 3.2.

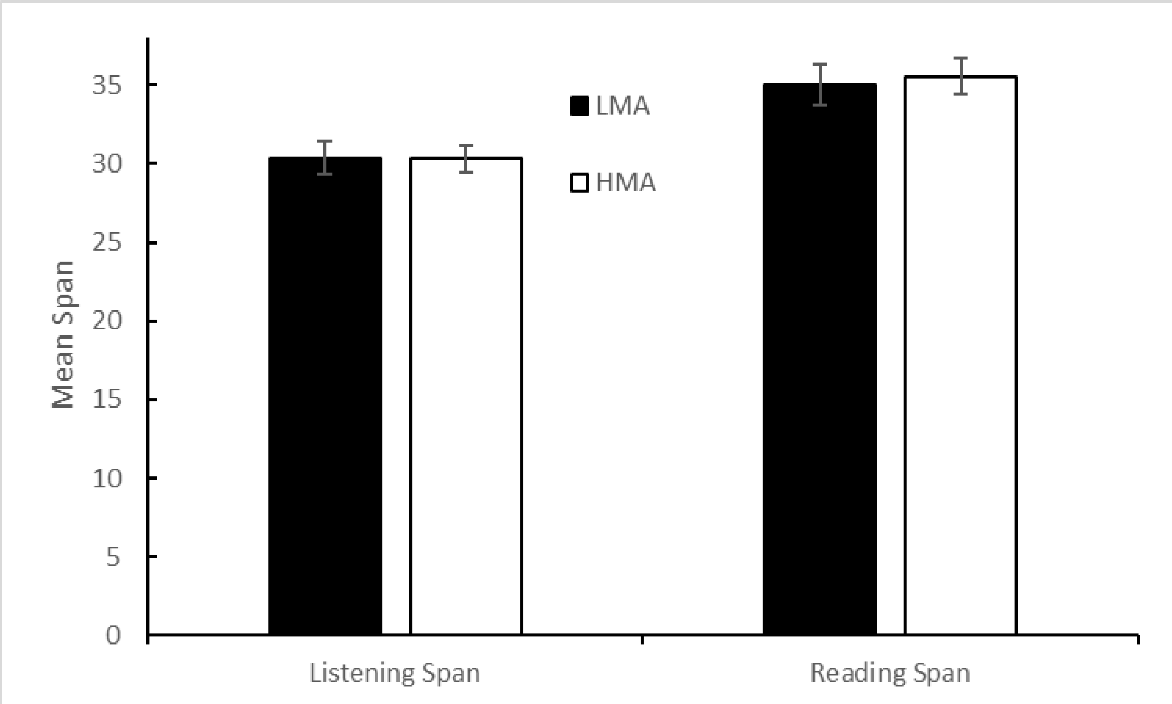

Figure 3.2. Number of correctly recalled words on the two complex working memory span measures. The scores are divided between participants with low mathematics anxiety (LMA) and participants with high mathematics anxiety (HMA). Error bars show ± 1 standard error.

To control for the effect of trait and state anxiety I ran an ANCOVA. The 2 (Type of complex working memory) X 2 (Group) mixed ANCOVA revealed a main effect of span measure, $F(1, 50) = 4.36, p = .042, \eta_p^2 = .08$. These results suggest that overall, the performance on the reading span was significantly higher than the performance on the listening span. On the other hand, the analysis revealed no main effect of Group, $F(1, 50) = 0.53, p = .469, \eta_p^2 = .01$, and no significant interaction, $F(1, 50) = 0.21, p = .646, \eta_p^2 < .01$. These results suggest that the groups show no significant differences in complex working memory; as can be seen in Figure 3.2. Moreover, the analysis showed that trait anxiety was not a significant covariate, $F(1, 50) = 0.04, p = .852, \eta_p^2 < .01$ with no significant interaction, $F(1, 50) = 1.89, p = .176, \eta_p^2 = .04$. Finally, also state anxiety was not significant as covariate, $F(1, 50) = 0.48, p = .491, \eta_p^2 = .01$, with no significant interaction, $F(1, 50) = 0.53, p = .469, \eta_p^2 = .01$.

3.3.4 Differences in the number of intrusions

From the complex working memory measures, I also obtained the number of intrusions. This is the number of wrongly recollected words during complex working memory tasks. Results can be seen in Figure 3.3 for the number of intrusions in the listening span task and Figure 3.4 for the number of intrusions in the reading span task.

Listening span. The measure of the intrusions in the listening span task showed a strong flooring effect and Shapiro-Wilk normality tests showed a problem with normality for the high mathematics anxiety group (p = .001) and the low mathematics anxiety group (p < .001). Moreover, skewness and kurtosis also suggested that the distribution was indeed not normal (skewness = 1.69; kurtosis = 4.11). For this reason, I used a non-parametric test for the analysis of the intrusions in the listening span task and could not perform the ANCOVA that I originally planned to use. A Mann-Whitney test showed that the number of intrusions in the low mathematics anxiety group (*Mdn* = 1, IQR = 1) was not significantly different than the number of intrusions in the high mathematics anxiety group (*Mdn* = 1, IQR = 2), U = 338.50, p = .642. The distribution of intrusions for the two groups can be seen in Figure 3.3.

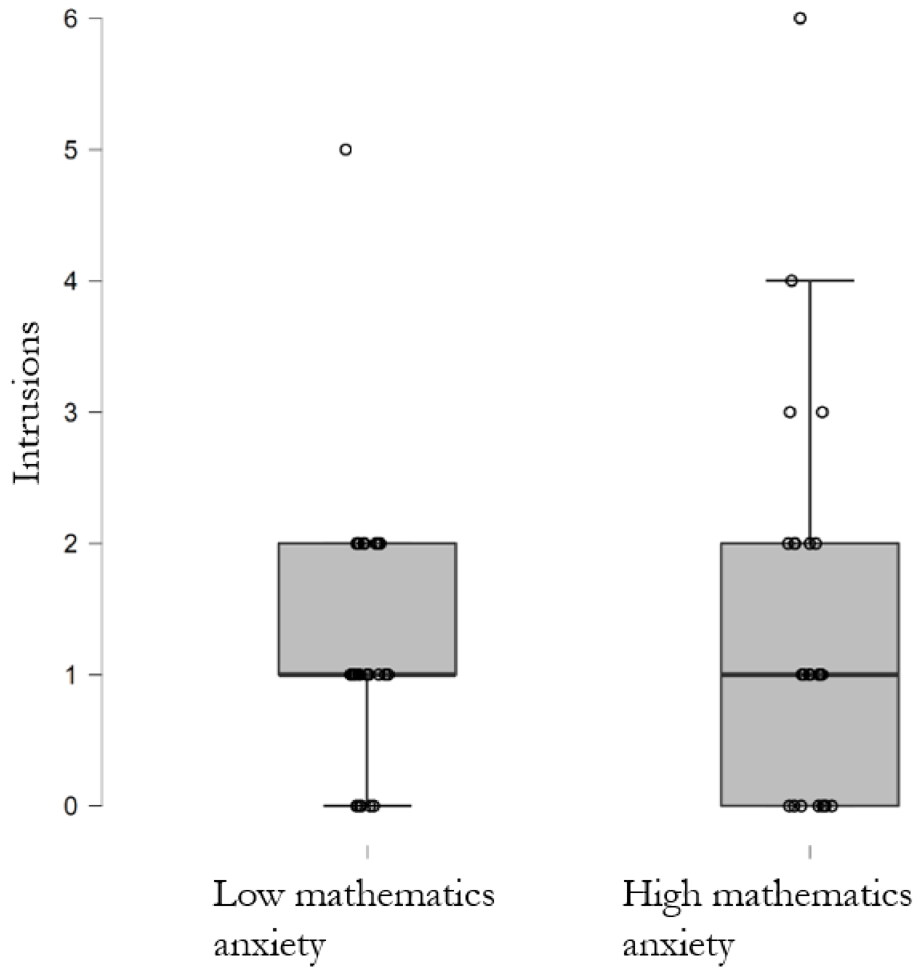

Figure 3.3. Boxplot showing the number of intrusions in the listening span task. The scores are divided between participants with low mathematics anxiety and participants with high mathematics anxiety.

Reading span. Shapiro-Wilk normality tests showed a problem with normality for the low mathematics anxiety group (p = .004). However, the ANOVA is a robust test, and skewness and kurtosis are within the acceptable limits for this measure (skewness = 0.91; kurtosis = 0.68). For this reason, I decided to run an ANCOVA with general and state anxiety as covariates. Moreover, Osborne and Overbay (2004) suggest removing outliers of a specific group instead of the whole sample. For this reason, since two participants of the low mathematics anxiety group were clear outliers (i.e., score more than 3 SDs above the group mean), I removed them from the analysis. I only removed them from this analysis as they were clear outlier for their low mathematics anxiety group, but in the other comparisons did not show such different performance, hence I decided to not exclude these two participants from the rest of the analyses. The two participants excluded were the participant number three and the participant number 34. Participant number three was 18 years old, had low mathematics anxiety (AMAS = 12), average reasoning abilities (Reasoning abilities = 25), and average mathematical performance (WRAT-4 mathematical subtest = 47). Participant number 34 was 18 years old, had low mathematics anxiety (AMAS = 15), average reasoning abilities (Reasoning abilities = 24), and average mathematical performance (WRAT-4 mathematical subtest = 40). The one-way ANCOVA showed that Group was a significant factor in the number of intrusions for the reading span task, $F(1, 48) = 7.14$, $p = .010$, $\eta_p^2 = .13$. Both trait anxiety, $F(1, 48) = 0.44$, $p = .509$, and state anxiety, $F(1, 48) = 0.05$, $p = .824$, were not significant covariates of number of intrusions in the reading span task. In Figure 3.4 we can see that the number of intrusions is significantly higher in the high mathematics anxiety group compared with the low mathematics anxiety group in the reading span task. These results suggest that higher levels of mathematics anxiety are associated with a higher number of intrusions during the completion of the reading span task. This relationship is independent of general and state anxiety.

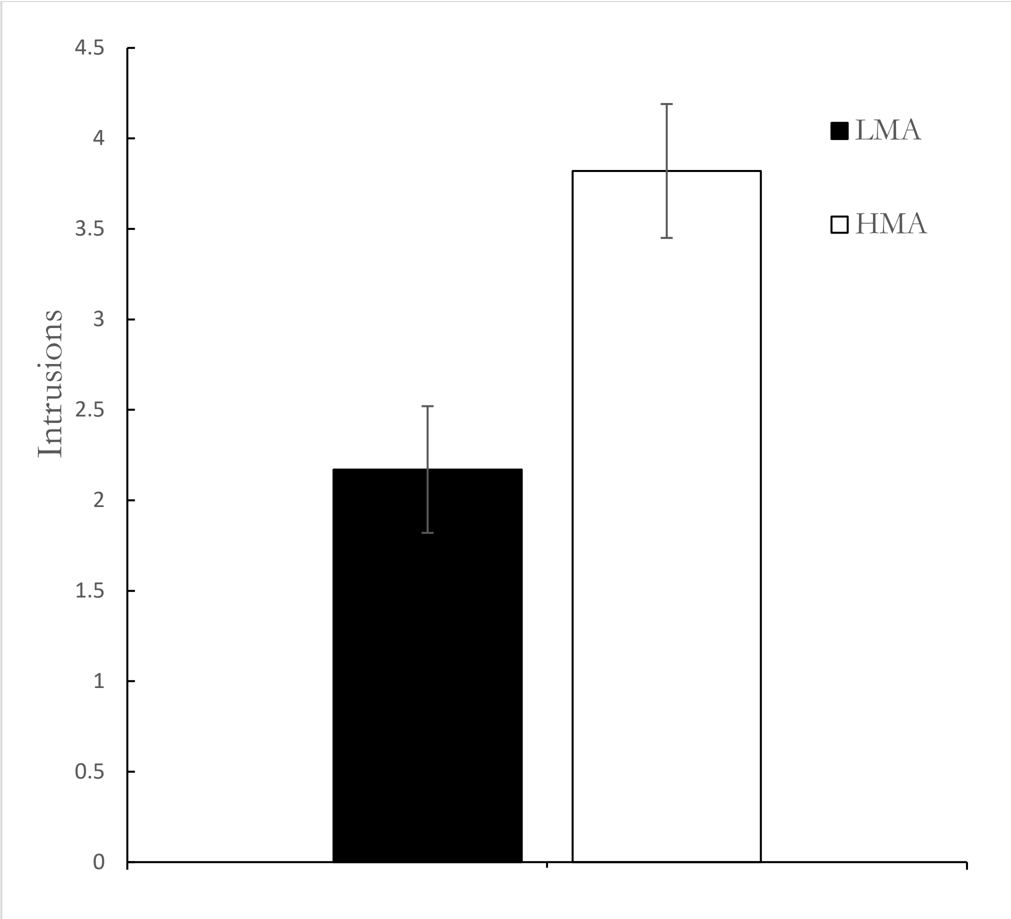

Figure 3.4. Mean number of intrusions in the reading span task. The scores are divided between participants with low mathematics anxiety (LMA) and participants with high mathematics anxiety (HMA). Error bars show ± 1 standard error.

3.4 Discussion

Based on results presented in chapter 2, in the current study I used an extreme group design to further investigate the following predictions:

1) The high mathematics anxiety group will show lower scores in verbal and visuo-spatial working memory than the low mathematics anxiety group;

2) The high mathematics anxiety group will show a lower performance on the listening and the reading span tasks (Total score) than the low mathematics anxiety group;

3) The high mathematics anxiety group will show a higher number of intrusions in the reading span task, but no significant difference in the listening span task, than the low mathematics anxiety group.

Results show that high mathematics anxiety and low mathematics anxiety groups did not show significant differences in simple and complex working memory tasks. The number of intrusions in the listening span task was also not significantly different between the two groups. On the other hand, the participants with high mathematics anxiety showed significantly more intrusions in the reading span task compared with the participants with low mathematics anxiety. This difference was still significant after controlling for the effect of general and state anxiety.

3.4.1 Simple Working Memory

The first hypothesis in this study stated that there would be a significant difference in simple working memory spans between the low mathematics anxiety group and the high mathematics anxiety group (Ganley & Vasilyeva, 2014; Passolunghi et al., 2016). For example, Passolunghi and colleagues (2016) found significant differences in a verbal working memory task and Ganley and Vasilyeva (2014) found a significant difference in a visuo-spatial working memory task; hence, I expected similar findings with my participants. In line with the literature, in the previous study (please see chapter 2) I did find significant differences between the two groups in verbal and visuo-spatial working memory. However, against my predictions, the participants of the current study in the low mathematics anxiety group did not show a significantly different span from the participants in the high mathematics anxiety group in either of the measures. A possible explanation could be that I used a different study design. In chapter

2.3.1 the groups were created based on a median split, whereas in the current investigation I opted for an extreme group design. Some theories propose an inverted U relationship between anxiety and performance (Mair et al., 2011). This hypothesis, also known as the Yerkes-Dodson law (Corbett, 2015), states that low and high levels of arousal are associated with lower levels of performance. According to this hypothesis, by cutting away part of the distribution, I excluded the area where I could have found the differences. However, the results from the literature do not suggest that this is the case for mathematics anxiety. Miller and Bichsel (2004), for example, suggested a linear relationship between mathematics anxiety and mathematical performance. On a broader level, Westman and Eden (1996) in their study found support for a negative linear relationship between arousal and performance. In general, many authors (e.g., Corbett, 2015; Jamal, 2007) think that the inverted U hypothesis is no longer a good explanation of the relationship between anxiety in general and performance.

Moreover, it is possible that the results in the previous study were a spurious finding. Because the sample was of 32 participants it is possible that random effects drove significant results (e.g., some participants in the high mathematics anxiety might have had lower working memory scores for reasons unrelated to mathematics anxiety). If this was the case, it is possible that simple working memory span is not related to mathematical anxiety. Indeed, previous reports of differences in simple working memory between groups with low mathematics anxiety versus high mathematics anxiety are mixed. Several found group differences for visuo-spatial but not verbal working memory. Mammarella and colleagues (2015) measured simple verbal and visuo-spatial working memory in Year 6 to 8 students with forward word span and forward matrices. The authors found that the students with high math anxiety showed poorer scores in the forward matrices task (simple visuo-spatial working memory) but not in the forward word span. However, Mammarella and colleagues' study tested primary school students and there may be differences in the relationship between working memory and mathematics anxiety between adults and children. Verbal and visuo-spatial working memory might be related to mathematics anxiety in primary school students, but not in adults. Interestingly, in university students, Georges and colleagues (2016) also found no significant differences in verbal working memory (backward digit span) between groups with high versus low mathematics anxiety. Thus, finding no difference in the verbal working memory in my study might not be entirely unexpected, even though I did find a difference in the verbal working memory in Study 1.

On a different note, it is interesting that neither trait anxiety nor state anxiety were significant covariates. This suggests that neither of these factors influence performance on simple working memory tasks. However, this does not mean that trait and state anxiety were not related to mathematics anxiety, it only means they did not affect working memory. Existing literature suggests a relationship between mathematics anxiety and other types of anxiety (Dowker et al., 2016), and my sample is in line with these results showing significant relationships between mathematics anxiety and trait anxiety ($r(53) = .36, p = .008$) and between mathematics anxiety and state anxiety ($r(53) = .27, p = .047$). For the complete correlation matrix of the current study, see Table B.1 in Appendix B.1.

3.4.2 Complex Working Memory

The second hypothesis in this study was that there would be significantly higher complex working memory spans (i.e., listening and reading span) in the participants with low mathematics anxiety compared with the participants with high mathematics anxiety. I found a significant effect on the listening span in the previous experiment and the listening span task was the same task that I used as a complex working memory measure in the previous study. Besides, I expected also an effect on the reading span. I developed this task to have a more sensitive measure, in particular for the number of intrusions. While the reading span indeed was more sensitive to intrusions (see next section), against my predictions, I did not find a significant difference in the number of words correctly recollected between the participants in the two groups for either complex working measure.

In both tasks the differences between the low mathematics anxiety and the high mathematics anxiety groups were non-significant. There are different possible explanations for these results. A possibility is that males and females show different relationships with mathematics anxiety. In fact, the literature suggests a significant difference in the relationship between mathematics anxiety and mathematical performance between females and males (Hembree, 1990; Miller & Bichsel, 2004). It is possible that the same could be the case for the relationship between mathematics anxiety and working memory. Indeed, when selecting only female participants from the sample of the previous study reported in Chapter 2, the analysis showed that the differences in the listening span between the groups with high and low mathematics anxiety were no longer significant[3]. The analysis reported in footnote 3 shows that indeed the relationship between mathematics anxiety and complex working memory span is different between males and females. Females did not show a significant relationship, whereas males showed a significant relationship. In fact, although the p-value is only marginally significant, the effect size suggests a large effect. Hence, the non-significance may be due to the sample size being too small. Put together, the current results and the results from the previous study might suggest that although males with mathematics anxiety show a reduced span in complex working memory tasks, females might not show this effect. To the best of my knowledge, this option has not been assessed yet, and future studies might want to address this question further to understand the reasons behind this potential difference between females and males.

[3] Female Listening Span: The 2 (Group) X 2 (Session) ANOVA show that there is not a significant effect of group on the span with LMA (M=32.83; SD=3.49) showing non-significantly higher span than HMA (M=29.46; SD=6.12) participants, $F(1, 18) = 2.16$, $p = .159$ $\eta_p^2 = .11$.
Male Listening Span: The 2 (Group) X 2 (Session) ANOVA show that there is a marginally significant effect of group on the span with LMA (M=34.19; SD=4.28) showing a higher span than HMA (M=29.00; SD=3.24) participants, $F(1, 10) = 4.50$, $p = .060$ $\eta_p^2 = .31$.

Another possible reason why I did not find a significant difference could be that previous results were spurious findings and there is no significant difference in the population. Indeed, some researchers found significant differences in complex working memory span between individuals with high and low mathematics anxiety (Mammarella et al., 2015) while other researchers didn't find significant differences (Miller & Bichsel, 2004; Ashcraft & Kirk, 2001). Mammarella and colleagues (2015), for example, found significant differences in backward word span and backward matrices span between participants with high and low levels of mathematics anxiety. However, the authors tested Year 6 to 8 students. Other authors tested adults and found no significant differences between participants with low and high levels of mathematics anxiety when using non-mathematical stimuli. For example, Miller and Bichsel (2004) found no significant relationship between reading span and mathematics anxiety in university students. Interestingly, the reading span task they used was similar to the reading span used in the current study. Moreover, Ashcraft and Kirk (2001) used a Listening Span task (L-Span) and a Computation Span task (C-Span). Both tasks were significantly related to mathematics anxiety, but once the relationship was controlled for the common variance between both tasks, only the C-Span was significantly related to mathematics anxiety. In Experiment 3 the authors showed that only the C-Span, and not the L-Span, showed a significant decline with the increase of mathematics anxiety, suggesting that the relationship between mathematics anxiety and working memory is more evident when numerical instead of neutral material is used. These results suggest that there might be differences in the relationship of mathematics anxiety and working memory between adult university students and primary and secondary school students. Possibly there are no differences in complex working memory measures using non-mathematical material (like in my case) between groups with high and low mathematics anxiety in university students.

This finding was unexpected. An alternative explanation could be that university students with high mathematics anxiety might have developed strategies to overcome their difficulties and possibly recruited more cognitive resources, to compensate for their lower efficiency. There is some evidence from neuroimaging studies (Lyons & Beilock, 2012a) that between the participants with high mathematics anxiety, the ones that performed well on mathematical tasks showed higher recruitment of frontoparietal regions involved with high-level control functions (e.g., inhibition processes) when preparing for a math task. This was interpreted as supporting evidence that participants that can recruit more cognitive resources show less detrimental effects of mathematics anxiety. The psychology department of the University where I tested has strict acceptance rules. To be a student in the department where I tested you need to have a history of academic success. To be successful in academia the students might have developed coping mechanisms to overcome their deficits. In fact, Reis and colleagues (2000) found that students with learning disabilities can succeed in college by developing compensation strategies. Investigating differences in strategy use between individuals with high mathematics anxiety and low mathematics anxiety might be an interesting idea for future studies.

3.4.3 Intrusions

The third hypothesis in this study regards the number of intrusions in the complex span tasks. For the listening span task, I did not expect to find significant differences between low and high mathematics anxiety groups, because I used the same task as in Chapter 2 and there were no significant effects of mathematics anxiety on intrusions in the listening span task. In line with the previous findings, I did not find a significant difference in the number of intrusions between the two groups.

Because of the flooring effect on the listening span reported in the previous chapter, I created a new measure of intrusions, a reading span, with the aim of increased sensitivity to measuring intrusions. I predicted that this increase in sensitivity would allow the recording of an effect if there were one. For this reason, I expected that there would be a significantly lower number of intrusions in the reading span task for the participants in the low mathematics anxiety group compared with the participants in the high mathematics anxiety group. Indeed, this is what I found, suggesting that the sensitivity manipulation was successful. While overall the number of intrusions was still low in both groups, the group with high mathematics anxiety made on average 1.05 (37.91%) more intrusion errors than the group with low mathematics anxiety.

It is plausible that participants with high mathematics anxiety show more intrusions in the reading span because their cognitive control processes are deficient. Cognitive control refers to the processes that allow voluntary control over stimuli, cognition, and behaviours. Moreover, it refers to the capacity to selectively focus on specific stimuli and cognitions (Tiego et al., 2018). That participants with high mathematics anxiety have lower efficiency of the cognitive control processes is supported by studies showing differences in cognitive control between participants with high and low levels of anxiety behaviourally (Shields et al., 2016). The authors induced anxiety in one group of their participants by making them write an autobiographical essay about an anxiety-inducing situation. Then the authors compared the scores on the Berg Card Sorting Test (BCST, a task that loads on executive functions in general, on working memory, cognitive flexibility, and inhibition) for this group with a group of participants who wrote a neutral essay. Results showed that the anxious participants showed significantly lower cognitive control, a difference that remained significant after controlling for the effect of baseline executive functions. Moreover, this interpretation is in line with some neuroimaging studies. For example, Young and colleagues (2012) found that while performing mathematical tasks, participants with high mathematics anxiety showed reduced activation in a brain area that is supposed to be involved in cognitive control processes, the dorsolateral prefrontal cortex, compared with participants with low mathematics anxiety.

My results suggest that participants with high mathematics anxiety have a specific form of cognitive control deficit: a lower efficiency of the inhibitory processes. In fact, the number of intrusions is thought to be a measure of the efficiency of the inhibition processes (De Beni et al., 1998; Passolunghi et al., 2016). One possible explanation could be that individuals with high mathematics anxiety fail to inhibit information that has recently been relevant but is no longer relevant. This would be a similar mechanism to the mechanism proposed in poor text comprehenders. In fact, De Beni and colleagues (1998) found that poor text comprehenders showed significantly more intrusion errors in a listening span task than good text comprehenders. Moreover, they replicated the results while using a simple string of words instead of sentences. The authors suggested that poor comprehenders maintain information active in their working memory that is no longer relevant. Moreover, De Beni and colleagues suggested that the reason why this occurs is that poor comprehenders have lower efficiency of the inhibition processes. The lower efficiency leads to some information that was relevant but that now needs to be inhibited to be still represented as active information. Just as this suggests the lower efficiency of inhibition processes might explain poor comprehension this might also be a factor in mathematics anxiety. Moreover, the results of the study presented in this chapter are in line with previous research that found a lower inhibition efficiency in participants with high mathematics anxiety. Indeed, Hopko and colleagues (1998) found that participants with medium and high levels of mathematics anxiety had more difficulties in inhibiting irrelevant texts (with and without mathematical content) and took longer to read relevant texts as a consequence.

Existing literature suggests that trait (or general) anxiety is associated with lower efficiency of the inhibition processes (Moser et al., 2012). The authors found that when performing a visual search task, there was a significant positive relationship (r = .43) between distractor cost (the difference in reaction times between the distractor condition and the no-distractor condition) and trait anxiety (Moser et al., 2012). On the other hand, results suggest that state anxiety does not lead to lower performances in working memory tasks (Walkenhorst & Crowe, 2009). The authors divided participants in high and low worry. The participants were then tested on four different tasks, the backward digit span task, the spatial span backward task, a dual-task where they were required to perform a digit span task with a tracking task, and Daneman and Carpenter's reading span task (Daneman & Carpenter, 1980). The authors found no significant effect of worry on the tasks (Walkenhorst & Crowe, 2009). My results build on previous literature as although the high mathematics anxiety and low mathematics anxiety groups showed different levels of state and trait anxiety, in line with Walkenhorst and Crowe findings (2009) state and trait anxiety levels did not significantly influence the number of intrusions in the reading span task,. Thus, for the current study, we can exclude the possibility that the group differences in intrusions were driven by differences in state or trait anxiety.

3.4.4 Limitations and Strengths

Previous literature suggests that mathematics anxiety is more common in females than in males (Hembree, 1990). If we were to construct a sample based only on AMAS score, we might have had a different composition of males and females in the two groups. On the other hand, roughly 80% of Psychology students in the department where I tested are females, rendering it difficult to construct groups with equal gender division. To make sure that my results were not biased by the gender composition of the group, I included only female participants. However, in this way, I excluded all male participants from the laboratory testing, thus that my findings have limited generalizability. Moreover, to enhance the power of the study, I included only participants with the highest and lowest scores on the AMAS score. This means that the analysis did not include part of the distribution of mathematics anxiety. Although this is a limitation, the use of an extreme group design is also a strength of the study. In fact, by using an extreme group design I improved the efficiency of the study.

Moreover, I included three different measures of working memory, to inspect the different systems together. To the best of my knowledge, no study attempted to include this variety of measures.

In the current study I also included two different anxiety measures that are related to mathematics anxiety and are possible sources of bias (Eysenck & Calvo, 1992; Zohar, 1998). By controlling for their effects, I can exclude that the relationships I found were driven by these third variables. Finally, by controlling for the effect of reasoning abilities I excluded another known possible source of bias (Engle, 2002; Engle et al., 1999). In conclusion, although I did not manipulate mathematics anxiety experimentally in this study, I controlled many of the possible confounding variables in the design, improving the quality of my results.

3.4.5 Conclusion

My data suggest that, at least in university students, there are no differences in working memory scores between participants with high mathematics anxiety and low mathematics anxiety. On the other hand, the results suggest that participants with high mathematics anxiety have lower efficiency of the inhibition processes as measured with intrusions in the reading span task. This lower efficiency is influenced neither by general nor by test anxiety; thus, suggesting that mathematics anxiety alone has a strong relationship with lower efficiency of the inhibition processes. In light of the finding of the previous study that there were no differences between a mathematical session and a non-mathematical session, this seems to suggest that people with high levels of mathematics anxiety tend to have lower efficiency of the inhibition processes in general.

Chapter 4 - Concurrent predictors of mathematics anxiety and mathematical performance in secondary school students.

4.1 Introduction

The two previous studies presented in this thesis were behavioural studies with adults. The next two chapters will focus on a longitudinal study with students in Year 7. The current chapter will focus on the concurrent data from Time 1 of the study. The relationships between mathematics anxiety, mathematical performance, working memory, and mathematics self-belief will be explored, and the effect of gender will be investigated.

4.1.1 The relationship between mathematics anxiety and mathematical performance in primary and secondary school students

There is strong evidence that the negative relationship between mathematics anxiety and mathematical performance is already present in secondary school students. In fact, Hill and colleagues (2016) used the AMAS to measure mathematics anxiety in primary and secondary school students. The authors found that, after partialling out trait anxiety, mathematics anxiety was still significantly negatively related to mathematical performance in secondary school students (males $r = -.22$; females $r = -.28$). On the other hand, mathematics anxiety was no longer a significant predictor of mathematical performance in primary school students (males $r = -.04$; females $r = -.11$) suggesting that, at least from secondary school onwards, mathematics anxiety is significantly related to mathematical performance. Moreover, Passolunghi and colleagues (2016) divided secondary school students in a high mathematics anxiety group and a low mathematics anxiety group. The groups were paired in trait anxiety and verbal IQ. The authors found that the group with low mathematics anxiety outperformed the group with high mathematics anxiety in the written calculation task and in the number knowledge task. Additionally, Hembree's meta-analysis (1990) summarised the relationship between mathematics anxiety and mathematical performance in 151 studies and found that there was a moderate negative relationship between the two factors (r = -.34 in Years 7 to 11).

In contrast, the evidence for the presence of the relationship between mathematics anxiety and mathematical performance in primary school students is mixed. On the one hand, some authors found a significant negative relationship between mathematics anxiety and mathematical performance also in primary school students (Haase et al., 2012; Vukovic et al., 2013; Wood et al., 2012; Wu et al., 2012). On the other hand, several other studies did not find a significant relationship between mathematics anxiety and mathematical performance in primary school students (Dowker et al., 2012; Hill et al., 2016; Krinzinger et al., 2009).

Haase and colleagues (2012) found that in students aged 7 to 12 years old (primary school in Brazil), mathematics anxiety was a significant predictor of mathematical performance (β = -.35). Moreover, Vukovic and colleagues (2013) assessed mathematics anxiety in a longitudinal study in Year 2 and 3 students. They also measured calculation ability, solving of mathematical story problems, solving of algebraic equations, and solving of probability and data analysis problems. After controlling for reading ability, early numeracy, and visual working memory, the authors still found that mathematics anxiety was a significant predictor of mathematical performance in all four mathematical tasks. Additionally, Wood and colleagues (2012) found a significant relationship between mathematical performance and mathematics anxiety in Brazilian and German primary school students. This relationship was significant even after controlling for the effect of verbal and visuo-spatial working memory. In Brazilian students, the authors also investigated the performance in simple and complex speeded calculations and found that there was a significant negative relationship between mathematics anxiety and performance on the speeded calculation tasks. However, this relationship was significant only for complex calculations (complex subtractions, simple and complex multiplications), not for simple calculations (simple and complex additions, simple subtractions). Recently, Orbach and colleagues (2020) assessed state mathematics anxiety in fifth and fourth graders (mean age for Year 4 students = 10 years old; mean age for Year 5 students = 11 years old) and found that it was a significant negative predictor of mathematical performance (β = -.16), while inhibition (β = .12), cognitive flexibility (β = .13), working memory capacity (β = .10), and global central executive functions (β = .15) were positive predictors of mathematical performance. Moreover, the authors assessed the mediation effect of inattention and working memory capacity in the relationship between mathematics anxiety and mathematical performance. The authors found that mathematics anxiety showed a significant direct effect on mathematical performance (β = -.10), but at the same time that it showed a significant indirect effect through inattention (β = -.03) and through inattention and working memory capacity (β = -.004). Finally, Wu and colleagues (2012) investigated the relationship between mathematics anxiety and mathematical performance in Year 2 and 3 students. The authors used the SEMA (Scale for Assessing Early Mathematics Anxiety) and the WIAT-II mathematical subtest. The authors found a significant negative relationship between mathematics anxiety and mathematical performance even after ruling out the effect of trait anxiety and IQ (β = -.26). Moreover, trait anxiety was not a significant predictor of mathematical performance.

Conversely, as we saw earlier, Hill and colleagues' (2016) results suggested that the relationship between mathematics anxiety and mathematical performance in Italian primary school students was not significant once the effect of trait anxiety was ruled out. Also, Krinzinger and colleagues (2009) investigated mathematics anxiety with a longitudinal design in students from the end of Year 1 until the middle of Year 3. The authors measured mathematics anxiety with the MAQ (Thomas & Dowker, 2000) and mathematical performance with simple and complex additions and subtractions. The concurrent analysis showed no significant correlation between mathematics anxiety and calculation ability in all three years. Moreover, in a

Structural Equation Model, there were no significant longitudinal effects of mathematics anxiety on calculation ability.

These findings prompted me to focus on secondary school students in the current study. Because the study aimed to assess the longitudinal relationships between mathematics anxiety and mathematical performance, I wanted to make sure that there was a relationship to assess. Moreover, I decided to start the study at the beginning of secondary school. In this way, the study can assess if the relationship is already present at the beginning of the secondary school, or if it emerges during the early stages of secondary school (Hill et al., 2016).

4.1.2 The relationship between mathematics anxiety and mathematical performance in female and male participants

Literature suggests that gender might interact with the relationship between mathematics anxiety and mathematical performance. Indeed, some studies suggest that female participants show a lower relationship between mathematics anxiety and mathematical performance. For example, Hembree's (1990) meta-analysis found that the correlation between mathematics anxiety and mathematical performance in female participants was lower compared with the relationship in males (females' $r = -.30$; males' $r = -.36$). More recently, Miller and Bichsel's (2004) analysis showed a significantly steeper regression slope for male than female participants. On the other hand, there is evidence for the opposite, and there are studies that suggested that the relationship is stronger in females than in males (Devine et al., 2012). Devine and colleagues (2012) measured mathematics anxiety in secondary school students. Participants were told to solve as many arithmetical problems as they could in 5 minutes. The authors analysed the relationship between mathematics anxiety and mathematical performance separately for female and male participants. The results showed that mathematics anxiety and mathematical performance were moderately negatively correlated in both females ($r = -.35$) and males ($r = -$

.18), but the difference in r-values between female and male participants was significant, suggesting that the relationship was stronger in females than in males.

There is also a third option, which is that the relationship is not significantly different between females and males (Ma, 1999; Meece et al., 1990). Ma's (1999) meta-analysis found no significant difference between males and females in the relationship between mathematics anxiety and mathematical performance. Meece and colleagues (1990) investigated the relationship between mathematics anxiety and mathematical performance in Year 7 and 9 students. Interestingly, the authors used grades in mathematics as a measure of mathematical achievement. In accordance with Ma's findings, the authors noted that the relationship between mathematics anxiety and mathematical performance was not significantly different between female and male participants. These mixed results prompted me to include gender in the current analysis when analysing the relationship between mathematics anxiety and mathematical performance.

4.1.3 The relationship between mathematics anxiety and working memory

Previous literature suggests that mathematics anxiety has a negative relationship with working memory (please see chapter 1.4.3, page 49 for the evidence).

Although most studies show a negative relationship between mathematics anxiety and working memory (for a review, see Dowker et al., 2016), it is still not clear if the relationship is between mathematics anxiety and verbal working memory, or between mathematics anxiety and visuo-spatial working memory, or between mathematics anxiety and both working memory systems. Some authors found a significant negative relationship between mathematics anxiety and verbal working memory. For example, Passolunghi and colleagues (2016) found that those with higher mathematics anxiety showed lower performances on the Word Span Forward task. Other authors found a significant effect of mathematics anxiety on visuo-spatial working memory tasks. For example, Miller and Bichsel (2004) found that mathematics anxiety was inversely related with performance on a visuo-spatial working memory task.

A third option is that there is a relationship between mathematics anxiety and both slave systems of working memory. In fact, Mammarella and colleagues (2015) reported how participants with high mathematics anxiety showed lower performance in both verbal and visuo-spatial working memory tasks than typically developing students matched for reading comprehension, trait anxiety and IQ. However, there was no evidence for differences in verbal or visuo-spatial working memory between groups of adults with high versus low mathematics anxiety in the study discussed in the previous chapter.

The fourth and final option is that mathematics anxiety is related to poorer performance of the central executive and that in turn the slave systems in students are affected by the lower amount of resources available. Evidence for this hypothesis comes from studies that find significantly lower performance in tasks that involve the central executive in students with high mathematics anxiety compared with participants with low mathematics anxiety. In Passolunghi and colleagues (2016), for example, secondary school students with high mathematics anxiety showed poorer performance on a working memory capacity task than students with low mathematics anxiety. Given this array of findings, I included measures for all three working memory systems when investigating the relationship between mathematics anxiety and working memory.

4.1.4 Mathematics anxiety and mathematics self-belief

Self-beliefs, in general, refer to the perception that people have about their own competencies/abilities when completing a task, such as solving a mathematical problem or understanding a written text (Stankov et al., 2012). For a review of these two constructs, please see chapter 1.2.5, page 30. The most common way to measure mathematics self-belief is through questionnaires. Most questionnaires are short and quick to administer; for example, Lee (2009) used the PISA data where the questionnaire included 5 questions for mathematics self-efficacy and 5 questions for mathematics self-concept. However, some studies used longer questionnaires. For example, Justicia-Galiano and colleagues (2017) used the Self Description Questionnaire (SDQ I), which consists of 64 items that assess self-perceptions on academic and non-academic areas.

The existing literature suggests a relationship between mathematics self-beliefs and mathematics anxiety (Hoffman, 2010; Mcmullan et al., 2012; Pajares & Graham, 1999; Pajares & Miller, 1994). For instance, Mcmullan and colleagues (2012) found a significant and strong negative relationship (r = -.63) between mathematics anxiety and mathematics self-efficacy in second year nursing students. Pajares and Miller (1994) found a significant negative relationship between mathematics anxiety and mathematics self-efficacy (r = -.56). Moreover, the authors found a strong negative relationship between mathematics anxiety and mathematics self-concept (r = -.87). Finally, in their study mathematics self-efficacy and mathematics self-concept were strongly positively related to each other (r = .61). Pajares and Graham (1999) measured mathematics self-efficacy, mathematics self-concept, and mathematics anxiety in Year 6 students (the first year of middle school). The authors found that self-efficacy showed a strong negative relationship with mathematics anxiety (r = -.61) and a strong positive relationship with self-concept (r = .66). Moreover, the authors also found that self-concept showed a strong negative relationship with mathematics anxiety (r = -.68). Finally, Hoffman (2010) measured mathematics anxiety with the Mathematics Anxiety Scale and mathematics self-efficacy with self-reported confidence in solving eight different multiplication problems. The author found a strong negative correlation between mathematics anxiety and mathematics self-efficacy (r = -.48).

However, although the relationships between mathematics anxiety and mathematics self-belief reported in literature seem to be strong, existing literature suggests that mathematics anxiety, mathematics self-concept, and mathematics self-efficacy are three different constructs (Lee, 2009). Lee (2009) obtained the 2003 PISA data on mathematics self-concept, mathematics self-efficacy, and mathematics anxiety. Each of the three constructs was measured with a questionnaire with five items. The author used data from the 41 participating countries. An exploratory factor analysis suggested the presence of three separate factors: mathematics self-concept, mathematics self-efficacy, and mathematics anxiety. The resulting factors still showed high correlations between them. Mathematics self-concept showed a strong positive correlation with mathematics self-efficacy (r = .52) and a strong negative correlation with mathematics anxiety (r = -.67). Mathematics self-efficacy also showed a medium to strong negative relationship with mathematics anxiety (r = -.45).

Studies that investigate the relationship between mathematical performance and mathematics self-belief found a positive relationship between the constructs (Pajares & Graham, 1999; Pajares & Miller, 1994). There are different theories on the directionality of the relationship between mathematics self-belief and mathematical performance (for a review, see Huang, 2011). The directionality will be discussed further in the next chapter (please see chapter 5.1.2, page 177); for the current chapter, it is relevant to record that there is a positive relationship between the factors and that this relationship might be relevant in the assessment of the relationship between mathematics anxiety and mathematical performance. In fact, Pajares and Graham (1999) found that when including mathematics self-efficacy, mathematics anxiety, and mathematics self-concept in a regression model predicting mathematical performance, only mathematics self-efficacy was a significant predictor of mathematical performance. These results might suggest that the relationship between mathematics anxiety and mathematical performance is a spurious correlation. If by controlling the effect of mathematics self-belief, the relationship between mathematics anxiety and mathematical performance is no longer significant, it could mean that mathematics anxiety has no direct relationship with mathematical performance. Accordingly, Hoffman (2010), showed mostly moderate to strong positive relationships between mathematics self-efficacy and accuracy in solving problems (r = .46 for easy problems; r = .42 for hard problems). Moreover, mathematics anxiety showed moderate relationships with accuracy in solving problems (r = -.38 for easy problems; r = -.42 for hard problems). But, when mathematics anxiety, mathematics self-efficacy, and working memory capacity were considered together as predictors of accuracy on easy problems, only self-efficacy was a significant predictor. However, Hoffman also investigated which factors were the best predictors of performance in solving difficult problems. In this case, a multiple regression with mathematics self-efficacy, mathematics anxiety and working memory capacity as predictors and accuracy on hard problems as outcome measure found mathematics anxiety and working memory capacity were significant predictors of mathematical performance, but not self-efficacy. This might mean that mathematics anxiety is not a significant predictor for performance on easy mathematical tasks, but only for performance on difficult mathematical tasks, as suggested in the literature (e.g., Passolunghi et al., 2016). It is important to note that most studies (e.g., Hoffman, 2010) use multiple regression techniques. However, it is important to note that given the high covariance between the constructs, using multiple regression is not recommended as the b-values might be biased, as well as the individual importance of a single predictor (Field, 2013). For this reason, it is important to control covariance with collinearity statistics before running the analysis, and in any case, to interpret the results with caution.

It might also be important to consider gender when investigating self-belief. Previous studies suggest that female participants tend to have lower mathematics self-efficacy (Morony et al., 2013; Pajares & Miller, 1994; Villavicencio & Bernardo, 2016). Villavicencio and Bernardo (2016) measured self-efficacy and mathematics achievement in 1345 engineering students, and found a significant relationship between mathematics self-efficacy and gender, suggesting that males had a higher sense of self-efficacy. Morony and colleagues (2013) assessed mathematics self-efficacy, mathematics self-concept, and mathematical performance in students across Europe and Asia. The authors observed that female students had lower scores in mathematics self-efficacy and mathematics self-concept than their male counterparts. Finally, Pajares and Miller (1994) found that female participants in their study showed significantly lower scores in mathematics self-efficacy. However, contrary to Morony and colleagues' results, Pajares and Miller did not find a significant difference between male and female participants in mathematics self-efficacy. Given this discrepancy, it might be interesting to further assess the relationship between gender and mathematics self-belief.

The literature reviewed in this section suggests that mathematics self-belief and mathematics anxiety are constructs that share a large amount of variance. They might even be the same construct. However, most research in mathematics anxiety does not yet take mathematics self-belief into account. For this reason, I decided to include self-belief measures in the current study. I wanted to test whether mathematics self-concept, mathematics self-efficacy, and mathematics anxiety are separate constructs or not.

4.1.5 Inhibition and the Go/No-Go task

Inhibition is the suppression of thoughts, actions, and emotions (Verbruggen & Logan, 2008). It is believed to be an attentional process, and hence it is one of the processes of the central executive (Baddeley, 1996). Inhibition is part of selective attention, allowing us to attend selectively to one stream of information (for example, to the mathematical information presented in front of us) while discarding/inhibiting others (e.g., irrelevant thoughts of how much we are dreading that situation; Baddeley, 1996). Inhibition "involves being able to control one's attention, behaviour, thoughts, and/or emotions to override a strong predisposition or external lure, and instead do what's more appropriate or needed" (Diamond, 2013, p. 136).

In the previous studies, I used intrusions during a complex span task as a measure of the quality of inhibition processes. A higher number of intrusions should be an indicator of lower inhibition efficiency. Intrusions, however, might measure semantic inhibition, as the task requires the inhibition of irrelevant information. In the current study, I wanted to include another measure of inhibition that would show better sensitivity and have a lower risk of a flooring effect that was encountered for the intrusions in previous studies. For this reason, I decided to use a Go/No-Go task. A Go/No-Go task, however, is considered to be a measure of inhibition of motor responses (Hershey et al., 2010). A Go/No-Go task requires participants either to respond to a stimulus (the "Go" stimulus) as quickly as possible or to refrain from the response when another stimulus is present (the "No-go" stimulus). The No-go stimulus is typically less frequent than the Go stimulus (Gonzalez Alam et al., 2018). Correct responses to the task require the recruitment of different cognitive systems and processes, such as working memory, stimulus-driven attention, error monitoring, top-down control processes, and response inhibition (Chikazoe, 2010). For example, Chikazoe's review (2010) highlighted that areas such as the ventrolateral prefrontal cortex (VLPFC) and the pre-supplementary motor area (pre-SMA) are important for the performance in Go/No-Go tasks. These two areas have been proposed as regions implicated in the response inhibition processes (Chikazoe, 2010). Performance on the Go/No-Go task can be analysed using signal detection theory (Hershey et al., 2010). According to signal detection theory, decision-making is based on a state of uncertainty, which can be measured with the analysis of the correct responses (hit rate) and the number of incorrect responses (false alarms). The hit rate refers to the proportion of Go trials with correct responses. The number of correct hits, or inversely, the number of omissions on Go trials, is believed to be a measure of attention (Schulz et al., 2007). Reaction times are supposed to be a measure of behavioural execution (Schulz et al., 2007). False alarms instead are when a Go response is given on a No-go trial (Hershey et al., 2010). The number of false alarms is used as a measure of the quality of the inhibitory control, whereas the number of correct hits and the reaction times are not considered a good index of inhibitory control (Diamond, 2013). More specifically, a higher number of false alarms suggest a lower efficiency of the inhibition processes (Schulz et al., 2007).

4.1.6 Hypotheses

I expected to find a significant negative relationship between mathematics anxiety and mathematical performance in the current dataset in both male and female participants.

I expected higher mathematics anxiety to be related to lower working memory for all three working memory systems as low resources from the central executive could affect performance in the slave systems. In particular, I expected a lower efficiency of the inhibition processes in pupils with higher mathematics anxiety. Finally, I expected mathematics anxiety, mathematics self-concept, and mathematics self-efficacy to be three separate constructs albeit with strong correlations between them. I predicted mathematical performance to be higher in pupils with higher mathematics self-concept and with higher mathematics self-efficacy.

4.2 Methods

In this chapter, I report the data from time point 1 (T1) of a longitudinal study. These data were collected at the beginning of the academic year from students in Year 7.

4.2.1 Participants

I tested 168 students at the beginning of Year 7 from a school in Yorkshire. The school was rated "Good" by Ofsted in 2017 and has a non-selective admission policy. The school currently has more than 1000 students, of which roughly half are female. 7.8% of the students have special needs, and 3.6% of the students do not have English as their first language. 19.7% of the students are eligible for free school meals. Of the 168 students, three students were excluded from the analysis, because the school started a fire drill while I was testing them individually. An additional eight students were excluded because they did not want to participate in the individual testing. In the end, the sample for the analysis was composed of 157 participants (79 females; age range: 11-12 years old, mean age = 11.34 years, *SD* = 0.48) who completed all the testing. Of these, the computer started an automatic update during the computerised individual testing in five cases. This caused the loss of the scores for these five students for computer tasks. Because these scores were missing completely at random[4], I included their data and used the expectation-maximization algorithm to replace the missing values.

I decided to use opt-out consent from the parents as this allows for higher participation from the participants. However, aware of the ethical issues involved with this type of consent, I gave parents four weeks to decide whether they wanted their child to participate or to opt-out their child from the study. I also sought verbal consent from the participants and written consent from the headteacher. At every stage, I made clear that the participants were voluntarily taking part in the study and that they should in no way feel obliged to continue. I made sure that the participants were comfortable and that no harm was done to them. Every situation was handled to reduce the stress to the participants to a minimum. Participants were tested either in the classroom or in an empty corridor in the school. Ethical approval was granted by the University of York Psychology Department's ethics committee.

4.2.2 Materials

4.2.2.1 Classroom testing

Mathematics anxiety

To assess the participants' mathematics anxiety, I used the Revised Mathematics Anxiety Rating scale (RMARS; Taylor & Fraser, 2013). RMARS was developed for high school students,

[4] Little's MCAR test: $\chi^2_{(191)} = 201.48$, $p = .288$.

so I adapted the items to be comprehensible and relatable to secondary school students (e.g., "Watching a teacher work an algebra equation on the blackboard" from the original RMARS, became "Watching a teacher work out an arithmetic equation on the board."). RMARS is a self-report questionnaire composed of 24 items associated with different math-related situations (in school and everyday life; an example of a situation: "Watching a teacher work an arithmetic equation on the board"). Participants are asked to rate their feelings during those situations using a 5-point Likert scale (From 1 – No bad feelings; to 5 – Worst feelings) (Min RMARS score = 24; Max = 120). The RMARS showed good internal consistency in the current sample (α = .96).

Mathematical performance

To assess the participants' mathematical proficiency I used the blue form of the mathematical subtest of the Wide Range Achievement Test (WRAT-4; Wilkinson & Robertson, 2006). The WRAT-4 mathematical subtest showed high internal reliability in the current sample (α = .86).

The task was the same used in the first study, so for the details please see chapter 2.2.2, page 64.

Arithmetical fluency

To assess participants' fluency in arithmetic I used the Simple Calculations task. The task required the participant to solve as many calculations as possible within a specific time limit. The task included three operations: addition, subtraction, and multiplication.

I used the same items as in the first study, so for the details please see chapter 2.2.2, page 64 and Appendix A.4.

Trait anxiety

To assess participants' trait anxiety, I used the trait anxiety questionnaire from the State-Trait Anxiety Inventory for Children (STAIC; Spielberger, Edwards, Lushene, Montuori, & Platzek, 1973). I decided to use this questionnaire instead of the GAD-7 because the sample was composed of 11- to 12-year-old students, and I wanted to use a child-friendly test. The trait anxiety inventory has 20 items that assess the general level of anxiety of the participant. Each item (e.g., "I worry about making mistakes") requires the participant to choose how often they show this behaviour/have this feeling on a scale from "hardly ever" to "often". Items are rated on a 3-point Likert scale with 1 (hardly ever), 2 (sometimes) and 3 (often). The minimum score is 20; the maximum score is 60. In previous studies, the alpha coefficient showed good reliability for female elementary school students (α = .87) and for male elementary school students (α = .82) (Spielberger et al., 1973). In the current sample, I also found high internal reliability (α = .91).

Mathematics self-efficacy

To assess participants mathematics self-efficacy, I decided to use the mathematics self-efficacy scale from Stankov and colleagues (2012). The scale requires the participants to answer to 5 items how much they agree with the statements on a 5-point Likert-scale, from strongly disagree (1), to neither agree nor disagree (3), until strongly agree (5). An example of an item is "Even if the work in mathematics is hard, I can learn it.". The scale showed good reliability in my sample (α = .83).

Mathematics self-concept

To assess participants mathematics self-concept, I decided to use the mathematics self-concept scale from Stankov and colleagues (2012). The 4 item-scale requires the participants to answer how much they agree with each item on a 5-point Likert-scale, from strongly disagree (1), neither agree nor disagree (3), to strongly agree (5). An example of an item is "I learn mathematics quickly". The scale shows good reliability in my sample (α = .81).

4.2.2.2 Individual testing

Verbal working memory

To assess verbal working memory, I used a letter span task (Marcel, 1974) developed by myself. The task requires participants to repeat a series of letters after hearing them spoken aloud, in the same order as they heard them.

I used the same task as in the first study, so for the details see chapter 2.2.2 page 64 and Appendix A.1.

Visuo-spatial working memory

To assess visuo-spatial working memory, I used a computerized task to assess visual working memory load (McNab & Klingberg, 2008). In this task, participants are exposed to 16 squares displayed in a circle. In each trial, there is a red dot on either 3, 4, or 5 of the squares. The squares are presented for 3 seconds, after which there is a masking period of 3 seconds. During the masking period, participants need to retain visual information. After the masking period, the squares reappear, and the dots are not present anymore. Instead, one of the squares has a question mark in it. The question mark can be either in a square that previously had a red dot or next to a square that previously had a red dot. The participant has 3 seconds to press one of two buttons to indicate whether the question mark is in a square that previously had a dot in it (Numpad 1) or not (Numpad2). The instructions given to the participants ask them to be as precise as possible. The time of 3 seconds for each visual presentation was chosen after piloting the measure with the participants. In fact, I used the first 5 participants to assess the feasibility of the measure with students of that age (participants that were not included in the analysis). As the original measure required participants to reply after 1 second, I noticed that 1 second was not long enough for students and the task was causing stress in the participants, so I decided to find the best solution to not stress the participants, but at the same time to keep it a timed task.

The measure includes 45 trials, 15 for each load (i.e. for load 3, 4 and 5). In random order, participants are exposed to three red dots 15 times, four red dots 15 times, and five red dots 15 times. For each load, I calculated the k-value (McNab & Klingberg, 2008). K-values are calculated by taking the number of correct hits (the number of times the participants correctly pressed Numpad 1) and the number of false alarms (the number of times the participants pressed the Numpad 1 instead of the Numpad 2). The number of false alarms is subtracted from the number of correct hits. The resulting number is then multiplied by the array size (or load; i.e. 3, 4, or 5 dots). The resulting value is the k-value for that load. For each participant, I then averaged across k-values for each load to obtain an average k-value score over all load conditions.

Inhibition processes

To assess participants' efficiency of the inhibition processes, I used a Go/No-Go task. The version used is an adaptation of the task used in Gonzalez Alam and colleagues (2018), of which, I used only the figure subset. The figures used where the ones included by the researchers. Participants see an image of either a living or a non-living object. Participants are instructed to press the spacebar each time there is a picture of a non-living object and to not do anything when there is a picture of a living object. The participants are instructed to be as accurate and as fast as possible. Each image appears for one second (during which they should press the spacebar in the Go trials), after which there is masking of one second and then another picture appears. Participants are given a practice block where they are given feedback if they make a mistake in pressing or not pressing the spacebar. The practice trials consist of 14 pictures, 12 non-living objects (Go) and two living objects (No-Go). After the practice trials, the participants start the experimental block. In the experimental block, there are 210 pictures. Presented in random order, 40 of these are pictures of living objects (No-Go), whereas the remaining 170 are of non-living objects (Go). From this measure, I calculated the number of correct responses (correct Go and correct No-Go), mean reaction time of the correct Go responses, and the number of false alarms. The number of false alarms is considered a measure of the efficiency of the inhibition processes. However, it has an inverse relationship with efficiency inhibition, as the higher the number of false alarms recorded, the lower the participant's inhibition efficiency.

Conceptual understanding

To assess participants' understanding of mathematical concepts I used the mathematical conceptual understanding task developed by Gilmore and Cragg (available at http://reshare.ukdataservice.ac.uk/852106/). Participants are presented with an arithmetical equation with the correct answer. Once the participants read the equation, they pressed return and a second equation without the answer was shown. Participants then had to decide whether the first equation could help them (the equations are related) or not (the equations are not related) to answer the second equation by pressing 1 or 2 on the numerical keypad respectively. The equations could be related by the subtraction-complement principle (e.g., if 113 – 59 = 54; 113 – 54 = ?), they could be inverse operations (e.g., if 74 + 57 = 131; 131 – 74 = ?), and they could be commutative operations (e.g., if 63 + 68 = 131; 68 + 63 = ?). Importantly, participants were instructed not to solve the equation, but simply to state whether the first equation could help them or not to solve the second equation. The participants first had a practice block with 4 items. After the practice block, there were 30 more items, 18 of which were related and 12 were not related. I recorded the number of correct trials.

4.2.2.3 Testing apparatus

Computerized tasks were performed on two different computers used by the two experimenters. The first computer was an ASUS R556L 15.6" with a screen resolution of 1920 x 1080 pixels. CPU was Intel Core i5-5200U (2.2 GHz) and 8GB DDR3 RAM. The second computer was a TOSHIBA SATELLITE PRO C660-150 15.6" with a screen resolution of 1366 x 768 pixels. CPU was Intel Celeron T3500 (2.1 GHz) and 4 GB DDR3 RAM. Both computers run Windows 10 64-bit Professional. All participants used an external USB keyboard for their responses.

The visual working memory task and the conceptual understanding task were developed and assessed using PsychoPy for Windows ver. 1.85.3. The Go/No-Go task was developed and assessed using Python for Windows ver. 3.5.4.

4.2.2.4 Design and Procedure

Participants were tested in two separate sessions on separate days; the classroom session and an individual session. The classroom sessions started with the experimenters introducing themselves and giving the WRAT-4 mathematical subtest, the Arithmetical Fluency task, the mathematical self-concept and self-efficacy questionnaires, the RMARS questionnaire, and the trait anxiety questionnaire. During the individual session, each participant was taken out of the classroom individually and sat at a table in an empty hallway of the school with the experimenter. The letter span task was administered using a recording of the task. After this task, participants were introduced to the computer and performed the inhibition task, the visual working memory task, and the conceptual understanding task. At the end of the session, participants re-entered the class.

4.3 Results

4.3.1 Descriptive Statistics

Table 4.1. Descriptive Statistics divided by gender

	Females		Males				
Measure	M (SD)	Min-Max	M (SD)	Min-Max	T (155)	p-value	*d*
WRAT-4 Mathematical Subtest	25.84 (4.89)	8 - 35	25.55 (6.22)	11 - 39	0.32	**.751**	0.05
Fast Math	49.76 (15.00)	8 - 83	55.03 (16.38)	18 - 96	2.1	**.037**	0.34
Conceptual Understanding	28.02 (5.64)	4 - 34	27.81 (5.01)	14 - 34	0.25	**.803**	0.04
Trait Anxiety	33.43 (7.99)	21 - 57	31.42 (7.95)	20 - 51	1.58	**.117**	0.25
Mathematics Self-Efficacy	19.25 (3.88)	6 - 25	20.45 (3.20)	10 - 26	2.11	**.037**	0.34
Mathematics Self-Concept	12.46 (4.17)	4 - 20	13.62 (3.80)	4 - 20	1.82	**.070**	0.29
RMARS (Mathematics Anxiety)	48.11 (19.70)	24 - 103	45.45 (17.85)	24 - 85	0.89	**.377**	0.14
Letter Span total score	7.11 (1.63)	0 - 11	6.82 (1.33)	3 - 10	1.21	**.227**	0.19
Visual Working memory task	7.20 (5.77)	-9.67 - 19.67	6.70 (7.93)	-12.67 - 26.33	0.45	**.654**	0.07
Go/No-go N. of Correct Responses	187.59 (14.43)	98 - 208	186.85 (13.51)	141 - 208	0.34	**.738**	0.05
Go/No-go RT (ms)	575 (50)	441 - 729	581 (54)	453 - 692	0.73	**.469**	0.12
Go/No-go N. of False Alarms	8.97 (5.28)	0 - 23	8.63 (5.59)	1 - 34	0.4	**.690**	0.06

Table 4.1 reports the descriptive statistics divided by gender. Gender comparisons are assessed with non-adjusted independent t-tests. There were no significant differences in mathematical performance and conceptual understanding between male and female participants. The same can be said for mathematics anxiety and almost all other measures included. The only two tasks with significant differences between male and female participants were arithmetical fluency (female participants performed significantly worse) and mathematics self-efficacy (female participants showed significantly lower scores). It should be also discussed that mathematics self-concept is borderline significantly different between male and female participants (with female participants scoring on average lower scores). In all the cases the effect size is in the small to

medium range (Cohen, 1988). Please see Appendix C.1 for a full partial correlation matrix (controlling for trait anxiety).

4.3.2 Relationship between mathematics anxiety and mathematical processing

I wanted to investigate if there was a relationship between mathematics anxiety and mathematical processing at the beginning of secondary school. For this reason, I assessed the relationship between mathematics anxiety and different types of mathematical processing. I also controlled for the effects of trait anxiety and gender.

4.3.2.1 Mathematics anxiety and mathematical performance

The first relationship that I assessed was the relationship between mathematics anxiety and mathematical performance. I computed a stepwise linear regression with mathematics anxiety and trait anxiety as predictors of mathematical performance. Mathematics anxiety was a significant predictor of mathematical performance (β = -.33, p < .001), but not trait anxiety. The resulting model showed that mathematics anxiety explained 11% of the variance and that the model was a significant predictor of mathematical performance, F (1, 155) = 18.28, p < .001 as can be seen in Figure 4.1. Students with higher mathematics anxiety had a significantly lower mathematical performance.

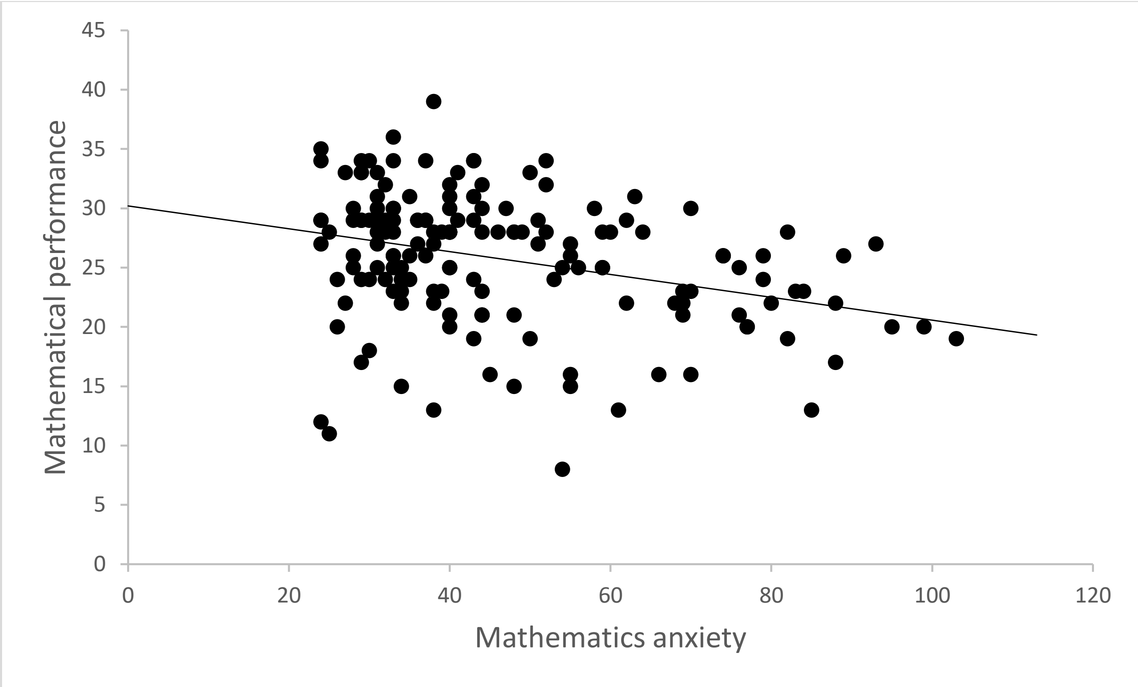

Figure 4.1. Scatterplot representing the relationship between mathematics anxiety and mathematical performance.

I then separated female and male participants and re-ran the analysis. It was found that in female participants mathematics anxiety was a significant predictor of mathematical performance ($\beta = -.43$, $p < .001$), but not trait anxiety. The resulting model showed that in female participants mathematics anxiety explained 18% of the variance and that the model was a significant predictor of mathematical performance, $F\ (1, 77) = 17.33$, $p < .001$.

Furthermore, in male participants mathematics anxiety was a significant predictor of mathematical performance ($\beta = -.25$, $p = .029$), but not trait anxiety. The resulting model showed that mathematics anxiety explained 6% of the variance in male participants and that the model was a significant predictor of mathematical performance, $F\ (1, 76) = 4.96$, $p = .029$.

On first sight the r-values in the models for female and male participants seem quite different in size, thus I ran a regression analysis including the interaction term of gender X mathematics anxiety to test whether the size of the relationship is larger in female than male participants. I found that neither gender nor the interaction of gender X mathematics anxiety were significant predictors of mathematical performance.

4.3.2.2 Mathematics anxiety and arithmetical fluency

The second relationship that was assessed was the relationship between mathematics anxiety and arithmetical fluency. I computed a stepwise linear regression with mathematics anxiety and trait anxiety as predictors of arithmetical fluency. The analysis showed that mathematics anxiety was a significant predictor of arithmetical fluency ($\beta = -.31$, $p < .001$), but not trait anxiety. The resulting model suggested that mathematics anxiety explained 10% of the variance and that the model was a significant predictor of arithmetical fluency, F (1, 155) = 16.80, $p < .001$ as can be seen in Figure 4.2. Higher mathematics anxiety predicted lower performance on arithmetical fluency.

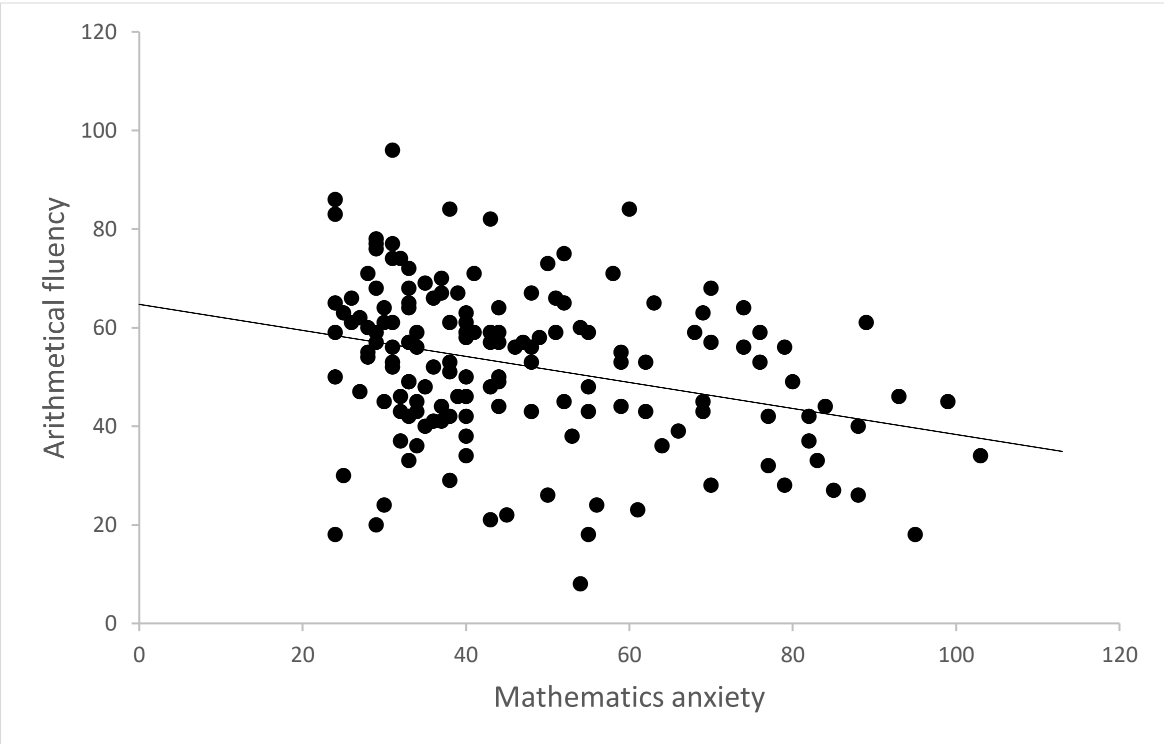

Figure 4.2. Scatterplot representing the relationship between mathematics anxiety and arithmetical fluency.

I then separated female and male participants and re-ran the analysis. It was found that in female participants mathematics anxiety was a significant predictor of arithmetical fluency (β = -.32, p = .004), but not trait anxiety. The resulting model showed that in female participants mathematics anxiety explained 10% of the variance and that the model was a significant predictor of arithmetical fluency, F (1, 77) = 8.68, p = .004.

I then analysed only the male participants and found that in male participants mathematics anxiety was a significant predictor of arithmetical fluency (β = -.30, p = .009), but not trait anxiety. The resulting model showed that mathematics anxiety explained 9% of the variance in male participants and that the model was a significant predictor of arithmetical fluency, F (1, 76) = 7.29, p = .009.

In line with the previous analysis, I ran a regression analysis including the interaction term of gender X mathematics anxiety. It was found that neither gender nor the interaction were significant predictors of arithmetical fluency.

4.3.2.3 Mathematics anxiety and conceptual understanding

The third relationship that was considered was the relationship between mathematics anxiety and conceptual understanding. I computed a stepwise linear regression with mathematics anxiety and trait anxiety as predictors of conceptual understanding. The analysis suggested mathematics anxiety was a significant predictor of conceptual understanding (β = -.24, p = .002), but not trait anxiety. The resulting model suggested that mathematics anxiety explained 6% of the variance and that the model was a significant predictor of conceptual understanding, F (1, 155) = 9.54, p = .002 as can be seen in Figure 4.3.

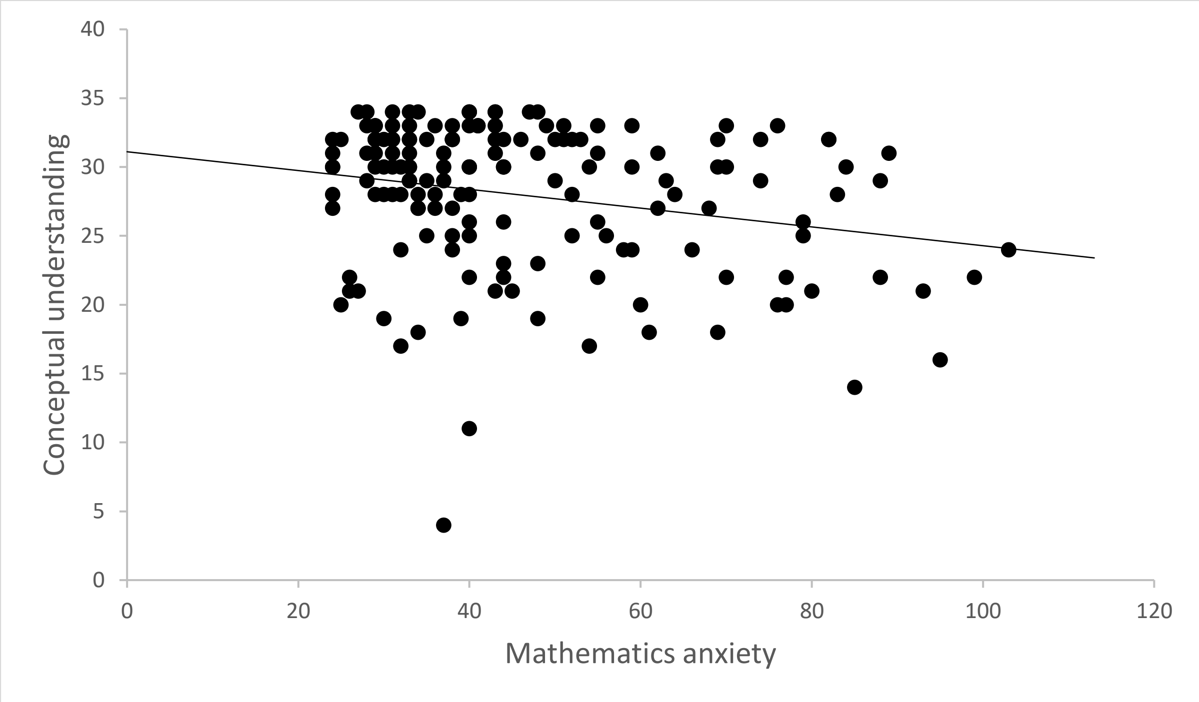

Figure 4.3. Scatterplot representing the relationship between mathematics anxiety and conceptual understanding.

I then separated female and male participants and re-ran the analysis. I found that mathematics anxiety was a marginally significant predictor of conceptual understanding in female participants (β = -.21, p = .065), but not trait anxiety. The resulting model suggested that mathematics anxiety explained 4% of the variance in female participants and that the model was not a significant predictor of conceptual understanding, F (1, 77) = 3.50, p = .065.

I found that in male participants mathematics anxiety was a significant predictor of conceptual understanding (β = -.29, p = .011), but not trait anxiety. The resulting model showed that in male participants mathematics anxiety explained 8% of the variance and that the model was a significant predictor of conceptual understanding, F (1, 76) = 6.76, p = .011.

In line with the previous analysis, I ran a regression analysis including the interaction term of gender X mathematics anxiety. Neither gender nor interaction were significant factors on the conceptual understanding.

4.3.3 Relationship between mathematics anxiety and working memory

Next I investigated the relationship between mathematics anxiety and working memory at the beginning of secondary school. For this reason, I assessed the relationship between mathematics anxiety and different types of working memory tasks. I also controlled for the effects of trait anxiety and gender.

4.3.3.1 Mathematics anxiety and verbal working memory

The current analysis included bivariate correlations between mathematics anxiety, trait anxiety, and verbal working memory. The analysis showed neither mathematics anxiety ($r(155) = -.08$) nor trait anxiety ($r(155) = -.05$) were significantly correlated with verbal working memory. These results suggest that there is no relationship between mathematics anxiety scores and performance in the verbal working memory task, as can be seen in Figure 4.4.

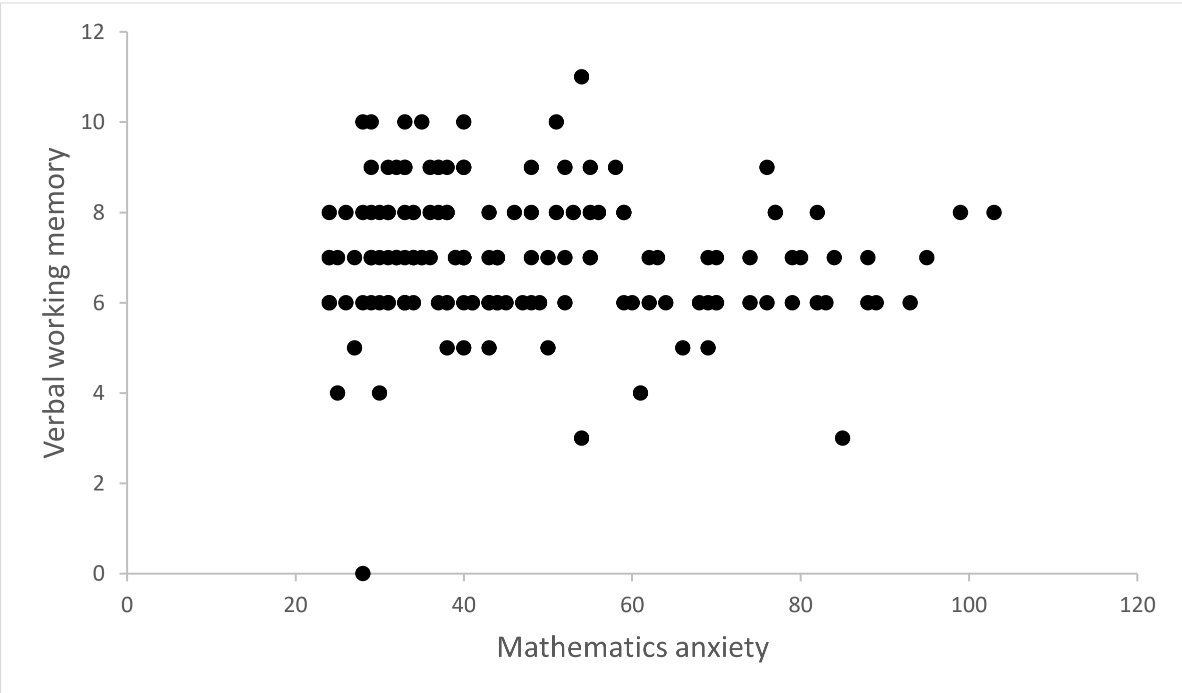

Figure 4.4. Scatterplot representing the relationship between mathematics anxiety and verbal working memory.

4.3.3.2 Mathematics anxiety and visuo-spatial working memory

The current analysis included bivariate correlations between mathematics anxiety, trait anxiety, and visuo-spatial working memory. Analysis showed neither mathematics anxiety ($r(155) = -.04$) nor trait anxiety ($r(155) = -.08$) were significantly correlated with visuo-spatial working memory. These results suggest that there is no significant relationship between mathematics anxiety and visuo-spatial working memory, as can be seen in Figure 4.5.

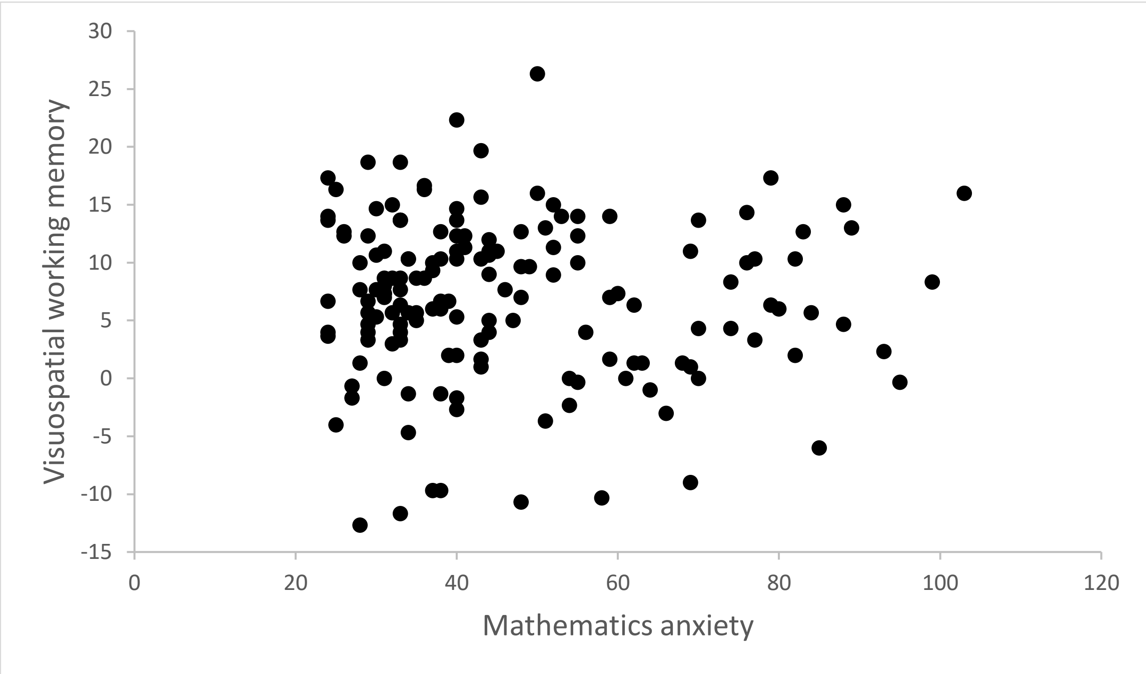

Figure 4.5. Scatterplot representing the relationship between mathematics anxiety and visuo-spatial working memory.

4.3.3.3 Mathematics anxiety and efficiency of the inhibition processes

Next, I considered the performance on the Go/No-Go task. This task allows the collection of three different measures, each with a different meaning. As discussed in the introduction (please see chapter 4.1.5, page 131) the number of false alarms is considered a measure of the efficiency of inhibition processes; more false alarms are associated with lower efficiency. I thus focused on this measure and computed bivariate correlations between mathematics anxiety, trait anxiety, and the efficiency of the inhibition processes. The analysis showed that mathematics anxiety was significantly positively correlated with the number of false alarms, $r(155) = .16$, $p = .042$. On the other hand, trait anxiety was not significantly related to the number of false alarms, $r(155) = .11$, $p = .160$. These results suggest that there is a significant relationship between mathematics anxiety and the efficiency of the inhibition processes, as can be seen in Figure 4.6.

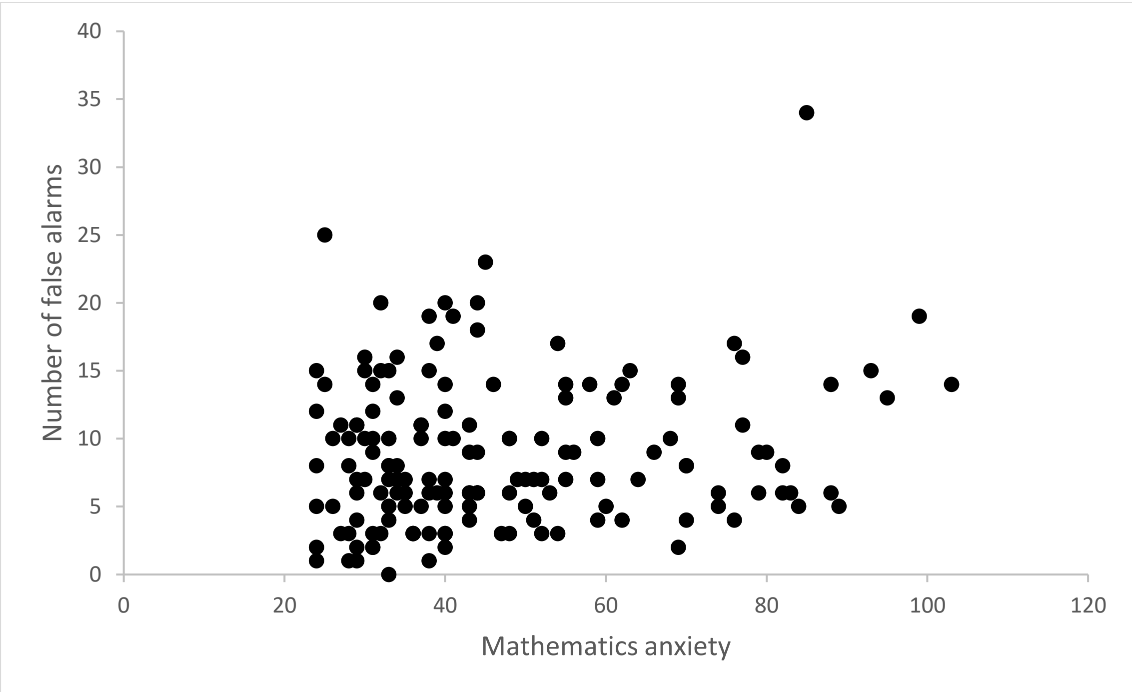

Figure 4.6. Scatterplot representing the relationship between mathematics anxiety and the number of false alarms.

As discussed in this thesis (please see chapter 1.2.2, page 27), mathematics anxiety and trait anxiety share a significant amount of variance. Moreover, previous literature suggests that trait anxiety also has a significant relationship with the efficiency of the inhibition processes (although this was not present in my sample). Given the strength of both of these correlations, I decided to exclude the shared variance between mathematics anxiety and trait anxiety and assess the partial correlation between mathematics anxiety and inhibition's efficiency while controlling for trait anxiety. The analysis showed that after controlling for trait anxiety the relationship between mathematics anxiety and inhibition's efficiency was no longer significant, $r(155) = -.12$, $p = .141$.

4.3.4 Mathematics anxiety and mathematics self-belief

In this study, I used mathematics self-belief measures for the first time along with the measure of mathematics anxiety. Thus, I was interested in how far these measures are related to mathematics anxiety. In the current dataset, I assessed the relationship between these two measures while controlling for trait anxiety and gender.

Before assessing this relationship, however, I decided to explore whether the questionnaires used to assess self-concept, self-efficacy and mathematics anxiety should be considered as one single factor or, as literature suggests (Stankov et al., 2012) as three separate factors. Indeed, as discussed previously, Lee (2009) found that mathematics anxiety, mathematics self-efficacy and mathematics self-concept were three different, albeit related, constructs in the PISA dataset. However, as can be seen in Table 4.2, the correlation between the three factors in the current data was high and suggested that the three questionnaires might be measuring one single construct. On the other hand, the correlation between mathematics anxiety and mathematical self-efficacy and the correlation between mathematics anxiety and mathematical self-concept were lower.

Table 4.2. Mathematics self measures correlation matrix

Measure	1	2	3
1. RMARS	-	-.59***	-.60***
2. Mathematical Self-Efficacy		-	.71***
3. Mathematical Self-Concept			-

Legend:
*: p < .05
**: p < .01
***: p < .001

Hence, I decided to run an Exploratory Factor Analysis (with the PCA method) to assess whether in the current data mathematics anxiety, mathematics self-concept, and mathematics self-efficacy should be considered as one, two, or three factors. At first, I considered an Exploratory Factor Analysis (EFA) with all three questionnaires. Hence the three questionnaires were subjected to EFA with oblique rotation (Promax rotation[5]). The Kaiser-Meyer-Olkin measure of sampling adequacy suggested a high strength of the relationships among variables (KMO = .94) and the Bartlett's test of sphericity showed that it was appropriate to use the factor analytic model on this set of data (χ^2 (528) = 3600.391, $p < .001$). I fixed the number of factors at three (mathematics anxiety, mathematics self-efficacy, and mathematics self-concept). The 3-factor solution accounted for 57.77% of the variance. However, the structure of the model showed two factors for the RMARS questionnaire, and one factor unifying mathematics self-efficacy and mathematics self-concept under one umbrella. The resulting structure can be seen in Table 4.3.

[5] I opted for an oblique rotation and not an orthogonal rotation because there is a high correlation between the factors. Orthogonal rotations should be avoided when there is a high correlation between the factors (Field, 2013).

Table 4.3. Exploratory Factor Analysis (Promax-Rotated) with PCA method of the Items of the mathematical self-measures.

	Factor		
Items	C1	C2	C3
RMARS18	.87		
RMARS19	.86		
RMARS20	.85		
RMARS4	.83		
RMARS3	.78		
RMARS14	.77		
RMARS13	.74		
RMARS17	.72		
RMARS21	.71		
RMARS5	.65		
RMARS9	.55		
RMARS7	.53		
RMARS23	.47		
RMARS24		.84	
RNARS11		.80	
RMARS10		.80	
RMARS16		.77	
RMARS1		.76	
RMARS22		.76	
RMARS8		.74	
RMARS2		.74	
RMARS6		.71	
RMARS15		.68	
RMARS12		.64	
MSC3			.81
MSE3			.78
MSE1			.77
MSC2			.77
MSC4			.76
MSE5			.75
MSC1			.70
MSE2			.67
MSE4			.63

Legend:
RMARS: Revised Mathematics Anxiety Rating scale
MSC: Mathematical Self-Concept
MSE: Mathematical Self-Efficacy

Existing literature suggests that the RMARS assesses two different factors, learning mathematics anxiety and mathematics evaluation anxiety (Taylor & Fraser, 2013). However, the factor division presented in Table 4.3 did not follow the division reported in literature. Moreover, I ran a confirmatory factor analysis (CFA) with the RMARS items divided into two factors as described in Taylor and Fraser (2013). This analysis suggested that this factor division did not fit the data well; $\chi^2(251) = 628.06, p < .001$, CFI = .84, GFI = .73, NFI = .76, RMSEA = .10[6]. Given that the focus of the current study was not to assess the effect of separate factors of mathematics anxiety, but of mathematics anxiety as a single factor, and given the poor fit of the factor division with the data, it was decided to consider mathematics anxiety as a single factor.

Regarding mathematics self-efficacy and mathematics self-concept, on the other hand, I decided to assess further the factor division to improve the quality of the analysis. Given the high factor loadings on all the mathematics self-efficacy and mathematics self-concept on a single factor, I decided to include these two questionnaires in an exploratory factor analysis with oblique rotation (Promax rotation[5]). The Kaiser-Meyer-Olkin measure of sampling adequacy suggested a high strength of the relationships among variables (KMO = .91) and the Bartlett's test of sphericity showed that it was appropriate to use the factor analytic model on this set of data (χ^2 (36) = 583.57, $p < .001$). Using eigenvalue of 1 as the cut-off point (Field, 2013) and by looking at the scree plot, the analysis yielded a 1-factor solution as the best fit for the data. The 1-factor solution accounted for 54.36% of the variance. A 2-factor solution would explain 64.11% of the variance, but the factor division would not reiterate the division proposed in literature. In fact, item 1 to 5 are from the mathematics self-efficacy questionnaire; and the items 6 to 9 from the mathematics self-concept. The current analysis instead would suggest dividing

[6] The model fit indices are explained in the next chapter (please see chapter 5.2.4, page 186). For the current analysis, here are the guidelines for models with a good fit. χ^2: non-significant. CFI, GFI, and NFI: over .95 (the maximum value is 1). RMSEA: lower than .07.

the factors in the following way. One factor composed of items 1, 2, 3, 6, 7, 8, and 9 and one factor composed of items 4 and 5. As can be seen, the division would not retrace the factor division presented in literature. For this reason, I decided to use the one-factor solution. The results of the one-factor analysis can be seen in Table 4.4. The composite factor, called mathematics self-belief, showed high reliability[7].

[7] The authors define *self-concept* as the perception that we have of ourselves, whereas *self-efficacy* as the beliefs about our own capabilities; defining two different factors. However, the exploratory factor analysis suggests that in this dataset self-concept and self-efficacy items load on one common factor that I will call mathematics self-belief. Reliability test ran on both questionnaires together showed high internal reliability ($\alpha = .90$).

Table 4.4. Exploratory Factor Analysis (Promax-Rotated) with PCA method of the items of the mathematics self-measures.

Items	Factor C1
In my mathematics class, I understand even the most difficult work.	0.809
I am sure I can do difficult work in my mathematics class.	0.79
I learn mathematics quickly.	0.783
I can do almost all the work in mathematics class if I do not give up.	0.779
I am sure I can learn the skills taught in mathematics class well.	0.778
I get good grades in mathematics.	0.766
I have always believed that mathematics is one of my best subjects.	0.687
Even if the work in mathematics is hard, I can learn it.	0.669
If I have enough time, I can do a good job in all my mathematics work.	0.633

4.3.4.1 Mathematics anxiety and mathematics self-belief while controlling for trait anxiety and gender

I wanted to investigate the relationship between mathematics anxiety and mathematics self-belief. I had no reasons to assume causality, thus I used correlations between the factors. Results showed a strong significant negative correlation between mathematics anxiety and mathematics self-belief, $r = -.64$, $p < .001$, as can be seen in Figure 4.7.

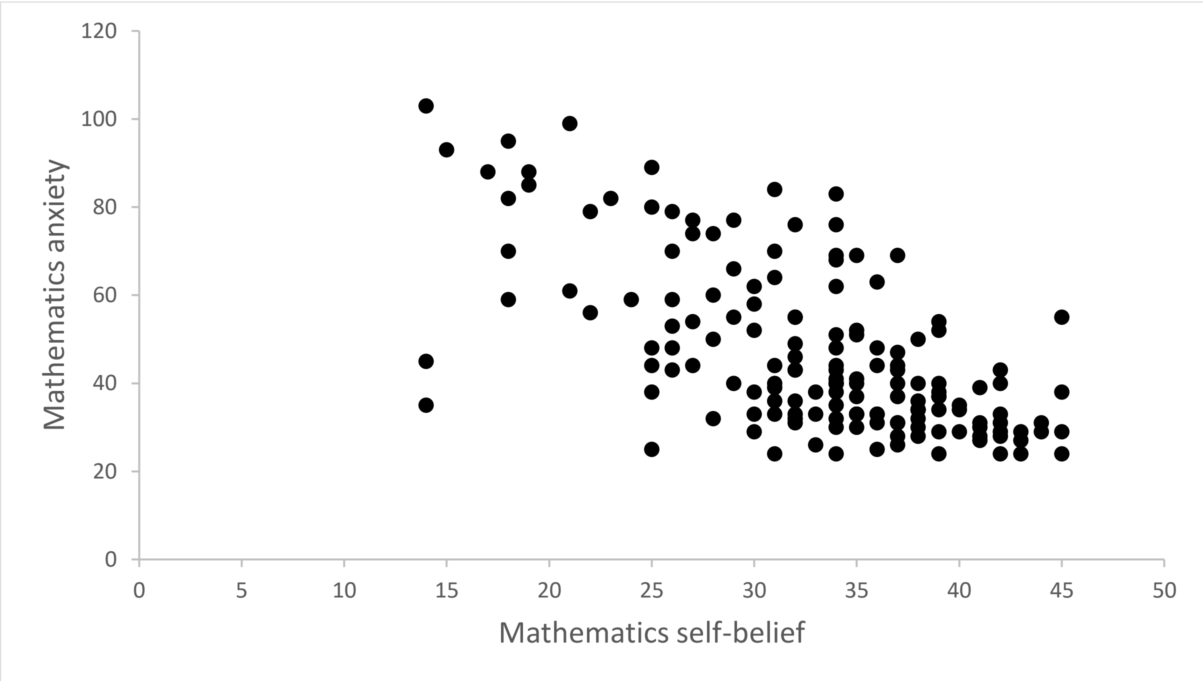

Figure 4.7. Bivariate correlation between mathematics anxiety and mathematics self-beliefs.

Since trait anxiety can be a source of bias, I ran a partial correlation between mathematics anxiety and mathematics self-belief while controlling for trait anxiety and the result showed that the correlation between mathematics anxiety and mathematics self-belief was still large and significant, $r = -.53$, $p < .001$. Finally, given the gender differences in the mathematics self-belief measure, I decided to investigate the correlation between mathematics anxiety and mathematics self-belief separately for males and females while controlling for trait anxiety. For females, the results showed a large significant negative correlation between mathematics anxiety and mathematics self-belief, $r(77) = -.63$, $p < .001$ as can be seen in Figure 4.8.

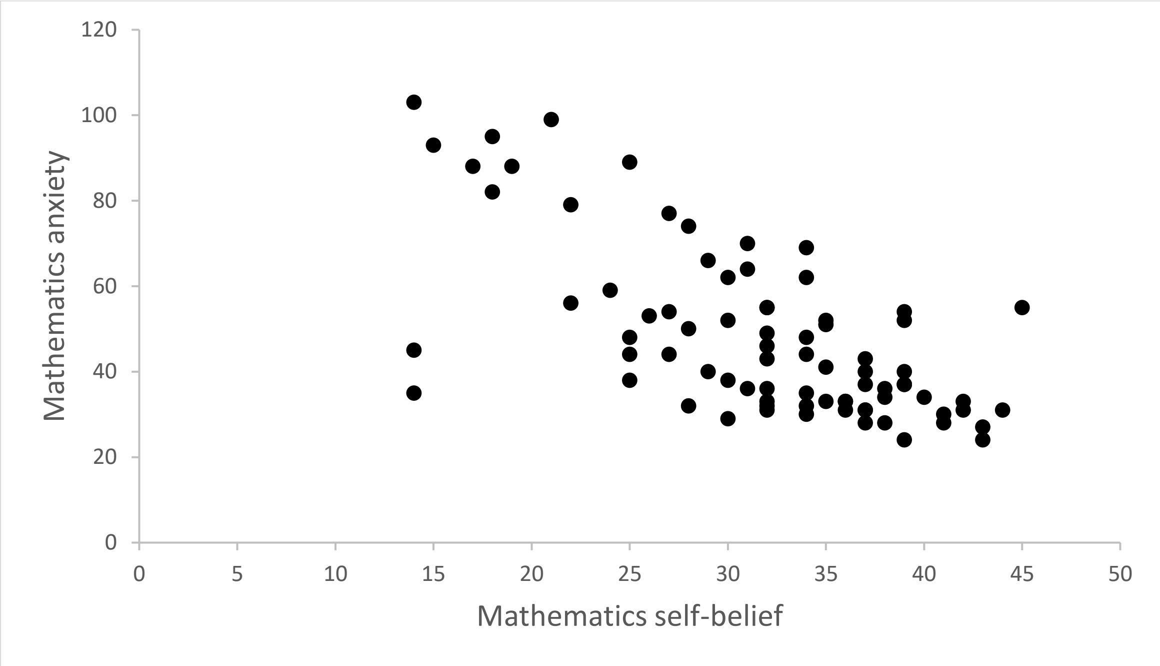

Figure 4.8. Bivariate correlation between mathematics anxiety and mathematics self-belief in female participants

For males the results showed a medium to large significant correlation between mathematics anxiety and mathematics self-belief, $r = -.40$, $p < .001$ as can be seen in Figure 4.9.

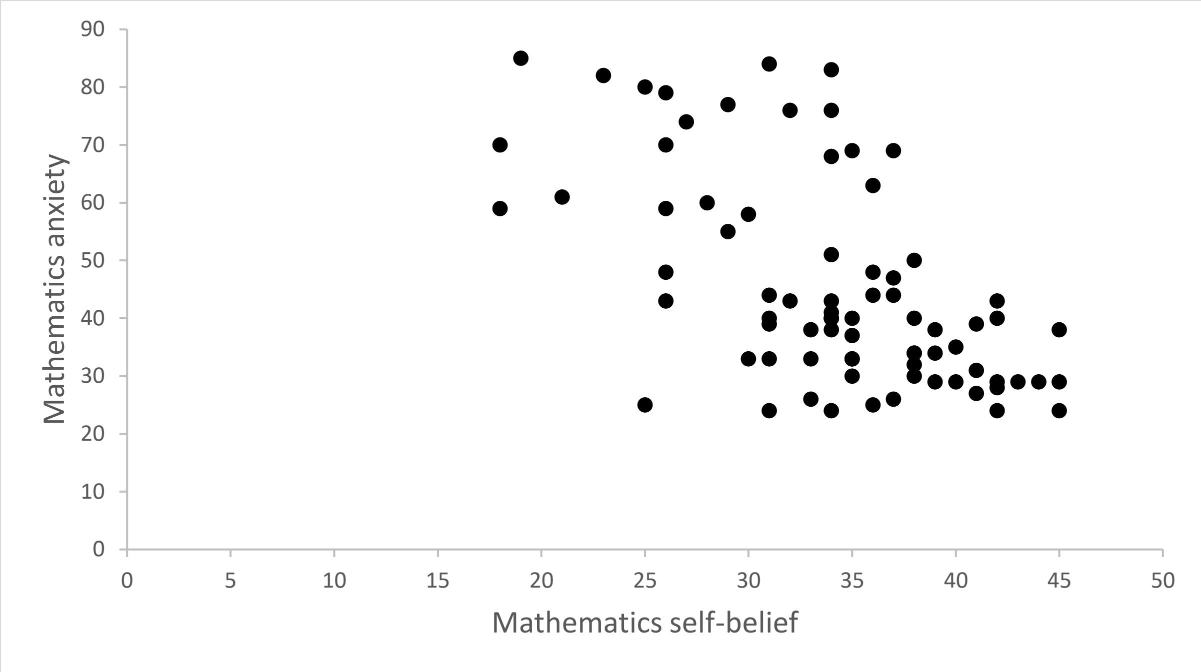

Figure 4.9. Bivariate correlation between mathematics anxiety and mathematics self-belief in male participants

The relationship between mathematics anxiety and mathematics self-belief differed marginally between females and males, $z = 1.95$, $p = .051$. These results suggest that the negative relationship between mathematics anxiety and mathematics self-belief might be stronger for female than male participants.

4.3.5 Mathematics self-belief and mathematical performance

I decided to assess the relationship between mathematical performance and mathematics self-belief while controlling for trait anxiety and mathematics anxiety. For this reason, I decided to run different regression models for the three measures of mathematical performance. Because previous research indicated significantly higher levels of mathematics self-belief in male students (Morony et al., 2013; Pajares & Miller, 1994; Villavicencio & Bernardo, 2016), I will also present the results separately by gender.

4.3.5.1 Mathematics self-belief and mathematical performance

The first analysis that I considered was regarding the relationship between mathematics self-belief and mathematical performance. I computed a stepwise linear regression with mathematics self-belief, mathematics anxiety, and trait anxiety as predictors of the mathematical performance. The analysis showed mathematics self-belief as a significant predictor of mathematical performance ($\beta = .39$, $p < .001$), but not mathematics anxiety nor trait anxiety. The resulting model showed that mathematics self-belief explained 15% of the variance and that the model was a significant predictor of mathematical performance, F (1, 155) = 28.05, $p < .001$ as can be seen in Figure 4.10[8].

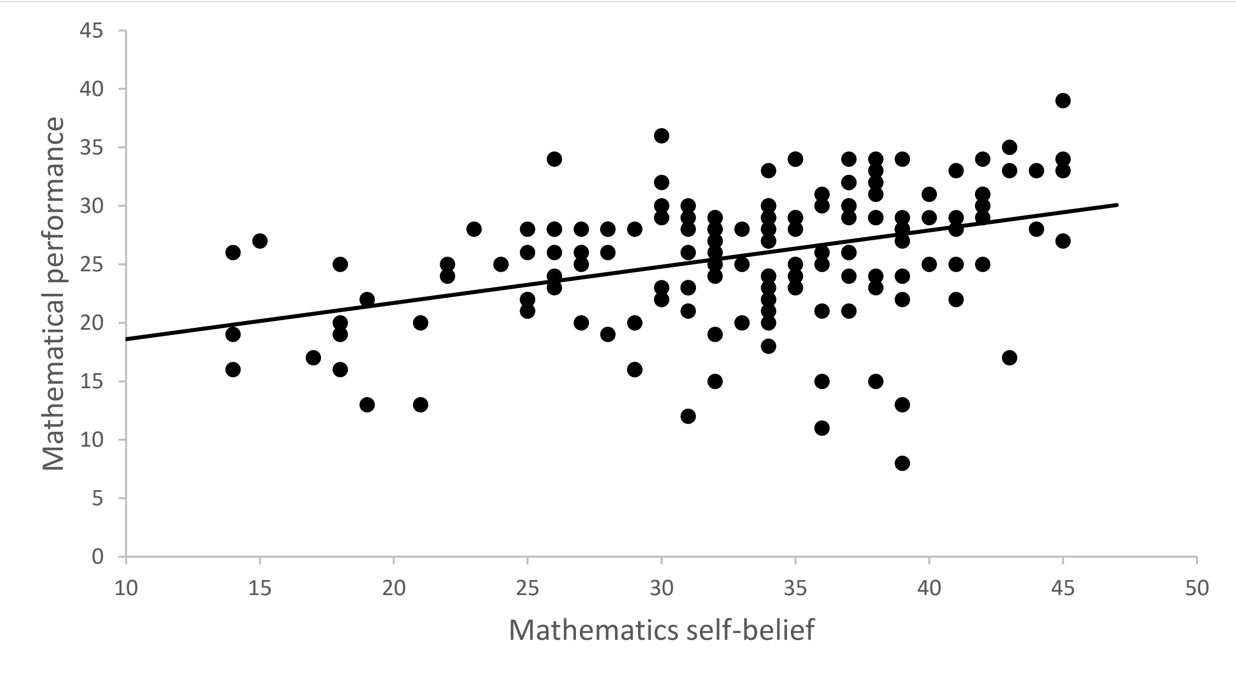

Figure 4.10. Scatterplot representing the relationship between mathematics self-belief and mathematical performance.

[8] VIF (Variance Inflation Factor) collinearity statistics suggest that although the predictors are highly related with each other, collinearity is not a cause for concern; mathematics anxiety VIF = 1.70, trait anxiety VIF = 1.22.

Given that the previous analysis suggested a significant difference in the relationship between mathematics anxiety and mathematics self-belief in female and male participants, I separated female and male participants and re-ran the analysis. It was found that in female participants mathematics self-belief was a significant predictor of mathematical performance (β = .48, $p < .001$), but not mathematics anxiety nor trait anxiety. The resulting model showed that in female participants mathematics self-belief explained 23% of the variance and that the model was a significant predictor of mathematical performance, F (1, 77) = 23.13, $p < .001$.

In male participants mathematics self-belief was a significant predictor of mathematical performance (β = .34, p = .002), but not mathematics anxiety nor trait anxiety. The resulting model showed that in male participants mathematics self-belief explained 12% of the variance and that the model was a significant predictor of mathematical performance, F (1, 76) = 10.17, p = .002.

In line with the previous analysis, I ran a regression analysis including the interaction term of gender x mathematics anxiety. I found that neither gender nor interaction were significant predictors of mathematical performance.

4.3.5.2 Mathematics self-belief and arithmetical fluency

The second analysis that I considered was regarding the relationship between mathematics self-belief and arithmetical fluency. I computed a stepwise linear regression with mathematics self-belief, mathematics anxiety, and trait anxiety as predictors of arithmetical fluency. The analysis showed mathematics self-belief as a significant predictor of arithmetical fluency (β = .43, $p < .001$), but not mathematics anxiety nor trait anxiety. The resulting model showed that mathematics self-belief explained 19% of the variance and that the model was a significant predictor of arithmetical fluency, F (1, 155) = 35.77, $p < .001$ as can be seen in Figure 4.11[8].

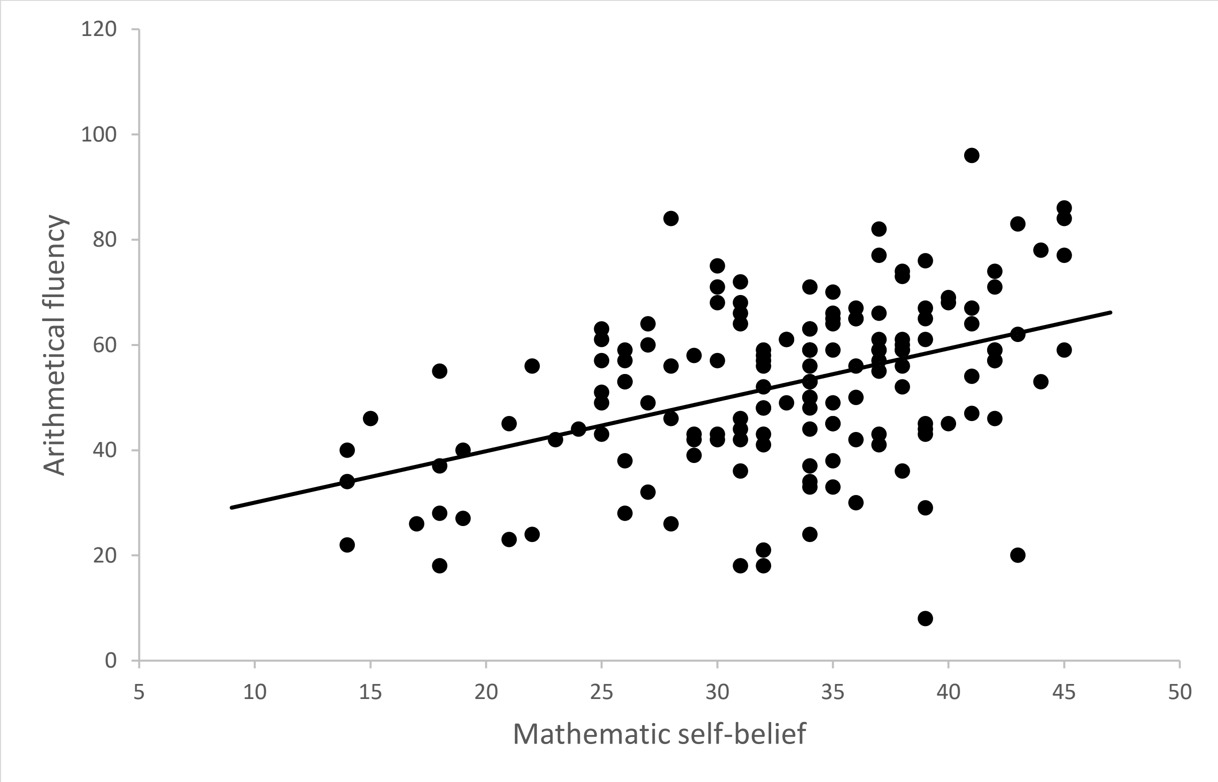

Figure 4.11. Scatterplot representing the relationship between mathematics self-belief and arithmetical fluency.

Given that the previous analysis suggested a significant difference in the relationship between mathematics anxiety and mathematics self-belief in female and male participants, I separated female and male participants and re-ran the analysis. In female participants, mathematics self-belief was a significant predictor of arithmetical fluency ($\beta = .45$, $p < .001$), but not mathematics anxiety nor trait anxiety. The resulting model showed that in female participants mathematics self-belief explained 20% of the variance and that the model was a significant predictor of arithmetical fluency, F (1, 77) = 19.49, $p < .001$.

In male participants, mathematics self-belief was a significant predictor of arithmetical fluency ($\beta = .39$, $p < .001$), but not mathematics anxiety nor trait anxiety. The resulting model showed that in male participants mathematics self-belief explained 15% of the variance and that the model was a significant predictor of arithmetical fluency, F (1, 76) = 13.50, p < .001. In line with the previous analysis, I ran a regression analysis including the interaction term of gender x mathematics anxiety. Neither gender nor the interaction terms were significant predictors of arithmetical fluency.

4.3.5.3 Mathematics self-belief and conceptual understanding

The third outcome measure that I considered was the conceptual understanding task. I computed a stepwise linear regression with mathematics self-belief, mathematics anxiety, and trait anxiety as predictors of conceptual understanding. The analysis showed mathematics anxiety as a significant predictor of conceptual understanding (β = -.24, p = .002), but not mathematics self-belief nor trait anxiety. The resulting model showed that mathematics anxiety explained 6% of the variance and that the model was a significant predictor of conceptual understanding, F (1, 155) = 9.54, p = .002 as can be seen in Figure 4.3[8].

Although the results showed that mathematics self-belief was not a significant predictor of conceptual understanding once mathematics anxiety was controlled for, I decided to assess if the relationship was different between female and male participants. It was found that in female participants mathematics self-belief was a significant predictor of conceptual understanding (β = .24, p = .036), but not mathematics anxiety nor trait anxiety. The resulting model showed that in female participants mathematics self-belief explained 6% of the variance and that the model was a significant predictor of conceptual understanding, F (1, 77) = 4.55, p = .036 as can be seen in Figure 4.12.

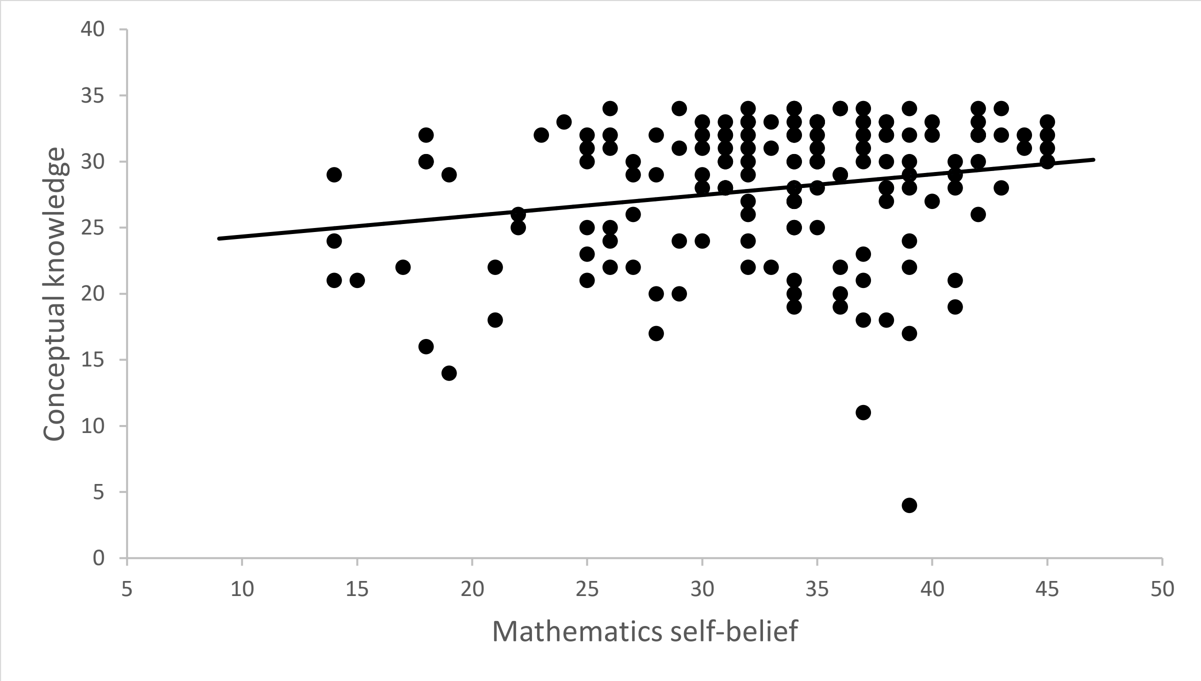

Figure 4.12. Scatterplot representing the relationship between mathematics self-belief and conceptual understanding in female participants.

On the other hand, in male participants mathematics anxiety was a significant predictor of conceptual understanding (β = -.29, *p* = .011), but not mathematics self-belief nor trait anxiety. The resulting model showed that in male participants mathematics anxiety explained 8% of the variance and that the model was a significant predictor of conceptual understanding, *F* (1, 76) = 6.76, *p* = .011 as can be seen in Figure 4.13.

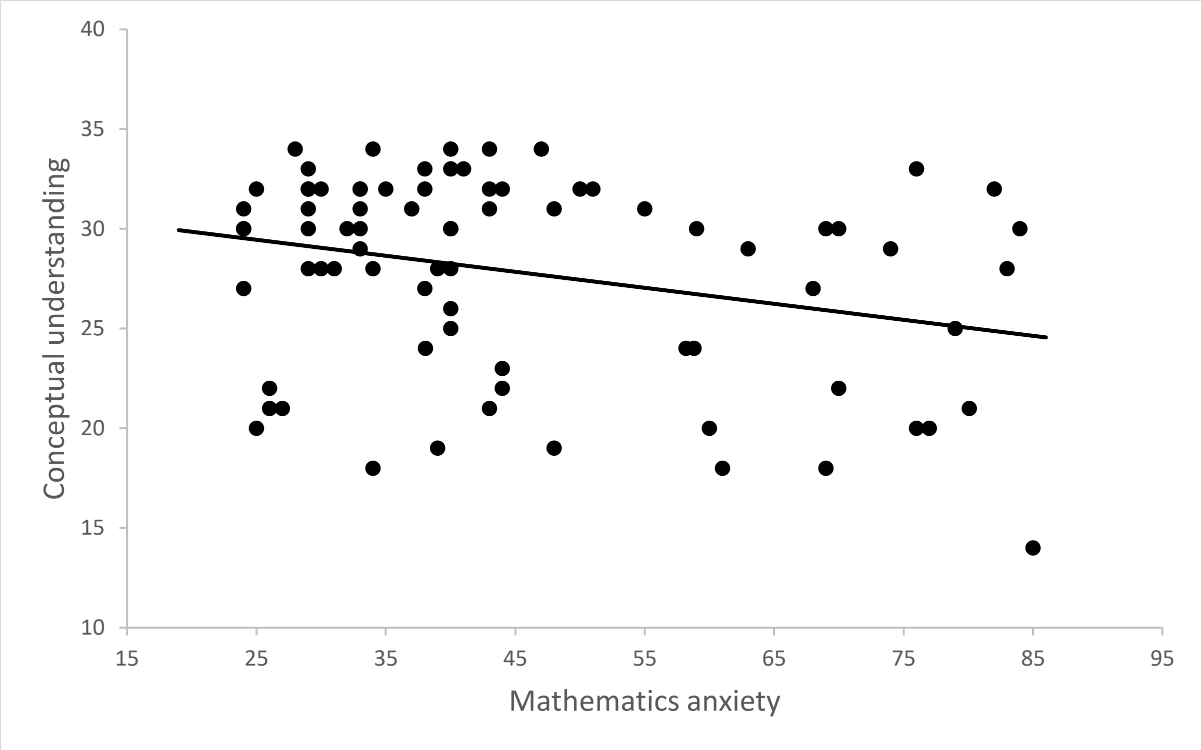

Figure 4.13. Scatterplot representing the relationship between mathematics anxiety and conceptual understanding in male participants.

These results suggest that the predictors for conceptual understanding are different between female and male participants. Whereas for female participants mathematics self-belief seems to be more important than their anxiety in predicting their mathematical understanding, in male participants, it seems to be the opposite.

4.4 Discussion

I used the Time1 data from the longitudinal study to assess the following hypotheses:

1) There is a significant relationship between mathematics anxiety and mathematical performance at the beginning of the first year of secondary school;
2) This relationship is significant in female and male participants;

3) Higher mathematics anxiety is related to significantly lower performance of the phonological loop, of the visuo-spatial sketchpad, and the inhibition processes;
4) Mathematics anxiety, mathematics self-concept, and mathematics self-efficacy are three different constructs;
5) Mathematics anxiety, mathematics self-concept, and mathematics self-efficacy show independent significant relationships with mathematical performance.

Current results suggest that there is a significant negative relationship between mathematics anxiety and mathematical performance at the beginning of the first year of secondary school. This relationship remained significant after controlling for trait anxiety. Moreover, it was found that in line with existing research (Ma, 1999; Meece et al., 1990) there were no differences between female and male participants in the relationship between mathematical performance and mathematics anxiety. Against predictions, results did not show significant concurrent relationships between mathematics anxiety and verbal or visuo-spatial working memory. On the other hand, the results did suggest a significant negative relationship between mathematics anxiety and the efficiency of the inhibition processes. Several new constructs, including mathematics self-belief (mathematics self-efficacy and mathematics self-concept), were added in this study. Mathematics anxiety emerged as a separate construct from the two measures of mathematics self-belief. However, current measures of mathematics self-concept and mathematics self-efficacy seem to load on one common factor, suggesting they measure the same construct. Finally, to my surprise, it was found that mathematics self-belief seems to be a stronger predictor of concurrent mathematical performance at the beginning of secondary school than mathematics anxiety. Controlling for mathematics self-belief renders most relationships between mathematics anxiety and mathematical performance non-significant.

4.4.1 The relationship between mathematics anxiety, mathematical performance, and mathematics self-belief

So far research suggests a moderate negative relationship between mathematics anxiety and mathematical performance (e.g., Ashcraft & Moore, 2009; Carey, Hill, Devine, & Szücs, 2016; Dowker et al., 2016; Hembree, 1990; Ma, 1999; Passolunghi et al., 2016). However, most research that evaluated the relationship between mathematics anxiety and mathematical performance either did not control for other motivational factors (Ashcraft & Kirk, 2001; Miller & Bichsel, 2004), or controlled for other types of anxiety (for a review see Dowker et al., 2016). Very few studies have investigated the relationship between mathematics anxiety and mathematical performance while also controlling for mathematics self-beliefs. Current results suggested that mathematics self-belief might be more strongly related to concurrent mathematical performance than mathematics anxiety.

In simple mathematical tasks, Hoffman (2010) found that the relationship between mathematics anxiety and mathematical performance was explained by mathematics self-belief. However, in Hoffman's study, the relationship between mathematics anxiety and mathematical performance was still significant in more complex mathematical tasks. With regard to simple tasks, current results were in line with Hoffman's findings (Hoffman, 2010). In fact, the relationship between mathematics anxiety and arithmetical fluency was no longer significant once the effect of mathematics self-belief was ruled out. However, current findings were not in line with Hoffman's findings regarding more complex mathematical tasks (in the current case, the WRAT-4 mathematical subtest). Once the effect of mathematics self-belief was controlled, mathematics anxiety was no longer a significant predictor of mathematical performance. Hoffman's (2010) study used pre-service teachers, whereas the current data was from secondary school students. It is possible that the age difference can explain the discrepant findings.

Interestingly, mathematics self-belief scores were a better predictor than mathematics anxiety on all mathematical tasks except for conceptual understanding, for which the results suggested that mathematics anxiety was a significant predictor whereas mathematics self-belief was not. Moreover, the relationship between mathematics self-belief, mathematics anxiety, and conceptual understanding was influenced by gender. In female participants, mathematics self-belief was positively correlated with conceptual understanding and when self-belief was included mathematics anxiety was no longer a significant predictor of performance on the conceptual understanding task. This is in line with findings on the other two mathematical tasks. For male participants, however, their scores on the mathematics self-belief questionnaire did not predict performance on the conceptual understanding task, but their mathematics anxiety scores did. Lower mathematics self-belief might lead to a bias to select the answer 'yes – the previous answer can help me with the current answer' less often because participants are not confident about their own knowledge. Male participants with higher mathematics anxiety might respond differently to the conceptual understanding task than female participants with higher mathematics anxiety. Male participants with higher mathematics anxiety might have rushed and answered the questions quickly, i.e., showing the so-called 'local avoidance' (Hopko, 2003). This then could have led to a trade-off between speed of execution and quality of performance. Trying to be as quick as possible might have led to more errors. If this was the case, I would have expected males with high mathematics anxiety also to try to finish as soon as possible in other untimed mathematical tasks, e.g., the WRAT-4 mathematical subtest. Consequently, there should be a stronger correlation between the score on the WRAT-4 mathematical subtest and score on the conceptual understanding task for male participants compared with female participants. Indeed, this is what I found[9]. On the other hand, this explanation does not explain why female participants did not show such local avoidance. One possible cause for this

[9] Correlation between WRAT-4 and conceptual understanding task in female participants $r = .29$ Correlation between WRAT-4 and conceptual understanding task in male participants $r = .51$.

discrepancy can be found in the findings from Cohen-Zada and colleagues' (2017) study. The authors examined the drop in performance during high-stakes situations in more than 8000 tennis players during the Grand Slam singles tournament. The authors found that in high-stakes situations, male tennis players tended to show a drop in performance and had a higher risk of losing the match. In female tennis players, this drop was not always present, and even when present, it was only about half the size of the drop observed in male players. The authors explain that these results are in line with biological literature that reports how the secretion of cortisol impacts males more than females. Although the context is quite different from the current one, it might be that female and male students reacted differently in front of items that they were not sure about while under the pressure from anxiety-related arousal. Future studies might involve the assessment of salivary cortisol (Mattarella-Micke et al., 2011) in male and female participants, and assess if salivary cortisol levels are different between the groups, and if they are related to local avoidance effects.

4.4.1.1 The relationship between mathematics anxiety and mathematics self-belief

In the current study, in line with the existing literature (Hoffman, 2010; Mcmullan et al., 2012; Pajares & Graham, 1999; Pajares & Miller, 1994), mathematics anxiety showed a strong correlation with mathematics self-belief. Suggestions have been made on why researchers find this relationship. For example, Hoffman (2010) suggested that having higher mathematical self-beliefs might work as a protecting factor against the development of mathematics anxiety. Alternatively, other authors (Meece et al., 1990; Pajares & Kranzler, 1995) suggested that it might be that higher mathematics anxiety causes the participants to develop less trust in their own mathematical skills. Although the data suggest a relationship between the constructs, given the concurrent nature of the design it is not possible to draw conclusions on the directionality of this relationship. However, recent research suggested a reciprocal relationship (Ahmed et al., 2012).

This study will be further discussed in the next chapter (please see page 5.1.3, chapter 178); the authors found a reciprocal longitudinal relationship between mathematics self-concept and mathematics anxiety. This suggests that high trust in mathematical skills can work as a protective factor against the development of high mathematics anxiety, but that on the other hand higher mathematics anxiety can also cause the loss of trust in the mathematical skills. The concurrent data presented in this chapter is in line with all three interpretations presented. However, in the next chapter I will analyse longitudinal data that might help to shed light onto the question of the directionality of this relationship.

4.4.1.2 Mathematics self-belief as one factor

Lee (2009) provided evidence that mathematics self-efficacy and mathematics self-concept are two separate constructs. The current exploratory factor analysis, however, suggested that items measuring mathematics self-concept and mathematics self-efficacy load on the same single factor. These discrepant findings likely emerged because of the specific items I used. As discussed on chapter 1.2.5, page 30, mathematics self-efficacy is usually defined as trust in our abilities in carrying out very specific tasks (e.g., how confident the participant is that given a specific multiplication they could solve it correctly), whereas mathematics self-concept includes a wider range of more general skills in dealing with mathematical operations. Lee (2009) used very general questions as items for their mathematics self-concept questionnaire, such as "I have always believed that mathematics is one of my best subjects." (Lee, 2009, pp. 358). Moreover, Lee's questionnaire for mathematics self-efficacy used very specific situations, such as "How confident do you feel about calculating how much cheaper a TV would be after a 30% discount?" (Lee, 2009, pp. 358). The mathematics self-belief questionnaire that was used in the current study was adopted from Stankov and colleagues' scale (2012). The questionnaire included four mathematics self-concept items that were general questions about the participant's trust in mathematical skills and five mathematics self-efficacy items. Upon inspection, it is clear that the items used for mathematics self-efficacy by us and based on Stankov et al. (2012) describe much fewer specific situations than the items used by Lee. For example, the item "I am sure I can do difficult work in my mathematics class", is about the general confidence in one's ability to solve mathematical tasks, not about the confidence in one's ability to solve a specific problem (or a specific type of problem, such as calculating the square root of a number). Given that the items in the mathematics self-efficacy questionnaire were more similar to Lee's self-concept items, the reason why in the current study all items loaded on one factor may be that most of the items I used measure mathematics self-confidence rather than mathematics self-efficacy.

It is clear that mathematics self-belief is an important and often neglected factor to consider when investigating the relationship between mathematics anxiety and mathematical performance. Although mathematics anxiety is probably a separate construct from mathematics self-efficacy and mathematics self-concept, the high correlation between these constructs poses difficulties when interpreting results. Longitudinal studies might be able to answer questions about the directionality of the relationship between mathematics anxiety and mathematical self-beliefs during the first year of secondary school.

4.4.2 Mathematics anxiety and mathematical performance

Leaving the mathematics self-belief measure aside, this study replicated the significant negative relationship between mathematics anxiety and mathematical performance reported in the literature (Haase et al., 2012; Hembree, 1990; Hill et al., 2016; Passolunghi et al., 2016; Vukovic et al., 2013; Wood et al., 2012). I added to this by investigating different types of mathematical performance. All three measures of mathematical performance included in the current study showed a significant relationship with mathematics anxiety. Interestingly, this relationship was not affected by controlling for trait anxiety. Furthermore, the strength of the relationship was similar between males and females, and there were also no differences in performance between males and females in mathematical performance and understanding. Males showed better performance on the speeded simple calculation task, but the effect of the difference was small, suggesting that the impact on daily life might not be important. Altogether, these results suggested that at the beginning of the secondary school female and male students do not show large differences in their average mathematical performance and that the relationship between mathematics anxiety and mathematical performance is modified by gender.

4.4.3 Mathematics anxiety and working memory

Regarding working memory, the situation is more complex. When looking at simple working memory measures, I did not find a relationship with mathematics anxiety, neither for verbal nor for visuo-spatial working memory. This suggested that in secondary school students mathematics anxiety did not affect the performance in simple working memory tasks.

However, mathematics anxiety was related to a measure of the efficiency of the inhibition processes, the number of false alarms on the Go/No-Go task. While mathematics anxiety and inhibition efficiency showed a significant negative relationship, trait anxiety did not show such correlation with inhibition efficiency. However, when running a partial correlation between mathematics anxiety and inhibition efficiency while controlling for trait anxiety, the relationship was no longer significant. This suggested that excluding the part of the variance in mathematics anxiety that is shared with trait anxiety, the remaining variance in mathematics anxiety was not strongly correlated enough with the inhibition efficiency anymore to be significant, i.e., the unique shared variance between mathematics anxiety and inhibition efficiency is not significant. These results suggest that the shared variance between mathematics anxiety and general anxiety is relevant, although not significant, in determining the relationship between mathematics anxiety and inhibition efficiency. We know that mathematics and general anxiety share genetic and environmental factors (Malanchini et al., 2017). Future studies might want to assess the relevance of each of these factors in explaining the relationship between mathematics anxiety and inhibition efficiency.

4.5 Conclusion

Current results show clearly that even at the beginning of secondary school students show mathematics anxiety and that mathematics anxiety is negatively related to concurrent mathematical performance. Interestingly, this chapter has highlighted that mathematics self-belief seems to be a better predictor of concurrent mathematical performance than mathematics anxiety. Thus, in future studies, it will be crucial to include measures of mathematics self-belief alongside measures of mathematics anxiety.

Chapter 5 - Longitudinal predictors of mathematics anxiety and mathematical performance in secondary school students.

5.1 Introduction

In the previous chapter, I explored concurrent relationships between mathematics anxiety and mathematical performance. Moreover, I introduced a new factor in this thesis, mathematics self-belief. The results in the previous chapter suggested mathematics self-belief is an important factor to consider when analysing the relationship between mathematics anxiety and mathematical performance. In the current chapter, I will concentrate on the longitudinal relationships between mathematics anxiety, mathematical performance and working memory during the first year of secondary school. Given the importance of mathematics self-belief highlighted in the previous chapter, I will include this factor also in the longitudinal analysis.

5.1.1 The Relationship between Mathematics Anxiety and Mathematical Performance in Primary and Secondary School Students

Up to this point, I have only presented concurrent data. Although concurrent data are helpful when investigating the relationships between factors, for a complete understanding of the development of these relationships it is important to use longitudinal data. Surprisingly, not many studies have assessed the longitudinal relationships between mathematics anxiety and mathematical performance.

Most research that investigated longitudinal relationships between mathematics anxiety and mathematical performance concluded that poor mathematical performance is a causal factor for the development of mathematics anxiety, whereas the development of mathematical performance is independent of mathematics anxiety (Ma & Xu, 2004; Vukovic et al., 2013).

Vukovic et al. (2013) investigated mathematics anxiety and mathematical performance in a longitudinal study with primary school students following them from Year 2 to Year 3. The authors tested visuo-spatial working memory, calculation skills, mathematical applications, and mathematics anxiety. Calculation skills were measured with a test that requires to answer 25 calculation questions in 20 minutes. Mathematical applications, on the other hand, was assessed by asking the participants to complete story problems, algebra problems, and data analysis problems. Finally, mathematics anxiety was assessed with the Mathematics Anxiety Scale for Young Children (Harari et al., 2013). When controlling for Year 2 visual-working memory, Year 2 mathematics anxiety did not significantly predict Year 3 calculation skills nor Year 3 scores in the mathematical applications test. Regarding secondary school students, Ma and Xu (2004) published a famous paper investigating mathematics anxiety and mathematical performance in 3116 students from Year 7 to Year 12. Mathematics anxiety was measured by two questions that used Likert-scale answers, whereas mathematical performance was measured using 4 different indicators (basic skills, algebra, geometry, and quantitative literacy). The researchers found that mathematics anxiety in the previous year was either not a significant predictor or only a significant predictor of mathematical performance with a very small effect size ($r = -.05$), suggesting that, in accordance with the other studies, mathematics anxiety does not affect strongly the development of mathematical performance. In contrast, results from a recent study by Ching (2017) assessed the relationship between mathematics anxiety and mathematical performance in 246 Year 2 students (mean age 86.25 months) in Hong Kong. The researcher assessed mathematics anxiety, working memory, general anxiety, test anxiety, non-verbal intelligence, and number skills during the second year of primary school. A year later, during the third year of primary school, the researcher tested calculation ability. Mathematics anxiety at Time 1 was a significant predictor of mathematical performance in difficult calculations at Time 2, even when controlling for Time 1 working memory, general anxiety, test anxiety, non-verbal intelligence, and number skills. Although the author did not assess the longitudinal effects of mathematical performance on mathematics anxiety, these results suggest that we need more data on the longitudinal effects of mathematics anxiety on mathematical performance. On the other hand, it could be argued that the author did not control for calculation ability at the first timepoint. The author used a multiple regression technique to assess the effect of mathematics on mathematical performance, the idea being that mathematics anxiety at the first timepoint comes before mathematical performance that is measured at the second timepoint. So, any significant relationship can be assumed to be directed from mathematics anxiety to mathematical performance. However, the presence of a clear temporal succession is not proof of causality, as it does not rule out possible third variables. For example, it could be that there was a relationship between mathematics anxiety and mathematical performance at the first timepoint, and it is possible that the longitudinal relationship in Ching's dataset (2017) was moderated by mathematical performance at the first timepoint, which was not assessed. Gunderson and colleagues (2018) also found similar results in the longitudinal relationship between mathematics anxiety and mathematical performance. The authors tested Year 1 and Year 2 students at the beginning of the school year (i.e., Time 1), and at the end of the school year (i.e., Time 2). The design included the assessment of the students' mathematics anxiety and mathematical performance. Longitudinal path analysis suggested that Time 1 mathematical performance was a significant predictor of Time 2 mathematics anxiety (β = -.20), and that Time 1 mathematics anxiety was a significant predictor of Time 2 mathematical performance (β = -.06).

Ma and Xu (2004) also assessed the effect of mathematical performance on the development of mathematics anxiety. The authors found that the mathematical performance of the previous year was a significant predictor of mathematics anxiety of the next year, with higher levels of mathematical performance associated with lower levels of mathematics anxiety. Recently Geary and colleagues (2019) assessed mathematics anxiety and mathematical achievement in Year 6 students (mean age = 12 years and 3 months), and then reassessed the same students in Year 7. The authors found that mathematical performance in Year 6 was a significant predictor of mathematics anxiety in Year 7 (β = -.14). Moreover, Wang and colleagues (2020) tested Italian high school students (mean age 15.86 years) and reassessed them after 6 months. In accordance with the previous studies, the authors found that mathematical performance at the first time point was a significant predictor of mathematics anxiety at the second timepoint.

These results suggest that although mathematical performance has a role in the developmental growth of mathematics anxiety, the debate is still open on whether mathematics anxiety affects the mathematical performance or not (Carey et al., 2016). The current study aimed to shed light onto this question.

5.1.2 Concurrent and longitudinal relationships between mathematics anxiety and working memory

The previous chapter presented concurrent relationships between mathematics anxiety, working memory, and inhibition processes (please see chapter 4.4, page 165). I did not find a concurrent relationship between mathematics anxiety and simple working memory measures. On the other hand, I found a significant negative relationship between mathematics anxiety and the efficiency of the inhibition processes, a measure related to complex working memory. This negative relationship observed is usually interpreted to mean that mathematics anxiety has a negative effect on (complex) working memory. However, my results in adults (please see chapter 2.3, page 70) suggested that the working memory deficit that has been described in relation to mathematics anxiety is present also in non-mathematical situations. Mathematics anxiety might be associated with general lower efficiency of the inhibition processes. In my previous study with adults whether the participants with high mathematics anxiety were in a mathematical situation or not did not affect the efficiency of their inhibition processes, thus it might be that participants with high mathematics anxiety present a general deficit in the inhibition processes. Given that having to deal with numbers might not cause a lower efficiency of the inhibition processes, I suggest that having lower efficiency of the inhibition processes could be a causal factor in the development of mathematics anxiety. Moreover, to the best of my knowledge, no studies have examined the longitudinal relationships between mathematics anxiety and working memory yet. Indeed, many studies have recorded a negative relationship between mathematics anxiety and mathematical performance, a relationship that proved stable at different ages and in different countries (for a review, please see chapter 1.3, page 36). However, few studies implemented a longitudinal design, meaning that the causal relationship is still under discussion between the researchers. Although a longitudinal study cannot give final description of causality, it can inform on the directionality of the relationship, and important step in understanding the causal relationship. These factors prompted the decision to include working memory measures to assess the longitudinal effects of working memory on mathematics anxiety.

5.1.3 Mathematics self-belief

As discussed in the previous chapter (please see chapter 4.4.1.2, page 170) mathematics self-concept and mathematics self-efficacy are often considered as two separate factors. However, a factor analysis showed that the mathematics self-concept and self-efficacy items used in my questionnaire were actually assessing only one factor. For this reason, in this chapter, I will use the term mathematics self-belief, because this term describes both mathematics self-efficacy and mathematics self-concept (Stankov et al., 2012). While mathematics self-belief was correlated with mathematics anxiety, it emerged as a more powerful predictor of concurrent mathematical performance than mathematics anxiety (please see chapter 4.4.1, page 167). Thus, I decided to include an analysis of mathematics self-belief and its concurrent and longitudinal relationships in this chapter.

Many studies suggest that low self-perception of ability is contributing to the development of mathematics anxiety (Meece et al., 1990; Pajares & Kranzler, 1995; Pajares & Miller, 1994). In Meece and colleagues' study (1990) there was a small to moderate negative longitudinal relationship between Year 1 perceived ability in mathematics and Year 2 mathematics anxiety (r = -.22). Likewise, Pajares and Miller (1994) found a strong negative concurrent relationship between mathematics self-concept and mathematics anxiety (r = -.87) and a strong negative concurrent relationship between mathematics self-efficacy and mathematics anxiety (r = -.56). Finally, Pajares and Kranzler (1995) tested 329 high school students' mathematics self-belief using the Mathematics Confidence Scale and their mathematics anxiety using the Mathematics Anxiety Scale. They also tested mathematical performance by giving the students the 18 problems that were previously used to test the students' confidence in solving them. The authors found that mathematics self-belief was a significant concurrent predictor of mathematics anxiety, finding strong negative concurrent relationships between mathematics anxiety and mathematics self-efficacy (r = -.53) and between mathematics anxiety and mathematics self-concept (r = -.46). But because the studies presented used concurrent data, or they did not check for the concurrent relationship in the longitudinal analysis, these results cannot determine the direction of the relationship between mathematics anxiety and mathematics self-belief.

Ahmed and colleagues (2012) proposed a model with a causal relationship from mathematics self-belief to mathematics anxiety, but without a reciprocal connection. They suggested that low self-concept could mean that the person does not believe that they can thrive in the situation. Feeling that they cannot cope with a situation can cause the person to perceive the situation as a threat, causing stress and influencing the development of mathematics anxiety. A second option is that mathematics self-belief influences mathematics anxiety, as discussed earlier, and at the same time that mathematics anxiety influences mathematics self-beliefs (Ahmed et al., 2012). The authors recruited 522 Year 7 students (mean age = 12.7 years). They measured mathematics self-concept with a questionnaire that assessed how good the participants thought they were at math. An example of an item that was reported was "How good at math are you?" (Ahmed et al., 2012, pp. 386). The researchers also assessed mathematics anxiety with the Mathematics subscale of the Academic Emotions Questionnaire. The subscale assesses students' mathematics anxiety in different situations (i.e., mathematics class, studying and doing homework, and taking math exams and tests). These measures were collected at three different time points: at the beginning of Year 7, in the middle, and at the end of Year 7. Using structural equation modelling the authors found a reciprocal relationship between mathematics anxiety and mathematics self-concept. In fact, all the cross-lagged coefficients were significant and negative. The cross-lagged relationships were quite stable between the different time points. In fact, mathematics anxiety at the beginning of Year 7 was a significant predictor of mathematics self-concept at the middle of Year 7 ($r = -.07$), and mathematics anxiety at the middle of Year 7 was a significant predictor of mathematics self-concept at the end of Year 7 ($r = -.06$). However, it must be noted that these longitudinal effects of mathematics anxiety on the development of mathematics self-concept were very small, i.e., even if they were significant, their effect in everyday life might be negligible. At the same time, mathematics self-concept at the beginning of Year 7 was a significant predictor of mathematics anxiety at the middle of Year 7 ($r = -.15$), and mathematics self-concept at the middle of Year 7 was a significant predictor of mathematics anxiety at the end of Year 7 ($r = -.14$). The author suggested that mathematics anxiety might have a negative effect on the development of confidence in dealing with mathematical situations, while mathematics self-concept could work as a protective factor against mathematics anxiety. The mechanism by which mathematics anxiety can influence mathematics self-belief was also discussed by Ahmed and colleagues (2012). They stated that anxiety can distort the image that the person has of their own capabilities, influencing the development of the person's self-belief.

In the previous chapter, I discussed the positive relationship between mathematics self-belief and mathematical performance ($r = .39$, please see chapter 4.3.5.1, page 160). Pajares and

Kranzler (1995) also described a positive relationship between mathematics self-efficacy and mathematical performance (r = .64). These studies, however, investigated only concurrent relationships between mathematics self-beliefs and mathematical performance. Kung (2009) analysed longitudinal relationships between mathematical performance and mathematics self-belief. The mathematical performance was measured with the students' school grades; and mathematics self-belief was assessed with two measures, a mathematics self-concept questionnaire, and a mathematics self-efficacy questionnaire. The study included students from Year 7 and Year 10 and tested mathematical performance, mathematics self-belief, and mathematics anxiety at the beginning of the study. Three years after the beginning of the study, mathematical performance was reassessed. Mathematical achievement at the first time point had a significant positive relationship with mathematics self-belief measures at the first timepoint. In fact, mathematical achievement showed a strong positive relationship with mathematics self-concept (γ = .69) and with mathematics self-efficacy (γ = .73). At the same time, both mathematics self-belief measures at the first timepoint had a significant positive effect on the mathematical performance at the second timepoint (β = .37 for mathematics self-concept; β = .44 for mathematics self-efficacy). Taken together, these results suggest the existence of a reciprocal relationship between mathematical performance and mathematics self-belief.

Finally, to the best of my knowledge, there are no studies that investigate specifically the relationship between mathematics self-beliefs and working memory. However, Hoffman and Schraw (2009) measured working memory capacity and mathematics self-efficacy. The study involved 58 university students, and the results showed a moderate positive concurrent relationship between mathematics self-efficacy and working memory capacity (r = .32). Moreover, Hoffman (2010) also found a significant positive concurrent relationship between mathematics self-efficacy and working memory (r = .35) in preservice teachers. On the other hand, Justicia-Galiano and colleagues (2017) did not find a significant concurrent relationship between mathematics self-concept and working memory (r = .03) in Years 3 to 5 students. This last result is in contrast with the first two studies presented which suggest a moderate relationship between mathematics self-belief and working memory. However, the first two studies were carried out with adults, whereas the study by Justicia-Galiano and colleagues tested students in Years 3 to 5. It is possible that the relationship develops with age, and becomes moderate in adults, whereas in students it is not yet significant.

5.1.4 Research Questions

Based on existing literature, I expected higher mathematical performance at Time 1 to predict lower mathematical anxiety at Time 2. The literature is less clear about the contribution of mathematics anxiety to the development of mathematical performance. However, on balance, given the results of the literature presented, I expected to find no significant negative effects of mathematics anxiety measured at Time 1 on mathematical performance measured at Time 2. A third research question involved the relationship between working memory and mathematics anxiety. Given the results of my studies in adults, I expected lower efficacy in the inhibition processes at Time 1 to lead to higher mathematics anxiety measured at Time 2. The next research questions involve mathematics self-belief. I expected significant positive cross-lagged longitudinal effects of mathematics self-belief on mathematical performance and of mathematical performance on mathematics self-belief. Moreover, evidence suggests that primary school students show no relationship between mathematics self-beliefs and working memory, whereas adult data suggest the presence of a significant positive relationship. If the development of the confidence in carrying out mathematical tasks is influenced by the amount of working memory resources that are available to the person, I would expect that working memory at Time 1 affects mathematics self-belief at Time 2. Finally, given the results from the Time 1 testing, I was interested in investigating mathematics self-belief further. The first research question regarding mathematics self-belief involved comparing the importance of mathematics anxiety against mathematics self-belief in the development of mathematical performance. The second research question involved assessing the role of mathematics anxiety and mathematical performance on the development of mathematics self-belief[10].

5.2 Methods

In this chapter, I report the data of a longitudinal study with 2 time points (Time 1 and Time 2). Time 1 data were collected at the beginning of the academic year (from October to December) in Year 7. Time 2 data were collected at the end of the academic year (June) from the same students in Year 7. Please note that while 168 students took part in Time 1 (as reported in the previous chapter), of which 157 completed the data collection, only 139 students took part in all sessions in both Time 1 and Time 2. Here I report only the data for the students who participated at both Time 1 and Time 2 data collection.

5.2.1 Participants

Of the 157 students with complete Time 1 data, 12 were not present during the classroom testing session of Time 2 so were excluded from the analysis and 6 no longer wanted to participate. The final sample for the analysis was composed of 139 participants (70 females; age range Time 1: 11-12 years, mean age Time 1 = 11.63 years, SD = 0.29 years; age range Time 2: 12-13 years, mean age Time 2 = 12.30 years, SD = 0.29 years). Moreover, one participant showed a score of 0 on the WRAT-4 mathematical subtest at Time 2. Given that the test allows 15 minutes, and the first few exercises are quite simple, and the fact that the same student

[10]The original design involved also the analysis of the reciprocal longitudinal relationship between mathematics anxiety and mathematics self-belief. However, the models showed a poor model fit and I decided not to include them here. Future research might address this problem with different models that show a better fit.

achieved a higher score on the WRAT-4 mathematical subtest at Time 1, I decided to exclude this participant from the analyses. I obtained formal consent from the headteacher and the parents before testing at Time 1 and I sought verbal consent from the participants during testing at both Time 1 and Time 2.

5.2.2 Materials

5.2.2.1 Measures included in Time 1 and Time 2 classroom testing

Mathematics Anxiety

To assess the participants' mathematics anxiety, I used the Revised Mathematics Anxiety Rating scale (RMARS; Taylor & Fraser, 2013). I used the same scale at Time 1 and Time 2, so for the details of this scale, please see chapter 4.2.2.1, page 135.

Mathematical Performance

To assess the participants' mathematical proficiency I used the blue form of the mathematical subtest of the Wide Range Achievement Test (WRAT-4; Wilkinson & Robertson, 2006). I used the same subtest and the same procedure at Time 1 and Time 2, so for the details of this subtest, please see chapter 2.2.2, page 64.

Arithmetical Fluency

To assess participants' fluency in arithmetic I used the Simple Calculations task. The task required the participant to solve as many calculations as possible within a specific time limit. The task included three operations: addition, subtraction, and multiplication. I used the same items and the same procedure for Time 1 and Time 2, so for the details please see chapter 2.2.2, page 64.

Mathematics Self-Belief Measures

To assess the participants' mathematics self-belief I used the 5 item-mathematics self-efficacy scale and the 4 item-mathematics self-concept questionnaire used by Stankov and colleagues (2012). I used the same measures and the same procedure at Time 1 and Time 2, so for details see chapter 4.2.2.1, page 135.

5.2.2.2 Measures included only in Time 1 individual testing

Verbal working memory

To assess verbal working memory at Time 1, I used a letter span task (Marcel, 1974). The task requires participants to repeat a series of letters after hearing them spoken aloud, in the same order as they heard them. The task is described in detail in the previous chapter, so for details please see chapter 2.2.2, page 64.

Visuo-spatial working memory

To assess visuo-spatial working memory at Time 1, I used a computerized task to assess visual working memory load which will be described as visual k-value (McNab & Klingberg, 2008). The task is described in the previous chapter, so for details please see chapter 4.2.2.2, page 137.

Inhibition processes

To assess participants' efficiency of the inhibition processes at Time 1, I used a Go/No-Go task. The version used is an adaptation of the task used in Gonzalez Alam and colleagues (2018). The task is described in the previous chapter, so for details see chapter 4.2.2.2, page 137. I will report the total number of false alarms.

5.2.2.3 Testing apparatus

The testing apparatus used was the same during Time 1 and Time 2 testing, do for details on the testing apparatus used please see chapter 4.2.2.3, page 140.

5.2.3 Design and Procedure

Time 1 and Time 2 data collection sessions were similar. Time 1 testing has been described in the previous chapter (please see chapter 4.2.2.4, page 140). Time 2 classroom testing was exactly as Time 1 classroom testing, except that at Time 2 I did not test trait anxiety. Time 1 individual testing is described in detail in the previous chapter (please see chapter 4.2.2.4, page 140). At Time 2 only conceptual understanding was assessed individually which is not analysed in the current chapter.

5.2.4 Data Analysis

My initial plan was to run structural equation modelling (SEM) for all the models presented in this chapter. However, the models including mathematics anxiety had a very poor fit to the data. For this reason, I decided to run path analyses instead of SEM.

The path analysis was carried out using IBM SPSS AMOS 25 Graphics using the maximum likelihood estimation (Arbuckle, 2017). Figures were created with the path diagram tool and the significance values were added manually afterwards.

Running a model predicting the data will result in data predicted (and explained) by the model. Ideally, the discrepancy between the predicted data and the actual measured data should be as small as possible. So-called model fit indices indicate how well the data predicted by the model fit with the actual data (Raykov & Marcoulides, 2006). In order to assess the fit of the model, several different fit indices can be calculated. The first index that needs to be considered is the Chi-Square value (χ^2). This test statistic assesses the null hypothesis that the theoretical model fits perfectly to the covariance matrix created from the data. If the χ^2 calculated is significant, the theoretical model is not considered a good fit to the data. However, results from this statistic always have to be considered carefully, because sample size strongly influences the χ^2 value, there is a spurious tendency to obtain significant values due to the sample size (Raykov & Marcoulides, 2006). This means that having big sample sizes can cause this statistic to be significant, even when it does not indicate a bad fit. Another fit index that is used is the Goodness of Fit Index (GFI). This index is a measure of the proportion of variance and covariance in the observed data that the theoretical model can explain. This index can vary between 0 and 1, with values closer to 1 indicating a better fit. Most researchers agree that an acceptable range is between .95 to 1 (Raykov & Marcoulides, 2006). The third model fit index that should be considered is the Normed Fit Index (NFI). It compares the chi-square of the theoretical model against the chis-square of the independence model, which assumes no relationships between any of the variables. The formula involves the computation of the difference between the chi-square of the null model and the chi-square of the proposed model, and then dividing this difference by the chi-square of the null model. The theoretical base for this index is that by comparing the proposed model against the worst possible model, the researcher can get an idea of how much better the fit of the proposed model is. For this index, values above .95 are considered a good fit. Another useful fit index is the Comparative-Fit Index (CFI). This index compares the theoretical model against the null model under the assumption that there are no relationships between the observed measures. While the NFI is based on the comparison of chi-square values, the CFI is based on the comparison of noncentrality. CFI is a ratio of the improvement in noncentrality of the theoretical model against the null model. The better the data fit the theoretical model, the more similar the two noncentrality measures will be, hence the closer the CFI will be to 1. Most researchers consider it as an indication of a good model fit if the CFI is in the range between .95 to 1 (Raykov & Marcoulides, 2006). The final fit index that I will consider is the Root Mean Square Error of Approximation (RMSEA). This index is often used because it is only weakly influenced by the sample size (Raykov & Marcoulides, 2006). Most researchers consider adequate RMSEA value to be less than .07 (Hooper et al., 2008).

For the mediation analysis, I used R version 3.6.3 with the "mediation" package for bootstrapping. The mediation package uses the Imai and colleagues algorithms to estimate the causal mediation effects (Imai et al., 2010). I used non-parametric bootstrapping with 500 simulations. For moderation, I used the Baron and Kenny technique (Baron & Kenny, 1986). The reported value of ACME stands for Average Causal Mediation Effects, and a value different from 0 is indicative of the presence of an effect of the mediator variable (Imai et al., 2010).

5.3 Results

5.3.1 Descriptive statistics

Table 5.1 reports the descriptive statistics of the data collected at Time 1 and Time 2 (N = 139).

Table 5.1. Descriptive statistics for Time 1 and Time 2 data

	Time 1			Time 2					
Measure	Cronbach's α	M *(SD)*	Min-Max	Chronbach's α	M *(SD)*	Min-Max	t(138)	p-value	*d*
WRAT-4 Mathematical Subtest	.89[a]	25.89 *(5.53)*	8-39	.89[a]	25.45 *(6.16)*	8-37	1.65	0.102	0.14
R-MARS	.96[b]	46.02 *(18.83)*	24-99	.95[b]	54.16 *(22.75)*	24-117	- 4.58	<.001	0.39
MSB	.89[b]	33.05 *(7.04)*	14-45	.91[b]	30.44 *(7.81)*	10-45	4.23	<.001	0.36
Letter Span total score		6.90 *(1.53)*	0-11						
Visual mean k-value		7.03 *(6.99)*	(-13)-26						
Go/No-go False Alarms		8.60 *(5.49)*	0-34						

Legend:
MSB: Mathematics Self-Beliefs
a: alpha comes from Wilkinson and Robertson (2006)
b: alpha comes from the study's dataset

Instead of improving over the year, students' mathematical performance on average actually slightly decreased during the first year of secondary school, although the difference was not statistically significant. At the same time, students' mathematical self-belief decreased significantly, while their mathematics anxiety increased significantly. The correlation matrix for these factors can be found in Appendix D.1.

5.3.2 Mathematics anxiety and mathematical performance

In this chapter, I will concentrate on the performance on the WRAT-4 mathematical subtest as the mathematical outcome measure, because most of the literature that investigated the relationship between mathematics anxiety and mathematical performance used standardised tests of mathematical performance (e.g., Cargnelutti et al., 2017; Ma & Xu, 2004; Passolunghi et al., 2016). First, I tested the longitudinal relationship between mathematics anxiety and mathematical performance. The result of the path analysis with the standardized coefficients is presented in Figure 5.1.

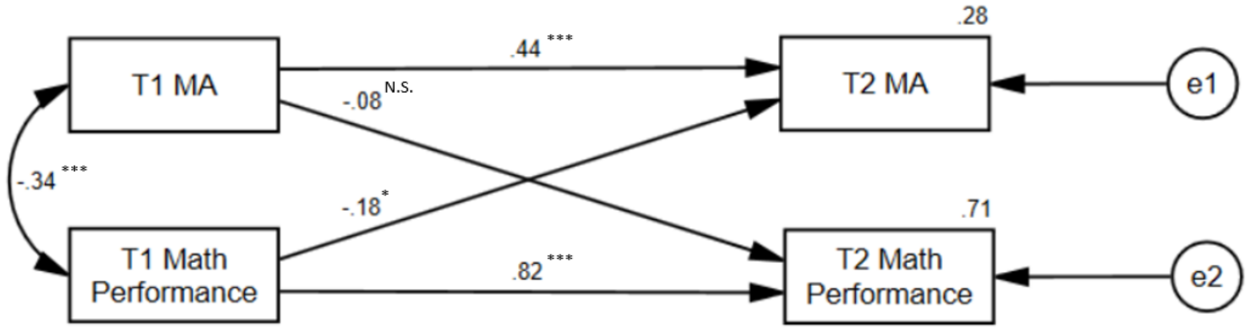

Figure 5.1. Path model on the longitudinal relationship between mathematics anxiety (MA, measured with R-*MARS) and mathematical performance (Math Performance, measured with the WRAT-4 mathematical subtest). T1 stands for Time 1, whereas T2 stands for Time 2. e1 and e2 are the residuals of the dependent variables. Legend: N.S.: Non-significant; *: $p < .05$; **: $p < .01$; ***: $p < .001$.*

The model in Figure 5.1 had a good model fit; $\chi^2(1) = 2.93$, $p = .087$, CFI = .99, GFI = .99, NFI = .99, RMSEA = .12. Although the RMSEA was slightly above the suggested range, all the other measures suggested a good fit of the data. The model indicated that mathematics anxiety and mathematical performance were significantly correlated at Time 1 ($\beta = -.34$, $p < .001$). Moreover, it showed that Time 1 mathematics anxiety significantly predicted Time 2 mathematics anxiety ($\beta = .44$, $p < .001$) and that Time 1 mathematical performance significantly predicted Time 2 mathematical performance ($\beta = .82$, $p < .001$). Finally, we can observe that mathematical performance at Time 1 significantly predicted mathematics anxiety at Time 2 ($\beta = -.18$, $p = .018$) and that mathematics anxiety at Time 1 did not significantly predict mathematical performance at Time 2 ($\beta = -.08$, $p = .111$). The model explained 71% of the variance of Time 2 mathematical performance and 28% of the variance of Time 2 mathematics anxiety.

5.3.3 Mathematics anxiety and working memory

In the next model, I investigated whether variability in working memory and inhibition at Time 1 influences the development of mathematics anxiety (see Figure 5.2).

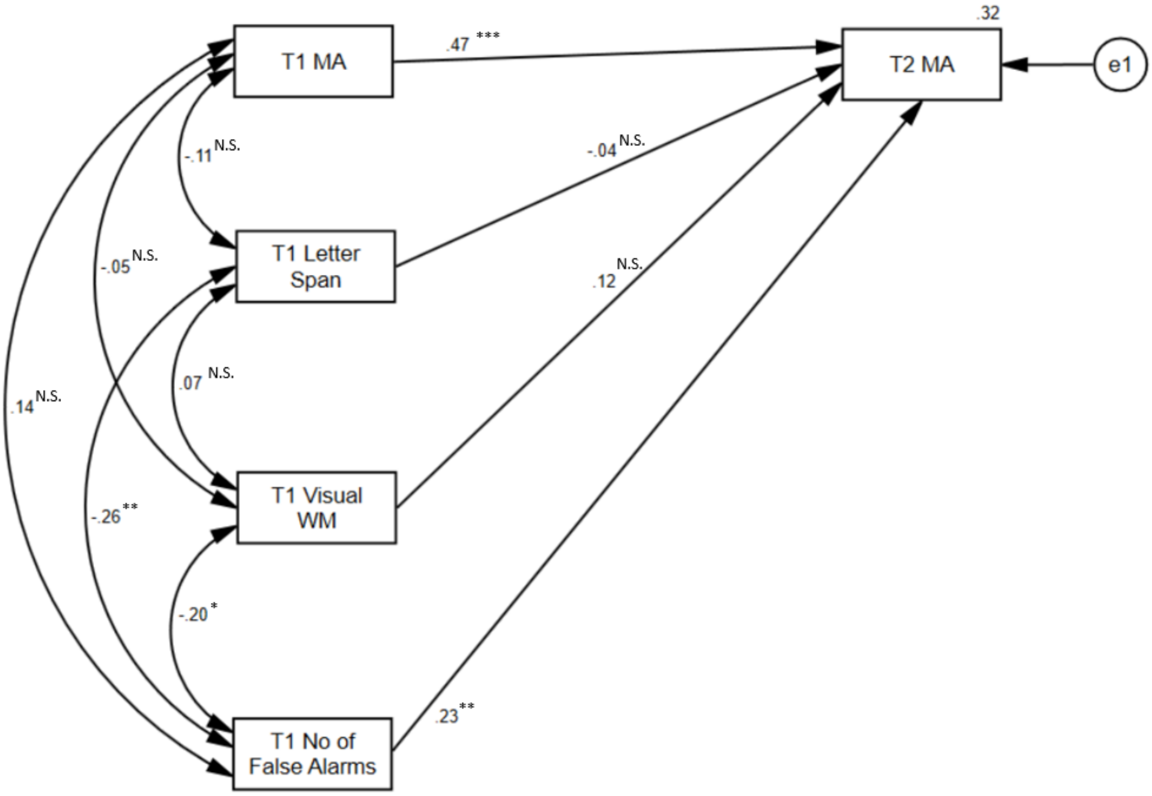

*Figure 5.2. Path model on the longitudinal relationship between mathematics anxiety (measured with R-MARS) and working memory measures. T1 stands for Time 1, whereas T2 stands for Time 2. e1 is the residual of the dependent variable. Legend: N.S.: Non-significant; *: p < .05; **: p < .01; ***: p < .001.*

The model was just identified with 0 degrees of freedom. For this reason, I decided to run a second model in which I did not include the non-significant paths (see Figure 5.3).

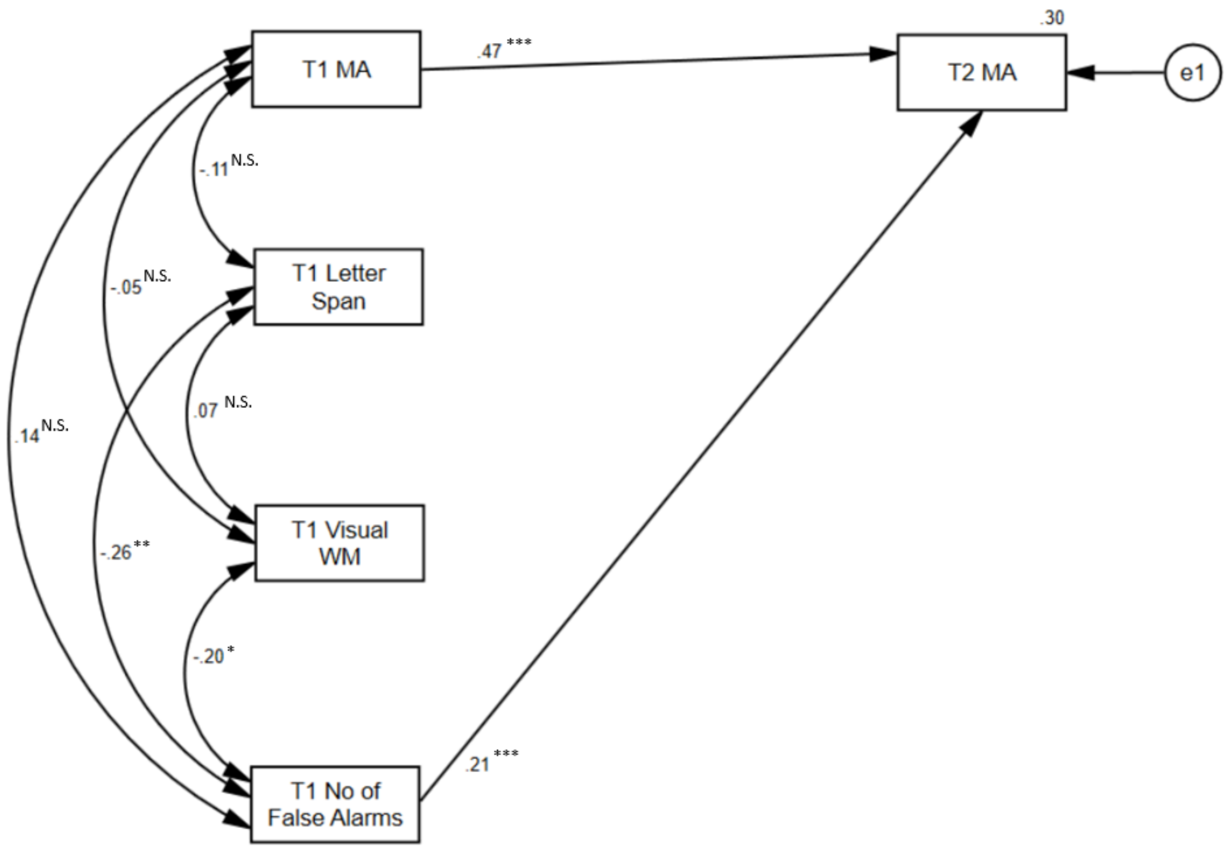

Figure 5.3. Second Path model on the longitudinal relationship between mathematics anxiety (measured with R-*MARS) and working memory measures. T1 stands for Time 1, whereas T2 stands for Time 2. e1 is the residual of the dependent variable. Legend: N.S.: Non-significant; *: p < .05; **: p < .01; ***: p < .001.*

The model presented in Figure 5.3 showed a good model fit; $\chi^2(2) = 2.95$, $p = .228$, CFI = .98, GFI = .99, NFI = .96, RMSEA = .06. The model suggested that mathematics anxiety at Time 1 was not significantly correlated with working memory measures. On the other hand, the model also showed that the number of false alarms in the Go/No-Go task at Time 1 significantly predicted mathematics anxiety at Time 2 ($\beta = .21$, $p = .003$). The model could explain 30% of the variance of Time 2 mathematics anxiety.

Given the significant paths from mathematical performance and number of false alarms to Time 2 mathematics anxiety, I decided to assess whether the mathematical performance was a mediator in the relationship between false alarms and mathematics anxiety. To this end, I ran a mediation analysis with mathematics anxiety as an outcome variable, number of false alarms as a predictor variable, and mathematical performance as mediator variable, as can be seen in Figure 5.4.

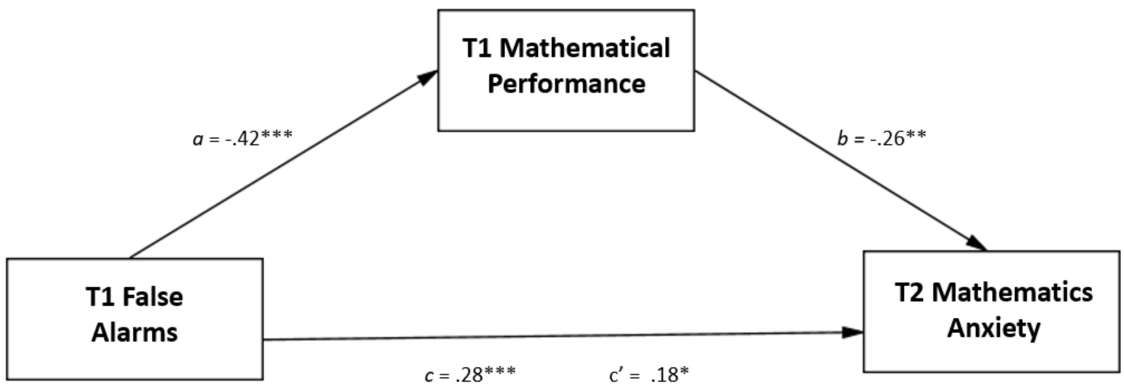

*Figure 5.4. Mediation model on the longitudinal relationship between the number of false alarms at Time 1 (False Alarms) and mathematics anxiety at Time 2 (Mathematics Anxiety), with mathematical performance at Time 1 as mediator variable (Mathematical Performance, measured with the WRAT-4 mathematical subtest). Legend: N.S.: Non-significant; *: $p < .05$; **: $p < .01$; ***: $p < .001$.*

In Step 1 of the mediation model, the regression of the number of false alarms on mathematics anxiety, ignoring the mediator, was significant, $\beta = .28$, $p < .001$. Step 2 showed that the regression of the number of false alarms on the mediator, mathematical performance, was also significant, $\beta = -.42$, $p < .001$. Step 3 of the mediation process showed that the mediator, mathematical performance, controlling for the number of false alarms, was a significant predictor of mathematics anxiety, $\beta = -.26$, $p = .004$. Step 4 of the mediation analysis revealed that controlling for the mediator, the number of false alarms was still a significant predictor of mathematics anxiety, $\beta = .18$, $p = .047$. A bootstrapping approach (Preacher & Hayes, 2004) revealed a partial mediation in the model, ACME = 0.45, 95% CI [0.16, 0.74], $p < .001$. The analysis suggested that mathematical performance partially mediated the relationship between the number of false alarms and mathematics anxiety.

5.3.4 Mathematics self-belief and mathematical performance

In the previous chapter, I investigated the role of mathematics self-belief and it was a stronger concurrent predictor of mathematical performance than mathematics anxiety (please see chapter 4.4.1, page 167). Thus, I decided to investigate the longitudinal relationships between mathematics self-belief and mathematical performance. This prompted me to run a path analysis in which instead of mathematics anxiety I assessed the longitudinal effects of mathematical self-belief in the development of mathematical performance. The path analysis with the standardized coefficients is presented in Figure 5.5.

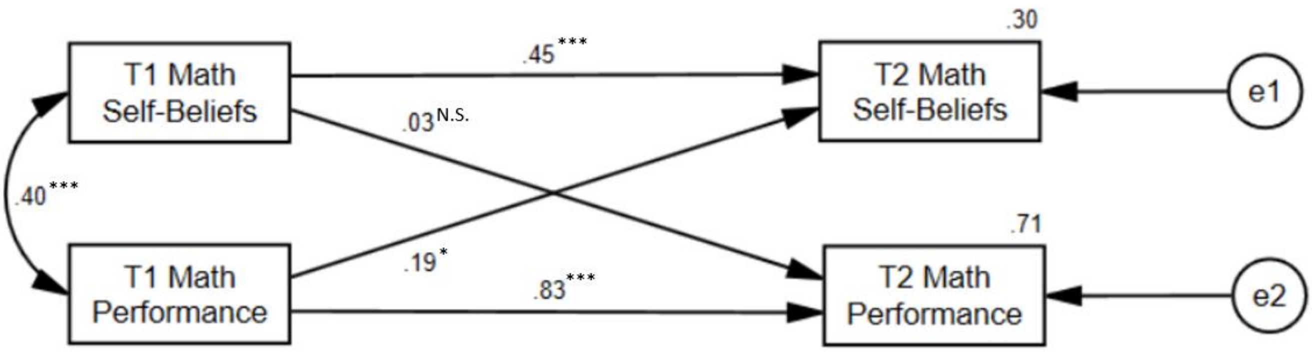

*Figure 5.5. Path model on the longitudinal relationship between mathematics self-belief (Math Self-Beliefs) and mathematical performance (Math Performance, measured with the WRAT-4 mathematical subtest). T1 stands for Time 1, whereas T2 stands for Time 2. e1 and e2 are the residuals of the dependent variable. Legend: N.S.: Non-significant; *: p < .05; **: p < .01; ***: p < .001.*

The model presented in Figure 5.5 did not have a very good fit; $\chi^2(1) = 7.34$, p = .007, CFI = .97, GFI = .98, NFI = .97, RMSEA = .21. The model fit indices CFI, GFI and NFI suggest a good fit. However, the RMSEA and the χ^2 suggested that there could be misspecification. Hence the parameters that are presented in this model need to be taken with careful consideration, as they might be biased. The model showed that mathematics self-belief and mathematical performance were significantly correlated at Time 1 ($\beta = .40$, $p < .001$). Moreover, it showed that Time 1 mathematics self-belief significantly predicted Time 2 mathematics self-belief ($\beta = .45$, $p < .001$) and that Time 1 mathematical performance significantly predicted Time 2 mathematical performance ($\beta = .83$, $p < .001$). Finally, we can see that mathematical performance at Time 1 significantly predicted mathematics self-belief at Time 2 ($\beta = .20$, $p = .011$), but that mathematics self-belief at Time 1 did not predict mathematical performance at Time 2 ($\beta = .03$, $p = .617$). The model explained 71% of the variance of Time 2 mathematical performance and 30% of the variance of Time 2 mathematics self-belief. This model suggests that mathematics self-belief was influenced by mathematical performance, but that the opposite was not true, and that the development in mathematical performance from Time 1 to Time 2 in the current data was not significantly influenced by variation in mathematics self-belief at Time 1.

5.3.5 Mathematics self-belief and working memory

To further investigate factors contributing to the decrease in mathematics self-belief from Time 1 to Time 2 I decided to investigate the longitudinal relationship between mathematics self-belief and working memory. The resulting model is reported in Figure 5.6.

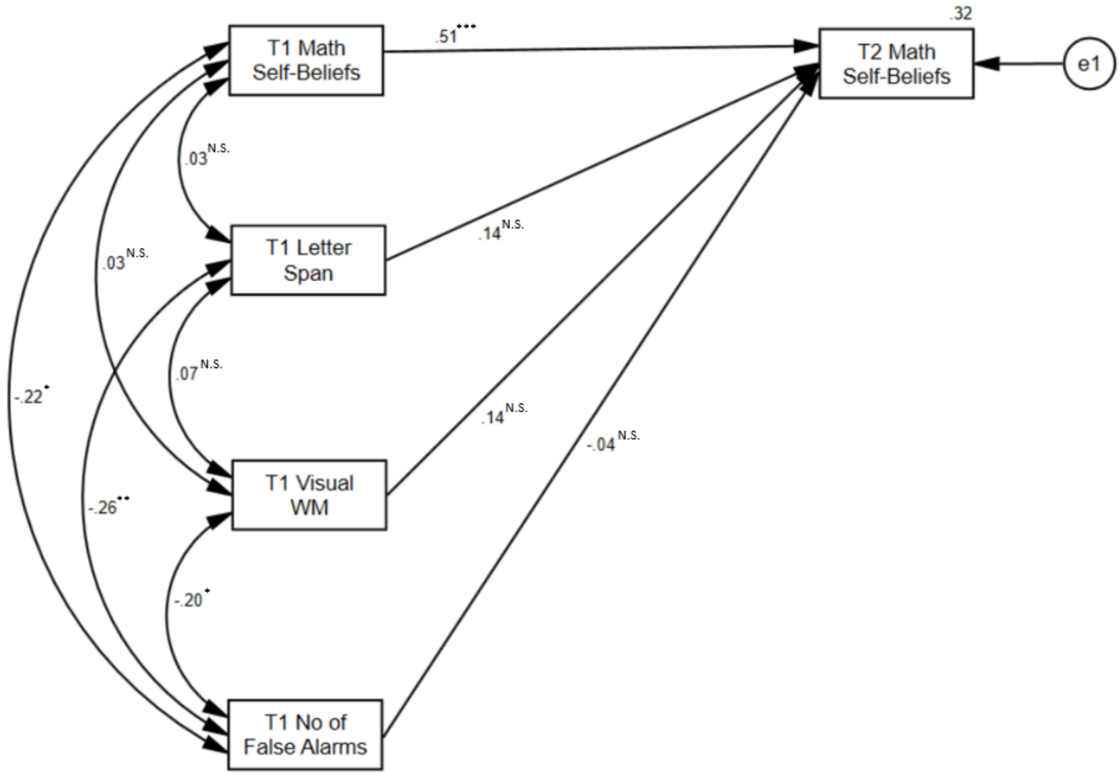

Figure 5.6. Path model on the longitudinal relationship between mathematics self-belief and working memory measures. T1 stands for Time 1 datapoint, whereas T2 stands for Time 2 datapoint.

The model was just identified with 0 degrees of freedom. Although Time 1 letter span and Time 1 visual working memory were non-significantly related to Time 2 mathematics self-belief, the p-value could be considered marginally significant (p = .059 and p = .058 respectively). Whereas, the path from Time 1 number of false alarms to Time 2 mathematics self-belief was non-significant (p = .581). For this reason, I decided to run a second model in which I did not include the number of false alarms' path. The resulting model can be seen in Figure 5.7.

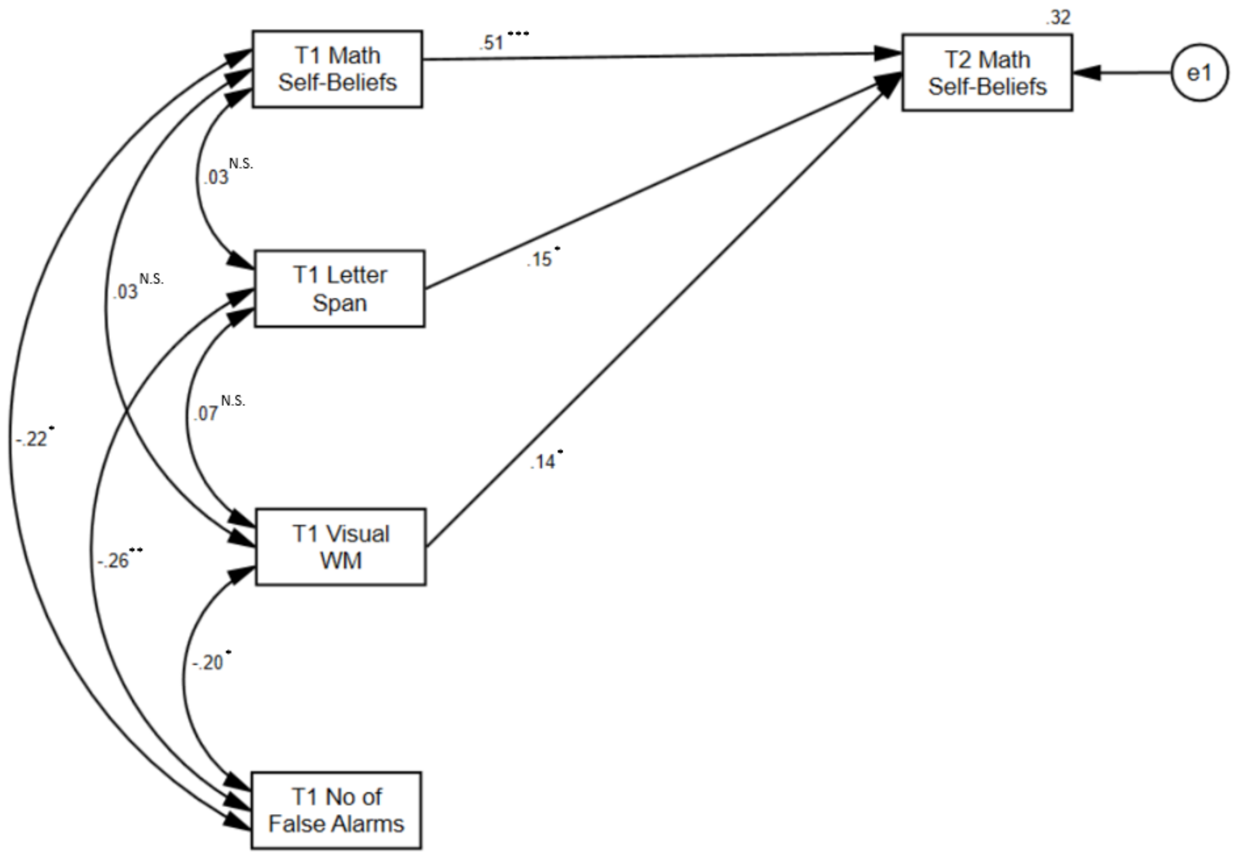

Figure 5.7. Second Path model on the longitudinal relationship between mathematics self-belief and working memory measures. T1 stands for Time 1 datapoint, whereas T2 stands for Time 2 datapoint.

The model presented in Figure 5.7 showed a good model fit; $\chi^2(1) = 0.30$, $p = .582$, CFI = 1.00, GFI = 1.00, NFI = 1.00, RMSEA = .00. Mathematics self-belief at Time 1 was significantly correlated with the number of false alarms ($\beta = -.22$, $p = .022$) but not with the working memory measures at Time 1. Both, the letter span at Time 1 ($\beta = .15$, $p = .037$) and the score on the visuo-spatial working memory task ($\beta = .14$, $p = .043$) significantly predicted mathematics self-belief at Time 2. The model explains 32% of the variance of Time 2 mathematics self-belief. These results suggested that the factors that influenced the increase of mathematics self-belief during the first year of secondary school were different from the factors that influenced the increase of mathematics anxiety.

5.3.6 Longitudinal effects of mathematics anxiety and mathematics self-belief on mathematical performance

So far in this chapter, I investigated mathematics anxiety and mathematics self-belief separately. In the previous chapter (please see chapter 4.4.1, page 167) investigating mathematics anxiety and mathematics self-belief as predictors of concurrent predictors of mathematical performance, only mathematics self-belief was a significant predictor when both mathematics anxiety and self-belief were included in the model. I now investigated those predictors in a longitudinal model including mathematics anxiety and mathematics self-belief at Time 1 and their effects on mathematical performance at Time 2. The resulting path model is shown in Figure 5.8.

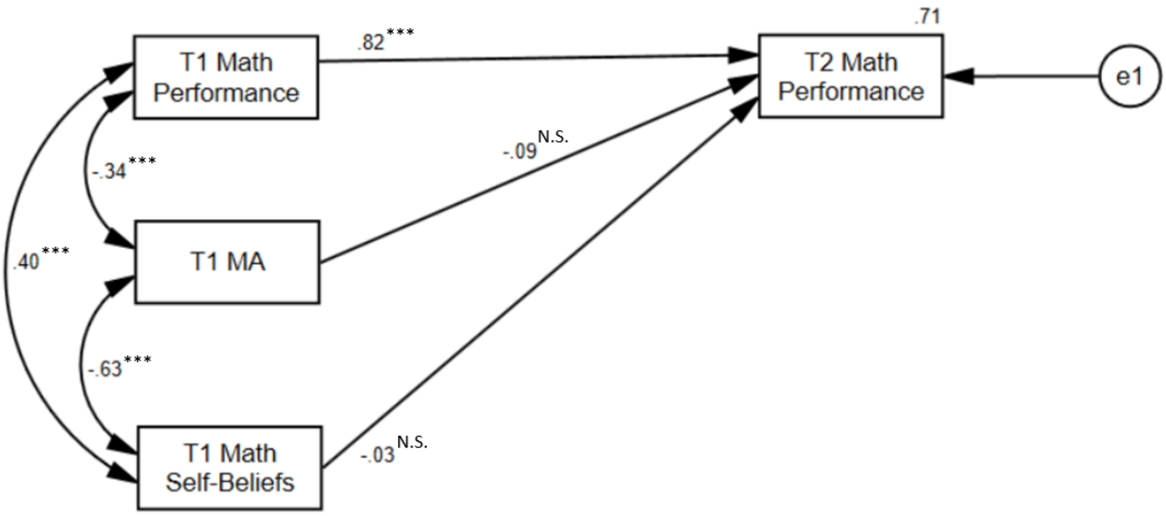

Figure 5.8. Path model on the longitudinal relationship between mathematics anxiety, mathematical performance, and mathematics self-belief. T1 stands for Time 1 datapoint, whereas T2 stands for Time 2 datapoint.

The model was just identified with 0 degrees of freedom. For this reason, I decided to run a second model in which I did not include the non-significant paths. This second model can be seen in Figure 5.9.

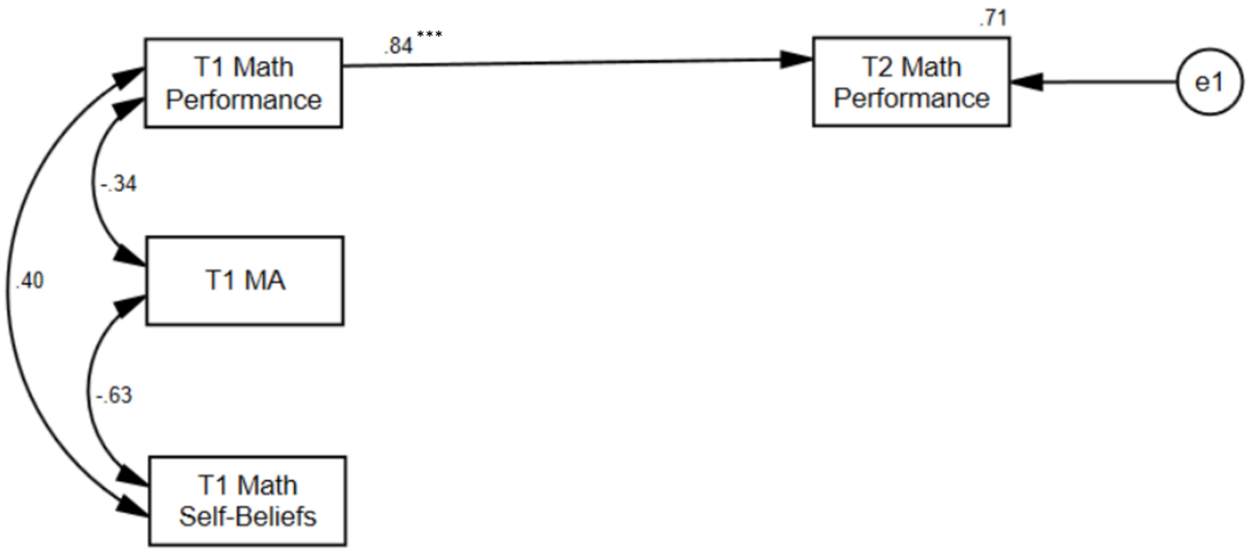

Figure 5.9. Second path model on the longitudinal relationship between mathematics anxiety, mathematical performance, and mathematics self-belief. T1 stands for Time 1 datapoint, whereas T2 stands for Time 2 datapoint.

The model presented in Figure 5.9 showed a good model fit; $\chi^2(1) = 2.76$, $p = .251$, CFI = 1.00, GFI =.99, NFI = .99, RMSEA = .05. Mathematics self-belief and mathematics anxiety at Time 1 were not significant predictors of changes in mathematical performance from Time 1 to Time 2. Unsurprisingly, mathematical performance at Time 1 significantly predicted mathematical performance at Time 2 ($\beta = .84$, $p < .001$). The model explained 71% of the variance of mathematical performance at Time 2.

5.3.7 Longitudinal effects of mathematics anxiety, mathematics self-belief, and mathematical performance on mathematics self-belief

In the final model, I explored the factors that might influence the development of mathematics self-belief. The resulting model is shown in Figure 5.10.

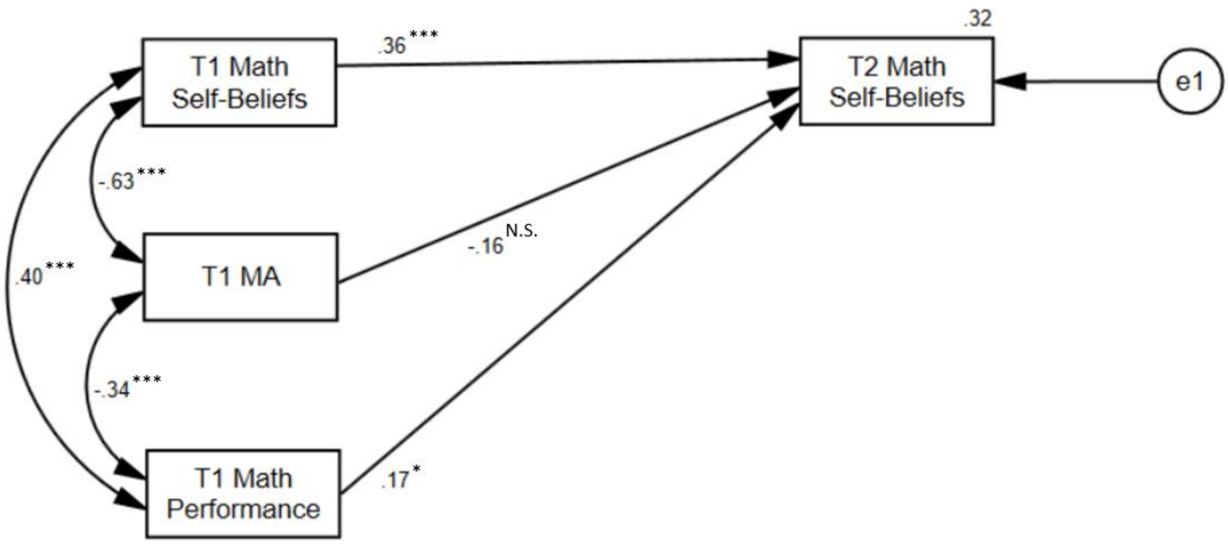

Figure 5.10. Path model on the longitudinal relationship between mathematics anxiety, mathematical performance, and mathematics self-belief. T1 stands for Time 1 datapoint, whereas T2 stands for Time 2 datapoint.

The model was just identified with 0 degrees of freedom. For this reason, I decided to run a second model in which I did not include the non-significant effects. This second model can be seen in Figure 5.11.

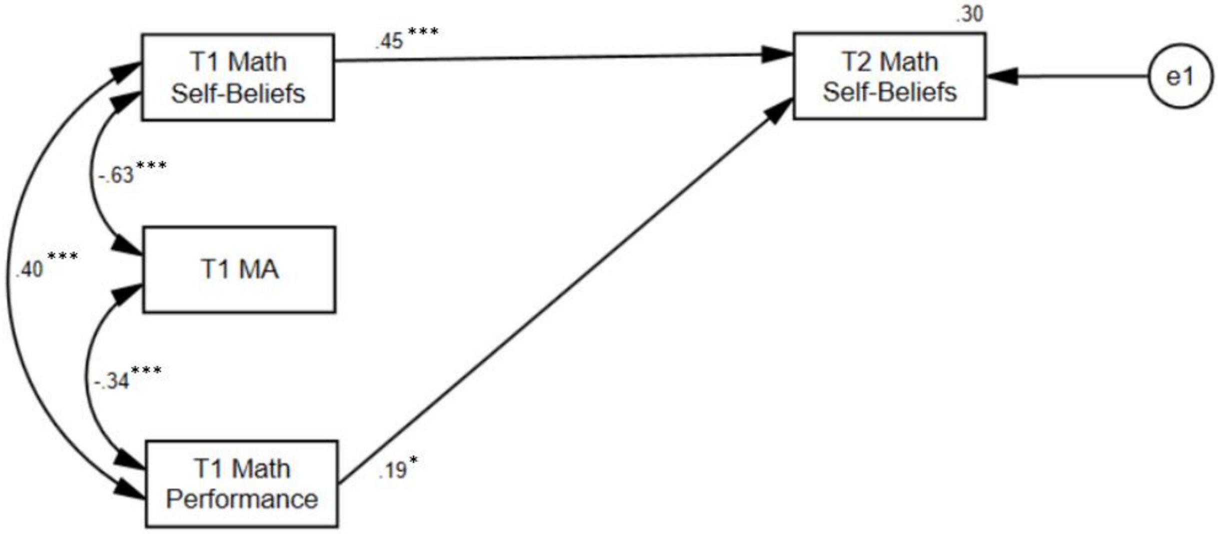

Figure 5.11. Second path model on the longitudinal relationship between mathematics anxiety, mathematical performance, and mathematics self-belief. T1 stands for Time 1 datapoint, whereas T2 stands for Time 2 datapoint.

The model presented in Figure 5.11 showed a good model fit; $\chi^2(1) = 2.93$, $p = .087$, CFI = .99, GFI = .99, NFI = .98, RMSEA = .12. Although the RMSEA was slightly above the suggested range, all the other measures suggested a good fit of the data. Figure 5.10 suggested that mathematics anxiety at Time 1 was not a significant predictor of the decrease in mathematics self-belief from Time 1 to Time 2. On the other hand, Figure 5.11 suggested that mathematics self-belief at Time 1 significantly predicted mathematics self-belief at Time 2 ($\beta = .45$, $p < .001$), and that mathematical performance at Time 1 also significantly predicted mathematics self-belief at Time 2 ($\beta = .19$, $p = .014$). The model explained 30% of the variance of mathematics self-belief at Time 2.

5.4 Discussion

The current chapter focused on the assessment of the development of mathematical performance and feelings towards mathematics during the first year of secondary school. The comparison between mathematical performance measured at Time 1 and at Time 2 suggests that performance on the WRAT-4 mathematical subtest did not change significantly during this period. At the same time, the students' mathematics anxiety increased significantly, and the students' mathematics self-belief decreased significantly. It seems that the first year of secondary school is a challenging time, that influences the students' feelings towards mathematics.

This chapter's main goal was to study the longitudinal relationship between mathematics anxiety and mathematical performance. Moreover, I also wanted to consider the role of working memory and mathematical self-belief in this relationship. The results suggest that during the first year of secondary school better mathematical performance plays a protective role against the development of mathematics anxiety and has a positive influence on the development of higher mathematics self-belief. At the same time, I observed that mathematics anxiety and mathematics self-belief measured at the beginning of the year had no significant influence on the development of mathematical performance over the first year of secondary school. I also observed that the efficiency of the inhibition processes measured at the beginning of the year was a significant factor in the development of mathematics anxiety over the school year, whereas visuo-spatial and verbal working memory at the beginning of secondary school were relevant factors in the development of mathematics self-belief. Finally, mathematics anxiety was not a significant factor in the development of mathematics self-belief.

5.4.1 Mathematical performance and mathematics anxiety

The first two research questions were about the relationship between mathematical performance and mathematics anxiety during Year 7. As expected, my results suggest that high mathematical performance at the beginning of Year 7 had a protective effect on the development of mathematics anxiety; i.e., the higher the mathematical proficiency of the student at the beginning of the first year of secondary school (Time 1), the lower their mathematics anxiety tended to be at the end of the same school year (Time 2). At the same time, current results showed that the increase of mathematics anxiety during the first year of secondary school did not have a significant effect on the development of mathematical performance over the same year. These results are in line with most of the available research. In fact, the literature suggests that mathematical performance has a role in the development of mathematics anxiety (Geary et al., 2019; Ma & Xu, 2004; Wang et al., 2020), which is in line with my findings that mathematical performance at Time 1 was a significant predictor of mathematics anxiety at Time 2. At the same time, the literature suggests that mathematics anxiety does not have a significant role in the development of mathematical performance (Ma & Xu, 2004; Vukovic et al., 2013), which is in line with current findings that mathematics anxiety at Time 1 was not a significant predictor of mathematical performance at Time 2. On the other hand, the current results are not in line with some studies that did find a reciprocal relationship between mathematics anxiety and mathematical performance (Cargnelutti et al., 2017; Ching, 2017; Gunderson et al., 2018). Ching (2017) found that mathematics anxiety in Year 2 (mean age 7 years old) was a significant predictor of mathematical performance in Year 3. However, as discussed in the introduction, Ching's study did not control for mathematical performance at the first time point. I suggested that the relationship between mathematics anxiety observed at Time 1 and mathematical performance observed at Time 2 in this study could be mainly driven by a relationship between mathematics anxiety and mathematical performance at Time 1. In fact, we can see in the current dataset that Time 1 mathematical performance is significantly correlated with mathematics anxiety at Time 1 ($r = -.34$, $p < .001$). At the same Time 1 mathematical performance is strongly related with mathematical performance at Time 2 (roughly 70% of the variance of Time 2 mathematical performance can be explained by Time 1 mathematical performance alone). It is possible that the effect observed by Ching (2017) of mathematics anxiety at Time 1 on mathematical performance at Time 2, is actually an indirect effect due to the shared variance between mathematics anxiety and mathematical performance at Time 1 and the high stability of mathematical performance from Time 1 to Time 2. This high stability has been observed often. For example, in Krinzinger and colleagues (2009) the average number of additions and subtractions that the students can complete does not change much between the different time points (e.g., number of correct large additions recorded at the middle of Year 2 = 11.85, number of correct large additions recorded at the middle of Year 3 = 13.23). Accordingly, running an analysis equivalent to the analysis presented in Ching's (2017) study with the current data showed a result in line with Ching's findings[11]. Moreover, Ching's results were based on a sample of students from primary school, which is a different age range than the current one. This difference in age can also be a reason why the results were different. It is possible that mathematics anxiety does affect the development of mathematical performance, but only in primary school, whereas this effect might no longer be present in secondary school. Current results are also not in line with the findings from Gunderson and colleagues (2018). The authors assessed mathematics anxiety and mathematical performance in Year 1 and Year 2 students (mean age = 7.2 years; age range = 5.4 ~ 9.11 years). The analysis suggested a negative longitudinal relationship between mathematical performance and mathematics anxiety, as in the current dataset. However, the authors also recorded a significant negative longitudinal relationship between mathematics anxiety and mathematical performance, which is not in line with current results. However, the size of the longitudinal relationship between mathematics anxiety and mathematical performance is in line with the current results. The authors found that

[11] A forced entry multiple linear regression with Time 1 mathematics anxiety, Time 1 verbal working memory, Time 1 visuo-spatial working memory, and Time 1 efficiency of inhibition as predictors of the Time 2 mathematical performance revealed Time 1 mathematics anxiety (β = -.29, $p < .001$) and Time 1 efficiency of inhibition (β = -.28, p < .001) as significant predictors of Time 2 mathematical performance, but neither Time 1 verbal nor Time 1 visuo-spatial working memory.

the relationship was weak (β = -.06), which is similar to the size of the relationship found in the current dataset (β = -.08). Gunderson and colleagues' (2018) study included more than 500 participants, giving it more power than the current study. It is possible that the current results show the same picture, just with less power. Either way, a weak correlation, even if significant, has likely little effect in the everyday life. Given the size of the relationships reported in Gunderson and colleagues' dataset, and in my dataset, it might be that even if a relationship were present, the effect would be negligible. Finally, Cargnelutti, Tomasetto and Passolunghi (2017) tested 80 students from Year 2 to Year 3 (mean age = 7 years and 7 months). The authors assessed mathematics anxiety using the Scale for Early Math Anxiety, and mathematical performance using the written computation test, the word problem test, and the module Number of the MAT-2. The authors interpreted their results as evidence for a reciprocal negative relationship between mathematics anxiety and mathematical performance, although indirect, as the path defined by the authors was from Year 2 mathematics anxiety to Year 3 mathematics anxiety, which then had a concurrent relationship with Year 3 mathematical performance (indirect β = -.23). However, given several limitations in this study (e.g., small sample size, low correlations between subtests factors and low stability of the measures) these findings need to be replicated with more solid measures.

However, there are some points to consider before reaching the conclusion that the development of mathematical performance during the first year of secondary school is independent from mathematics anxiety. First, in the current study mathematical performance did not change significantly between Time 1 and Time 2. This lack of intraindividual change could have limited the analysis because there wasn't much change to be explained.

Also, perhaps a generalised test such as the WRAT-4 mathematical subtest is not the best choice to assess secondary school students' mathematical proficiency. One reason why the scores on the WRAT-4 did not change significantly might be the type of material that the students were studying at the time of testing. Some calculations may be easier at a specific point in the academic year because the students have just learned about it or revised it in class. A good solution could be to use assessment tasks that are aligned to the curriculum content and delivery in the academic year. For example, the AC-MT 11-14 (Cornoldi & Cazzola, 2003) has a specific test for students at the beginning of Year 7, and a different test for students at the end of Year 7. However, using different tests at the two timepoints would mean I would no longer be able to test the growth anymore, so the analysis and the design would not fit the current predictions. In any case, these tests are based on the Italian secondary school curriculum, and for example include complex fractions, an important mathematical concept that is taught also in the UK during Key Stage 3 (Department for Education, 2014). Using a test more tightly designed around the British secondary school curriculum than the WRAT-4 could prove useful in gaining a better gauge on the development of the students' mathematical performance. For example, the KeyMaths3 UK (Connolly, 2014) is an assessment tool designed to assess UK students from 6 years of age to 16 years and 11 months of age. The assessment is designed around the UK school curriculum and presents normative data for each year.

Overall, current results suggest that mathematical performance has a protective effect against the development of mathematics anxiety, and at the same time that the development of mathematical performance over this period is independent of mathematics anxiety. This result may come as a surprise given the results discussed in the concurrent analyses in the previous chapter. In fact, most researchers suggest either a reciprocal relationship, or a negative effect of mathematics anxiety on mathematical performance, but rarely has a one-directional effect from mathematical performance to mathematics anxiety been proposed (for a review, see Carey et al., 2016). I will discuss this matter further in the general discussion (please see chapter 6.2, page 226); at the moment it can be argued that most longitudinal studies are in agreement with the current results, and it is possible that if there is a reciprocal relationship of mathematics anxiety on mathematical performance, this effect is either very small or not evident in longitudinal data.

It could be fruitful to investigate the effect of different levels of mathematics anxiety on mathematical performance with a concurrent design. In fact, there might be an online effect that cannot be captured with longitudinal data. Concurrent effects of mathematics anxiety on mathematical performance could be reflected in the concurrent relationship that is consistently found in the literature (Ashcraft & Kirk, 2001; Hill et al., 2016; Passolunghi et al., 2016; Wood et al., 2012), and was also found in the analysis presented in the previous chapter (please see chapter 4.4.2, page 171). For example, some researchers suggest that mathematics anxiety causes an interference in the retrieval of mnesic information (Carey et al., 2016); it is possible that this effect, being only present during mathematical tasks, does not have long-lasting effects, and can be assessed only by online changes in mathematics anxiety. Such an effect would be present only during mathematical tasks and wouldn't necessarily have longitudinal effects on mathematical performance in the long-term. If, for example, students are learning new material continuously, memory for old facts is not relevant, and the mnesic interference would not cause longitudinal effects. Another possibility is that the students can use mnesic strategies to help them to overcome the deficit. These strategies might require time, and would explain why some students take longer to perform mathematical tasks and are less efficient than the students with low mathematics anxiety (Maloney et al., 2011). To assess this theory, it could be interesting to assess semantic memory (and memory intrusions) during mathematical word problem solving and while reading a story. In both cases, it could be interesting to assess whether the participants with high and low mathematics anxiety show the same performance and can answer the same questions in the story. Accordingly, I would not expect longitudinal effects of this mechanism on mathematical performance, but only concurrent effects.

Another goal of this study was to find good models that can explain the development of mathematical performance and mathematics anxiety during the first year of secondary school adequately. These models need to be accurate and relevant so that they can be used to capture how mathematics anxiety develops during school years and can aid teachers in their attempts to reduce the impact of mathematics anxiety. My models showed that mathematics anxiety at the beginning of Year 7 and previous mathematical performance explained 71% of the variance of mathematical performance at the end of Year 7. This result suggests that this model is already a good predictor of mathematical performance in secondary school students. On the other hand, the same model only explained 28% of the variance in mathematics anxiety at Time 2. This suggests that although previous mathematics anxiety and previous mathematical performance are important factors in the development of mathematics anxiety during the first year of secondary school, there are other factors not included in the model that are important for the development of mathematics anxiety during this time period. Mammarella, Caviola, and Dowker (2019) summarised the views of academic experts in mathematics (Petronzi et al., 2017; in Mammarella et al., 2019) on what some of these possible additional factors could be. Some relevant factors they suggested that could be assessed in future studies include teaching methods that cause boredom and lack of motivation in class. These, in turn, might lead to behaviours that cause the students to lose track of teaching. The negative attitudes of parents towards mathematics that might be transmitted to their children could be another factor, as could be the extent of students' fear of failure. In mathematics, it is nearly always clear whether an answer is correct or wrong, and some students might experience more fear of wrong answers than others. Another possible risk factor that can be interesting to assess could be higher emotional reactions to mathematical errors (Suaŕez-Pellicioni et al., 2013), which also might be strongly related to the previously discussed fear of failure. In an ERP study, Suaŕez-Pellicioni and colleagues (2013) divided students into two groups, a high and a low mathematics anxiety group. The two groups were created so that they would be different in mathematics anxiety, but neither in trait nor state anxiety. The authors then analysed the error-related ERP negativity and the correct-related ERP negativity during a normal Stroop task and during a numerical Stroop task. The authors observed that the participants with high mathematics anxiety showed a bigger negative ERP response in relation to errors than to correct trials. This difference was not evident in participants with low mathematics anxiety. Moreover, this difference was not present in the normal Stroop task in both groups. The error-related negative ERP response is believed to be influenced by the participant's emotional reaction to the error; the bigger the emotional reaction, the bigger the ERP negativity (for a review, see Suaŕez-Pellicioni et al., 2013). Hence, the authors concluded that the participants with high mathematics anxiety showed a bigger emotional reaction to errors than the participants with low mathematics anxiety. It would be interesting to assess if being especially sensitive to mathematical errors can have longitudinal effects on the development of mathematics anxiety. If so, it could be useful to assess if it is possible to modify the emotional response to mathematical errors with the goal of reducing the development of mathematics anxiety.

5.4.2 Cognitive control, working memory, and mathematical anxiety

In the bid to understand more about the factors that might influence the development of mathematics anxiety, I decided to assess the longitudinal effects of working memory and cognitive control on mathematics anxiety. The models presented in Figures 5.2 and 5.3 in this chapter showed that, as predicted, verbal and visuo-spatial working memory were not significant factors in the development of mathematics anxiety during the investigated time period. On the other hand, as predicted, the efficiency of the inhibition processes was a significant predictor of the development of mathematics anxiety to Time 2. Indeed, having lower efficiency of the inhibition processes at Time 1 was associated with higher levels of mathematics anxiety at Time 2. Previous findings were mostly based on semantic inhibition (which falls into the category of "attentional inhibition" as described by Tiego et al., 2018); for example, the listening span task used by Passolunghi and colleagues (2016) and in the first two studies in this thesis (please see chapter 2.2.2, page 64) measures the number of words erroneously remembered in a list of words. These are words that were previously presented but that the attentional control system was supposed to inhibit because they were not relevant, or words that are related to the semantic meaning of the sentence but were not presented. Hence, they were stimuli presented in the environment that needed to be inhibited. In the current study, instead, I used the number of false alarms in the Go/No-Go task. Clearly, this task measures different aspects of inhibition than the listening span. Arguably, the Go/No-Go task can be considered as a motor inhibition task. The participant is asked to resist the impulse of a motor action, and not to inhibit semantic information. The inhibition presented in the Go/No-Go task is also defined as response inhibition (Cragg & Nation, 2008). In fact, the automatic response in a Go/No-Go task is to press the button (i.e., to Go), since the Go-trials are much more frequent. The participant needs to actively inhibit the automated response to avoid a false alarm. However, even though performing well in the Go/No-Go task and in the listening span might involve different types of inhibition, whether I used the number of intrusion from the listening span measure or the number of false alarms in the Go/No-Go task, all three studies are highlighting a significant relationship between mathematics anxiety and inhibition. Results in this chapter suggest that having lower efficiency of the inhibition processes at the beginning of secondary school could be a risk factor for an increase in mathematics anxiety over the school year.

Given that Passolunghi and colleagues (2016) tested students of a similar age and found a relationship between semantic inhibition and mathematics anxiety, and that my results are in line with these findings while using a different measure of inhibition, the relationship may be valid for both types of inhibition. This might mean that there is a common deficit in the central executive that causes the lower efficiency of both types of inhibition. Because of lower inhibition efficiency, I then would expect a lower working memory capacity. Cognitive control functions, like motor and semantic inhibition, affect the amount of resources that the passive storage has available (Tiego et al., 2018). Recently, Tiego and colleagues (2018) constructed a hierarchical model for inhibitory control. Through structural equation modelling, the authors tested various theoretical models to explain the relationships between working memory capacity, attentional inhibition, and response inhibition. The authors suggested that response inhibition and attentional inhibition are independent from each other, but that they are related through working memory capacity, i.e., working memory capacity is related to both inhibition systems and works as a mediator in the relationship between the two inhibition processes. Concerning the current results, it can be argued that both types of inhibition could influence the cognitive resources used by secondary school students for learning mathematics. The lower efficiency of the (semantic or motor) inhibition processes could cause lower cognitive resources for the working memory capacity. Lower resources then could lead to lower mathematical performance, which in turn could be a risk factor for developing mathematics anxiety, as the student would experience a higher number of failures and more difficulties in dealing with mathematical tasks. Future studies might want to assess the longitudinal relationships between mathematics anxiety and semantic inhibition to understand if it shows the same pattern or not as I observed in this longitudinal study with motor inhibition. I would expect a similar pattern given that Passolunghi and colleagues (2016) found a concurrent relationship between mathematics anxiety and sematic inhibition in secondary school students.

It is possible, however, that the relationship between inhibition processes and mathematics anxiety is mediated by mathematical performance. In fact, existing literature suggests that a higher efficiency of the inhibition processes is associated with better concurrent and longitudinal mathematical performance (Blair & Razza, 2007; Bull & Scerif, 2001). Bull and Scerif (2001) tested mathematical performance and the efficiency of attentional inhibition with a Stroop task in Year 3 students (mean age = 7 years and 4 months). The authors found that inhibition efficiency was a significant concurrent predictor of mathematical performance, even after controlling for reading ability and IQ. Blair and Razza (2007) tested children in preschool (mean age 5 years and 1 month), and then again in the kindergarten year (mean age = 6 years and 2 months). The authors assessed response inhibition in preschool children with a peg tapping task and mathematical performance in kindergarten. The peg tapping task requires the students to tap once if the experimenter taps twice, and to tap twice when the experimenter taps once. In both cases, the students need to inhibit the automatic response to mimic the experimenter. Inhibitory control in preschool was a significant longitudinal predictor of mathematical performance in kindergarten. These results suggest that the efficiency of the executive functions plays a role in the development of mathematical performance already in preschool years.

The current study also suggested a longitudinal relationship of mathematics anxiety with mathematical performance and inhibition efficiency. The relationship between inhibition efficiency and mathematics anxiety could include indirect effects from mathematical performance, i.e., mathematical performance could be mediating the relationship between inhibition efficiency and mathematics anxiety. Having lower efficiency of the inhibition processes might cause more difficulties in performing mathematical tasks. More difficulties might then make the student more nervous while solving mathematical tasks. With time this nervousness might develop into mathematics anxiety.

To test this hypothesis, I ran a mediation analysis with inhibition efficiency as predictor, mathematics anxiety as outcome, and mathematical performance as mediator. Indeed, the analysis showed that mathematical performance was a significant mediator in the relationship between inhibition efficiency and mathematics anxiety, suggesting that this could be one way in which inhibition influences mathematics anxiety. However, the effect of inhibition on mathematics anxiety was still significant after the mediator's effect was controlled for. This suggests that inhibition efficiency has also a direct effect on the development of mathematics anxiety that is independent of the performance in mathematical tasks.

Clearly, further research is needed to better understand how exactly this might work. One possible explanation is that having lower efficiency of the inhibition processes means that the person is less able to inhibit anxious thoughts about mathematical situations. The fact that the person cannot inhibit these thoughts efficiently causes the person to experience more of these thoughts when dealing with mathematical tasks.

However, in the first study presented in this thesis (please see chapter 2, page 56), I found that the adult participants with high mathematics anxiety had lower working memory capacity also in non-mathematical situations. This can either suggest that the deficit is also present in other situations, or that it is only present in mathematical situations at 11 years of age, and that it becomes more generalized with development. My prediction is that it is always more generalized, but that mathematics is most vulnerable to the effects of this deficit. For this reason, the student that suffers from this deficit develops mathematics anxiety and not, or to a lesser extent, general or test anxiety.

Independent of the possible influence of age on this relationship, more research on the underlying mechanisms is necessary. For example, I suggest that experiencing intrusive thoughts and not managing to inhibit irrelevant information, makes the person nervous and feeling less in control of the situation. Little by little, these nervous thoughts could lead to the development of even higher levels of mathematics anxiety. This mechanism would also be in line with the neuroimaging results observed by Young and colleagues (Young et al., 2012). The authors recorded fMRI data while the participants completed mathematical tasks. Subsequently, the authors compared brain activation patterns in participants with low mathematics anxiety with brain activation patterns in participants with high mathematics anxiety. In the participants with high mathematics anxiety, the authors observed a greater activation of the in the right amygdala, and lower activation in various cortical and subcortical areas, including the dorsolateral prefrontal cortex area. While the amygdala is a brain region involved in the physiology of anxiety (Rauch et al., 2003), the dorsolateral prefrontal cortex is an area involved with cognitive control (Chang, Crottaz-Herbett, & Menon, 2007; in Young et al., 2012). The authors suggested that the lower activation in the dorsolateral prefrontal cortex was caused by higher mathematics anxiety.

An alternative explanation, however, would be that the lower activation of the cognitive control areas, and hence the lower efficiency of the cognitive control, is not caused by mathematics anxiety. Instead, a generally lower cognitive control could lead to the development of mathematics anxiety as previously discussed. However, the authors did not report baseline activation patterns, thus it is unclear whether the lower activation of the dorsolateral prefrontal cortex in participants with higher mathematics anxiety was also present during non-mathematical tasks or not. Future studies could assess brain activation during mathematical and non-mathematical tasks and investigate if the participants with high mathematics anxiety show the same pattern during non-mathematical tasks as described during mathematical tasks. Given the results presented in this work, I would expect to find the reduced activation also during non-mathematical tasks, not only during the execution of mathematical tasks.

Future studies might want to influence students' cognitive control. For example, in a review, Barenberg and colleagues (2011) concluded that inhibition efficiency can be improved by performing physical activities. Hence, by training Year 7 students daily with physical activities it might be possible to improve their inhibition efficiency. If the manipulation worked, it would be interesting to assess its effect on mathematics anxiety longitudinally compared to a control group that perform daily non-physical activities. Given the results presented in the current study, the improvement of the inhibition efficiency could possibly reduce the development of mathematics anxiety.

5.4.3 Mathematics self-belief and mathematics anxiety

Results from concurrent analyses in the previous chapter suggested that mathematics self-belief is an important factor to consider for the development of mathematics anxiety and mathematical performance in secondary school. Existing literature (e.g., Ahmed et al., 2012) suggests a reciprocal relationship between mathematics anxiety and mathematics self-belief. In the longitudinal analyses presented in this chapter mathematical performance was a significant positive factor in the prediction of the development of mathematics self-belief during Year 7. Adding mathematics anxiety as a predictor did not alter this relationship. Moreover, mathematics anxiety was not a significant predictor of mathematics self-belief measured at Time 2. This result is in contrast with the results of Ahmed and colleagues (2012). The authors found that mathematics anxiety had longitudinal negative effects on mathematics self-belief. However, the researchers did not include mathematical performance in their design. As discussed earlier in this chapter, I could not assess the reciprocal relationships between mathematics anxiety and mathematics self-belief. Although I cannot assess Ahmed's and colleagues model with my data, in my study, the inclusion of mathematical performance suggested no direct longitudinal relationship of mathematics anxiety to mathematics self-belief. Current results then seem to suggest that mathematical performance influences both mathematics anxiety and mathematics self-belief. The reciprocal relationship observed by Ahmed and colleagues (2012) could be the result of the indirect effect of mathematical performance on both of these factors. From the current result, it appears that working on improving mathematical performance in secondary school students might help them develop higher feelings of confidence when dealing with mathematical tasks.

5.4.4 Mathematics self-belief and mathematical performance

In the previous chapter, mathematics self-belief emerged as an additional interesting factor potentially influencing mathematical performance. Thus, in this chapter, I decided to assess cross-lagged longitudinal relationships between mathematics self-belief and mathematical performance. Mathematical performance was a significant predictor of the development of mathematics self-beliefs. The higher a student's proficiency in mathematics was at Time 1, the higher their mathematics self-belief was at Time 2. On the other hand, mathematics self-belief was not a significant factor in the development of mathematical performance. These results suggest that mathematical performance plays a role in the development of mathematics self-belief, whereas the reciprocal relationship is not significant, at least not in the time-period I investigated. In the current dataset, there was very little change in mathematical performance from Time 1 to Time 2 and thus, it is possible that there just wasn't enough variation in the data to observe a significant effect. Another possibility is that how confident students are in dealing with mathematical tasks at the beginning of secondary school does not influence the change in mathematical performance over the school year at the beginning of secondary school. This is not in line with most of the current literature, which suggests an involvement of mathematics self-belief in the performance in mathematical tasks in secondary school students (Stankov & Lee, 2017) and adults. Abu-Hilal (2000) defines the idea that mathematics self-belief can have an involvement in the development of mathematical performance as "self-enhancement approach", meaning that affective variables, such as self-confidence, have a causal effect on achievement. According to this approach, mathematics self-belief would have a causal effect on mathematics achievement (e.g., higher mathematics self-belief would cause higher mathematical performance). There is a second approach called "skill development approach" (Abu-Hilal, 2000). According to this second approach, achievement is what causes the development of the affective variables. This approach would predict that mathematical performance causes the levels of mathematics self-belief (e.g., being better at mathematics would cause the person to develop higher mathematics self-belief). The author tested this second approach and measured mathematics self-concept and mathematics achievement in students in Year 6 through 9 with a concurrent design using structural equation models. The author interpreted the findings as evidence that mathematics achievement causes the development of mathematics self-concept, supporting the skill development approach. In accordance with Abu-Hilal (2000), the results presented in this chapter suggest that mathematical performance is involved in the development of mathematics self-belief. However, the current results need to be interpreted with caution. Although most model fit indices (CFI, GFI, and NFI) suggested a good fit, the χ^2 and the RMSEA values of the model presented in Figure 5.5 were suggesting a suboptimal fit of the model. Especially the RMSEA was particularly high, suggesting that the current model might not fit the data well enough. This suggests that we should be cautious in the interpretation of the parameters presented, as the variances and regression coefficients that are calculated might be biased as they can be either overestimated or underestimated. In fact, the RMSEA is a measure of how close the model's approximation is to the data (Hutchinson & Olmos, 1998), and an excessive amount of error might cause the bias of the parameters (the calculated variances and regression coefficients), which then will not represent the real values (Kaplan, 1988).

Interestingly, only 30% of the variance of Time 2 mathematics self-belief was explained by the model represented in Figure 5.5. This means that although previous mathematics self-belief and previous mathematical performance are important determiners of the current confidence, other important factors might determine the decrease in mathematics self-belief during secondary school that I am currently not capturing. What could be those other factors? Lent and colleagues (Lent et al., 1991, 1996) suggest that the development of mathematics self-efficacy is influenced by two further factors in addition to mathematics anxiety: a history of successes and social persuasion. Personal accomplishments can be defined as the history of successes and failures in a task. The history of successes was found to have a positive relationship with mathematics self-efficacy, i.e., the more accomplishments somebody had achieved in mathematics, the stronger their history of successes, the more likely it was that the person developed high levels of mathematics self-efficacy (Lent et al., 1991). Social persuasion can be defined as how others encourage or discourage engagement with specific activities. For example, social persuasion from peers and parents to do well (e.g., parents that push for having good grades) in mathematics also showed a significant positive relationship with mathematics self-efficacy.

Based on this evidence the authors suggested that if the environment promotes engagement, the person will tend to develop higher levels of mathematics self-efficacy (Lent et al., 1991). The current study assessed the effect of performance, which can be related to personal accomplishments (i.e., the higher the mathematical performance, the more likely is the student to have a history of personal accomplishments). However, the current study did not assess the involvement of social persuasion. Future studies could include measures of social persuasion and assess its longitudinal effects. An example of a task that could be used to measure elements of social persuasion is the questionnaire developed by Lent and colleagues (1991). The questionnaire includes 10 items that measure how the participants perceive social persuasion in mathematics (e.g., "My friends have discouraged me from taking math classes"; in Lent et al., 1991, pp. 425).

5.4.5 Mathematics self-belief and working memory

The fifth research question involved the longitudinal effects of working memory and inhibition efficiency on the development of mathematics self-belief during Year 7. If the relationship between working memory and mathematics self-belief develops with time, I would expect to find an effect of verbal and visual working memory on the development of mathematics self-belief in the current study. Indeed, this is what was found. First, the efficiency of the inhibition processes was not a significant factor in the development of mathematics self-belief between Time 1 and Time 2. At the same time, both visual and verbal working memory had a significant positive effect on the development of students' mathematics self-belief. However, it needs to be pointed out that the effect sizes of these effects are small (r = .15 for verbal and r = .14 for visuo-spatial working memory), therefore the actual importance of the effect of these factors should be considered with caution. Taken together, these results suggest that having better working memory (both visuo-spatial and verbal) might lead to a higher perception of competencies in dealing with mathematical tasks. It has been suggested that verbal and visuo-spatial working memory might be relevant factors for mathematical performance, i.e., higher working memory would normally allow for better performance (for a review, see Gilmore et al., 2018). Hence, it might be that the students that have greater verbal and visuo-spatial working memory feel more at ease when dealing with mathematical tasks as they have more processing power and develop a higher confidence in dealing with numbers. However, considering the mathematics anxiety results, it is unclear why passive working memory is associated with self-belief, whereas cognitive control is associated with anxiety. This will be discussed further in the general discussion (please see chapter 6.5, page 235), but the underlying mechanisms may be different.

On one side, better working memory allows the students to experience confidence when dealing with mathematical tasks because of having more resources to deal with the task nurtures confidence. In fact, current results and existing literature suggest an involvement of verbal and visual working memory in mathematical performance (Friso-van Den Bos et al., 2013; Hawes & Ansari, 2020). The results of the current study suggest a moderate relationship between mathematical performance and verbal working memory (please see Appendix D.1). The relationship with visuo-spatial working memory is less clear, but there appears to be a longitudinal relationship, and it is possible that the concurrent relationship does not reach significance because of a lack of power[12]. Moreover, the literature suggests that both systems are relevant in mathematical processing, and this relationship might change with age (De Smedt et al., 2009; Fürst & Hitch, 2000; Miller & Bichsel, 2004). A student with lower verbal and/or visuo-spatial working memory, when in front of a mathematical task, performs less well than a student with higher working memory (Friso-van Den Bos et al., 2013; Hawes & Ansari, 2020),

[12] Time 1 mathematical performance showed a small correlation with visuo-spatial working memory ($r = .16$). Power analysis suggests that for an effect size of $r = .16$ to be correctly identified with $\alpha = .05$ and $\beta = .80$ I would need a sample of 304 participants. My sample size was N = 138, i.e., the results might have been not-significant due to lack of power.

whether they are good at inhibiting irrelevant information or not. This student experiences more difficulties and struggles more with mathematical tasks which could, in turn, reduce mathematical self-belief (Kung, 2009). On the other hand, not being able to inhibit irrelevant information might lead to intrusive thoughts (Gorfein & MacLeod, 2007) during the performance of mathematical tasks. Irrelevant information and thoughts, in addition to overtaxing the cognitive system, can cause a negative experience. This negative experience might be recalled in future occasions and then cause more anxiety in anticipation of the mathematical task. The student would then be more likely to experience difficulties, and in fact, mathematics anxiety and mathematics self-belief share a great deal of variance, but the reason for the lower performance, and its emotional outcomes, would be different.

Another point raised by these results is whether this relationship is specific for mathematics self-belief, or it is a more general effect. To the best of my knowledge, the relationship between self-belief and working memory has not been investigated yet. However, with regards to reading ability, researchers suggest that good verbal working memory is predictive of good reading comprehension (Cain et al., 2004) and that higher reading self-efficacy is associated with better reading comprehension (Solheim, 2011). It would be possible that the same mechanism proposed beforehand would work also in reading comprehension; as having greater verbal working memory would allow the student to feel more at ease when reading a text, and for this reason, the student would then develop higher confidence in their ability to comprehend a written text. Nevertheless, the results presented in this chapter suggest the presence of a relationship between mathematics self-efficacy and verbal and visuo-spatial working memory.

However, the model only explained roughly one-third of the variance in mathematics self-belief at Time 2. Hence, these results once again suggest that we need further research to uncover additional factors (e.g., social persuasion) that might influence the development of mathematics self-belief.

5.4.6 Mathematical performance

The last research question involved the assessment and comparison of the longitudinal effects of mathematics anxiety and mathematics self-belief on mathematical performance. The previous chapter showed that when mathematics anxiety and mathematics self-belief were considered at the same time as predicting factors, only mathematics self-belief was a significant predictor of mathematical performance (please see chapter 4.4.1, page 167). Given these results, I decided to evaluate the individual contributions of the factors, expecting a pattern similar to the one obtained in the concurrent analysis. Contrary to my expectations, I found that neither Time 1 mathematics anxiety, nor Time 1 mathematics self-belief were significant predictors of change in mathematical performance from Time 1 to Time 2, whereas mathematical performance at Time 1 remained a strong and significant predictor of Time 2 mathematical performance. I have already discussed the results for mathematics anxiety above.

With regards to mathematics self-belief, the current results are not in line with the existing literature (e.g., Kung, 2009) which suggests a reciprocal relationship between mathematical performance and mathematics self-belief. However, Kung's original model showed poor goodness of fit. The reported indices of the goodness of fit are reached by adding correlations between the error terms. The practice of adding correlations between errors, although usually can improve model fit indices, is considered bad research practice because there are no theoretical reasons to do that (Hermida, 2015). The model presented in the paper may not be a close approximation of the real model, hence the parameters calculated might not be reliable. In contrast, the model fit indices in my model were all concordant with a good fit. More research is needed to gain further understanding of the topic, but the results of the analysis in this chapter suggest that the models presented in Figure 5.5, 5.9, and 5.11 are a better approximation than Kung's model.

Another point that needs to be considered is that mathematical performance showed no significant change during the considered time period. This little change makes it more unlikely for the analysis to find a significant effect. Another study, ran by Hannula and colleagues (2014) assessed longitudinally mathematics achievement and mathematics self-efficacy in Year 3, Year 6, and Year 9. The authors found that there was a reciprocal relationship between mathematics achievement and mathematics self-efficacy. Moreover, the authors suggested that the effect of mathematics achievement on mathematics self-efficacy was roughly twice the reciprocal effect of mathematics self-efficacy on mathematics achievement. Overall, one study is not enough to draw definitive conclusions, so there is a need for more research in this area. However, given that the effect from mathematics self-efficacy to mathematical performance is probably weaker than the reciprocal effect, it is possible that the small change of mathematical performance from Time 1 to Time 2 in the current sample did not allow for the detection of the effect. In conclusion, the current results suggest that mathematics self-belief has no significant effect on the development of mathematical performance in 7th graders, however, it is possible that the data lacked the power to detect the effect, had there been one, highlighting the importance to further address the involvement of mathematics self-belief in the development of mathematical performance. Although, given that in my analysis the longitudinal effect of mathematics self-belief on mathematical performance was very small (r = .03), i.e., we would need a very big sample size to detect a potentially significant effect[13] and that even if an effect was present, it would probably be negligible in everyday life.

[13] Power analysis suggests that for an effect size of r = .03 to be correctly identified with α = .05 and β = .80 I would need a sample of 8718 participants.

Based on my concurrent results in the previous chapter, it could have been proposed that mathematics anxiety and mathematics self-belief had a causal effect on mathematical performance. However, the results from the longitudinal analysis presented in this chapter do not support this hypothesis. Thus, the longitudinal relationship at the beginning of secondary school might just be one-directional, i.e., mathematical performance might have a causal effect on the development of both mathematics anxiety and mathematics self-belief. A way to test causality in future studies would be, for example, to manipulate mathematics self-belief and mathematics anxiety and to measure the online effect on mathematical performance. For example, it could be interesting to devise a study in which participants have to perform mathematical tasks in a normal situation, and then they have to perform it again but after going through a bout of expressive writing (Park et al., 2014) which has been shown to reduce mathematics anxiety. It could then be interesting to test whether the eventual reduction of mathematics anxiety improves mathematical performance or not. Another possibility would be to include participants in fake group testing, where all the other participants are collaborators that pretend to be either very good or very poor at mathematics. In this way, the self-efficacy of the participants should be affected (Lent et al., 1991, 1996). In fact, the self-belief would be expected to improve in the situation where the confederates pretend to be worse than the participant, and self-belief would be expected to decrease in the opposite situation. The study would involve the assessment of mathematical performance before and after this manipulation, and if there is an online effect, it would be expected that an increase of mathematics self-belief would result in an increase in mathematical performance.

5.4.7 Conclusion

Overall, mathematical performance at the beginning of secondary school is an important factor in the development of mathematics anxiety and mathematics self-belief over the school year. Neither mathematics anxiety nor mathematics self-belief seemed to be relevant factors in the development of mathematical performance during the first year of secondary school. Interestingly, the current study included mathematics anxiety and mathematics self-belief in the same model to assess individual contributions on the development of mathematical performance. While in concurrent analyses (Hill et al., 2016; Pajares & Kranzler, 1995) mathematics anxiety and mathematics self-belief were significantly related with mathematical performance, in my study they failed to predict the change in mathematical performance over the first year in secondary school. However, a limitation is that in the current study there was no significant change in mathematical performance over that time.

Taken together, these results suggest that it is important to work on improving mathematical performance in students that are struggling with mathematics in secondary school. If these students are not supported in improving performance, they will be more likely to develop higher levels of mathematics anxiety and lower levels of confidence to deal with mathematical tasks. This, in turn, might prevent them from pursuing math-related careers, having a profound effect on their lives. Moreover, existing literature suggests that motivation declines during the school years (Wigfield et al., 2006), even more so in mathematics and natural sciences. Self-belief can influence the development of motivation (Legault et al., 2006), which in turn can influence performance.

A new and interesting finding is that mathematical performance is a mediator in the longitudinal relationship between inhibition efficiency and mathematics anxiety. The current results suggest that having higher efficiency of the inhibition processes might lead to better mathematical performance, and this, in turn, works as a protective factor against the development of mathematics anxiety. The results are particularly important since they come from a longitudinal study, a type of design that is rarely used in assessing the relationship between mathematics anxiety and mathematical performance. And rarely research has included many different possible confounding factors to control for their involvement in this relationship. Investigating this further is a promising avenue for future research.

Chapter 6 - General Discussion

6.1 Overview

In this thesis, two behavioural experiments with adults and a longitudinal study in secondary school are reported. The main aim of the thesis was to gain a better understanding of the mechanisms that underlie the relationship between mathematics anxiety and mathematical performance and to assess the effect of two factors on this relationship that were neglected at the time this PhD work started, namely the inhibition efficiency of the central executive and mathematics self-belief.

I started with a behavioural within-subject experiment that required adult participants to perform working memory tasks twice, once in a neutral and once in a mathematical setting. The main findings from this study are that there were no differences in working memory spans between the two sessions. Although there were no differences between mathematical and neutral sessions when considering the relationship between mathematics anxiety and working memory, the listening span task (i.e., a complex working memory capacity span) had a unique significant relationship with mathematics anxiety. In the second study, I developed a bespoke measure for inhibition efficiency and tested inhibition efficiency in participants with high and low mathematics anxiety using an extreme group design. I found that the participants with high mathematics anxiety had significantly worse inhibition efficiency than the participants with low mathematics anxiety and that neither trait nor state anxiety were covariates of the relationship between mathematics anxiety and inhibition efficiency. Finally, I carried out a longitudinal study with secondary school students to assess the long-term effects of mathematical performance and inhibition efficiency on the development of mathematics anxiety and the long-term effects of mathematics anxiety and mathematics self-belief on the development of mathematical performance. I found that mathematical performance and inhibition efficiency had a significant negative longitudinal relationship with mathematics anxiety, whereas neither mathematics anxiety nor mathematics self-belief had a significant effect on the development of mathematical performance.

The comparison of data from adult and secondary school students presents several challenges, as developmental changes might influence the relationships between factors (e.g., De Smedt et al., 2009). This chapter will draw some conclusions based on the most relevant results presented in the previous chapters while considering the possible age differences.

6.2 Mathematics anxiety and mathematical performance

As introduced and discussed at length in this thesis, researchers agree that there is a significant negative relationship between mathematics anxiety and mathematical performance (e.g., Dowker et al., 2016; Hembree, 1990; Ma, 1999; Passolunghi et al., 2016; Zhang et al., 2019). In line with the findings from the literature, in each of the studies presented in this thesis, I found a significant negative relationship between mathematics anxiety and mathematical performance. What is still unclear is the direction of this relationship. Does mathematics anxiety cause a deficit in mathematical performance? Or does poor mathematical performance cause the development of mathematics anxiety? Or, finally, do both factors influence each other through a reciprocal relationship causing a negative loop which leads people to get worse in mathematical performance and higher in mathematics anxiety? The so-called 'chicken or egg question' is still under debate (Carey et al., 2016), and a consensus is yet to be reached.

While the results presented in this thesis are not definite enough to allow for a firm conclusion on the matter, they add relevant data to increase our understanding of the possible mechanisms that underlie this relationship. As discussed in the literature review (see chapter 1.3.3, page 43), most current research provides support for a reciprocal relationship between mathematics anxiety and mathematical performance. In line with this theory, I found that higher levels of mathematics anxiety were associated with lower concurrent mathematical performance in both adults and secondary school students. However, when I collected longitudinal data from secondary school students to gain information on the directionality of this relationship, the results showed that mathematics anxiety at the beginning of the school year was not a significant predictor of a decrease in mathematical performance over the school year, but rather that poor mathematical performance at the beginning of the school year was a significant predictor of the increase of mathematics anxiety over the school year. These findings are in line with previous studies that also found only a unidirectional causal effect of mathematical performance on mathematics anxiety (Geary et al., 2019; Ma & Xu, 2004; Wang et al., 2020). On the other hand, these findings are not in line with longitudinal studies in primary school students that found a longitudinal effect of mathematics anxiety on mathematical performance (Ching, 2017; Gunderson et al., 2018), and with concurrent studies that suggested a causal effect of mathematics anxiety on mathematical performance (Hembree, 1990; Park et al., 2014). As previously discussed (please see chapter 5.4.1, page 202), Ching (2017) did not control for mathematical performance at Time 1 thus effectively not investigating changes in mathematical performance over time. If I do not include the mathematical performance at Time 1 in the longitudinal study, and I assess the relationship between mathematics anxiety at Time 1 and mathematical performance at Time 2, like Ching, a significant longitudinal relationship between mathematics anxiety at Time 1 and mathematical performance at Time 2 is found. This suggests that although there is a concurrent relationship between mathematics anxiety and mathematical performance when we investigate the effect of mathematics anxiety on the development of mathematical performance and control for the concurrent relationship, the longitudinal effect is no longer significant or significant only with a small effect size (Gunderson et al., 2018). There might be two reasons for this; first, in the age group I tested there might be no longitudinal effects of mathematics anxiety on mathematical performance. This would not exclude that there might be longitudinal effects of mathematics anxiety on mathematical performance in other age groups. Second, in my dataset there was no significant change in mathematical performance from Time 1 to Time 2. Future studies might want to replicate current findings and either support them or find that in my dataset there was not enough variation in mathematical performance to detect an effect of mathematics anxiety on the development of mathematical performance. However, it still needs to be discussed further why my findings are not in line with the studies that observed that manipulating mathematics anxiety also affected mathematical performance. For example, expressive writing is an intervention that is designed to reduce worrisome thoughts. Park and colleagues (2014) observed that participants with high mathematics anxiety performed better in mathematical and word problem tasks after a bout of expressive writing. Moreover, Hembree (1990) observed that psychological treatments that reduced mathematics anxiety were also associated with gains in mathematical performance. In the case of systematic desensitization, for example, after the treatment, the participants with high mathematics anxiety showed a performance that was comparable with the participants with low mathematics anxiety (Hembree, 1990). These findings seem to suggest that mathematics anxiety can affect mathematical performance, although it is possible that this manipulation only works when mathematics anxiety is decreased, not when mathematics anxiety is increased. However, the effect should be an online effect, as the manipulation had concurrent effects on mathematical performance, and I did find significant concurrent relationships between mathematics anxiety and mathematical performance.

In summary, the results of the studies reported in this thesis suggest that there is a negative concurrent relationship between mathematics anxiety and mathematical performance, and that this effect is present in secondary school children and adults. Finally, my results from the secondary school students seem to suggest that the direction of this relationship might be in line with the suggestion of the skill development approach (Ahmed et al., 2012) indicating that mathematics anxiety is a consequence of achievement and not vice versa. This conclusion needs to be supported and findings to be replicated by further studies as the relationship might be different in primary school or other age groups.

6.3 Mathematics anxiety and working memory

Another key aim of this thesis was to investigate the relationship between mathematics anxiety and working memory. It had previously been suggested that mathematics anxiety may cause a deficit in working memory performance, which would, in turn, cause a deficit in mathematical performance (Carey et al., 2016; Passolunghi et al., 2016).

The relationship between mathematics anxiety and working memory was assessed in all the studies in the present thesis. First, I tested working memory of adults in mathematical and non-mathematical situations, to assess the effect of mathematics anxiety on their working memory. As mathematics anxiety is defined as the feeling of apprehension and fear that arises in people who have to deal with mathematics (Hembree, 1990), any effect of mathematics anxiety should be present (or at least stronger) in a mathematical situation and absent (or at least weaker) in a non-mathematical situation. Accordingly, my prediction was that participants would show a drop in performance in the mathematical session compared with the performance in the non-mathematical session and that this difference would be more marked in those with higher mathematics anxiety. However, while in my first study I found that the participants with low mathematics anxiety outperformed the participants with high mathematics anxiety in all working memory tasks, there was no difference between the working memory performance in a mathematical or in a non-mathematical situation. This result suggests that being in a mathematical situation does not affect working memory neither in participants with low mathematics anxiety nor those with high mathematics anxiety, and that mathematics anxiety might not have an online effect on working memory (at least in adults).

As a consequence, the observed relationship between mathematics anxiety and working memory needs an alternative explanation. A possible explanation could be that low working memory capacity might be a risk factor for developing mathematics anxiety. In line with this interpretation, in my first study, I found that working memory capacity (i.e., the performance on the listening span) was significantly negatively associated with mathematics anxiety. Moreover, once this effect was controlled for, verbal and visuo-spatial working memory were no longer significantly related to mathematics anxiety. Similarly, in my second behavioural study, I found that the number of intrusions was significantly higher for the participants with high mathematics anxiety, suggesting a negative relationship between mathematics anxiety and the efficiency of the inhibition processes. While these studies present concurrent relationships, the findings from the longitudinal study suggest that lower efficiency of the inhibition processes might indeed be a risk factor for developing mathematics anxiety. In the longitudinal study, I found a significant longitudinal effect of inhibition efficiency on mathematics anxiety, lower inhibition efficiency at Time 1 predicted higher mathematics anxiety at Time 2. In contrast, neither verbal nor visuo-spatial working memory had longitudinal effects on the increase of mathematics anxiety at the beginning of secondary school. This suggests that a deficit in the central executive might be a factor involved in the increase of mathematics anxiety in this age group.

As discussed in the introduction (please see chapter 1.4.4, page 51), the attentional control theory proposes that anxiety is associated with lower efficiency of the inhibition and shifting processes, i.e., individuals with high anxiety need more cognitive resources to perform at the same level as individuals with lower levels of anxiety. In line with this, I also observed that higher levels of (mathematics) anxiety were associated with lower inhibition efficiency. However, the results presented in this thesis suggest that low inhibition efficiency might be a risk factor for the development of mathematics anxiety, rather than the opposite. In line with the predictions of the attentional control theory, literature suggests that individuals with high mathematics anxiety require a larger amount of cognitive resources. However, consistent with my findings, there are studies showing that extra cognitive resources were needed also in a non-mathematical task by participants with high mathematics anxiety (Núñez-Peña et al., 2019). For example, Núñez-Peña and colleagues (2019) observed that participants with high mathematics anxiety were significantly slower on a mental rotation task compared to those with low mathematics anxiety. Moreover, the researchers recorded event-related potentials (ERP) and observed that the brain patterns of the participants with high mathematics anxiety suggested that they needed to recruit more cognitive resources to perform the mental rotation task. Given that the mental rotation task neither is a mathematical task, nor contains mathematical information, the fact that participants with high mathematics anxiety needed to recruit extra resources to perform the task support my findings that the working memory difficulties are not only present just in mathematical situations, but participants with high mathematics anxiety have a more general deficit extending to non-mathematical situations too.

In the literature review (please see chapter 1.4.4, page 51) I hypothesised that mathematics anxiety might cause a deficit in the inhibition processes. This deficit would deplete cognitive resources needed for the mathematical task, in turn causing the person with high mathematics anxiety to perform lower in mathematical tasks. Poorer mathematical performance would then cause a further increase in mathematics anxiety. However, based on my results, this might not be the case. The fact that being in a mathematical situation or not did not affect the listening span – along with the fact that inhibition efficiency proved to have longitudinal effects on the development of mathematics anxiety – suggests that rather than mathematics anxiety leading to an inhibition deficit, having an inhibition deficit might be a risk factor for developing mathematics anxiety.

6.4 Development of mathematics anxiety

If a deficit in inhibition efficiency is a cause for the development of mathematics anxiety, it might come as a surprise that such a deficit would not affect the development of general anxiety. After all, if the deficit is present in every aspect of life, individuals with lower inhibition efficiency should struggle with non-mathematical tasks as well. For example, better reading comprehension is associated with higher working memory capacity (Hannon, 2012). For this reason, someone with poor inhibition efficiency should struggle also with reading tasks and develop reading anxiety. However, reading comprehension anxiety seems to be less of an issue.

An explanation for this might reside in the very nature of mathematics in comparison to other academic pursuits, such as reading comprehension. In mathematics, unlike in many other academic areas, an error is usually very evident (Cornoldi, 1999), whereas, for example, an error in the comprehension of a written text is often less clear, can go undetected more often and is sometimes even open to interpretation. Moreover, a common belief is that being good at mathematics is a synonym of being smart (Cornoldi, 1999). This belief might contribute to feeling worse about a mistake in a mathematical task because this could be taken as evidence of limited cognitive skills. Besides, there is evidence that individuals who develop mathematics anxiety may have a heightened sensitivity for mathematical mistakes (Suaŕez-Pellicioni et al., 2013). This heightened sensitivity might affect the development of specific anxiety for mathematical material, as opposed to other kinds of material or anxieties. According to this interpretation, at least partly due to the very nature of mathematics, individuals with poor inhibition efficiency and heightened sensitivity for mathematical mistakes might be more at risk at developing anxiety specifically for mathematics. In line with this interpretation, Hunt and colleagues (2014) observed that the most common intrusive thoughts experienced by their participants were about the worry of making mistakes. Future studies should explore whether a heightened sensitivity for mathematical mistakes is a cause or a consequence of mathematics anxiety. They could, for example, use the cognitive reappraisal technique. Cognitive reappraisal involves the cognitive transformation of the situation to alter its emotional impact (Gross, 1998). Reappraising our sensations, e.g., during the viewing of a scary movie, can reduce the presence of negative feelings during the viewing. Reappraisal allows the reinterpretation of the emotions associated with an event, and it has been shown to be effective in regulating emotional responses before the creation of the emotion (Gross, 1998). In particular, researchers could attempt to reduce the salience of mathematical errors by supporting the reappraisal of their impact on individuals with higher sensitivity to mathematical errors, thus promoting more efficient emotional regulation and reduced sensitivity and then investigate whether this reduces the risk of developing mathematics anxiety.

As proposed earlier, inhibition deficits and the resulting poor mathematical performance may influence the development of mathematics anxiety. In line with this hypothesis, results from the mediation analysis in the longitudinal study (please see chapter 5.3.3, page 191) suggested that mathematical performance is a significant mediator of the longitudinal relationship between inhibition efficiency and mathematics anxiety. Although correlational data is not enough to draw strong conclusions, these results suggest that part of the development of mathematics anxiety may be explained by this mechanism. Literature suggests that working memory capacity predicts mathematical performance (e.g., De Smedt et al., 2009). If that is the case, it can be suggested that inhibition efficiency is a relevant factor in determining mathematical performance, and a deficit in inhibition is likely to contribute to poor mathematical performance. Poorer performance in a mathematical task should then be a risk factor for the development of mathematics anxiety. This would mean that working on improving the inhibition efficiency should also improve mathematical performance and the improvement in mathematical performance could also bring about a reduction in mathematics anxiety, or at least slow down its development.

However, inhibition efficiency was still a significant longitudinal predictor of mathematics anxiety after the mediated effect of the mathematical performance was ruled out. This suggests that there is also a direct effect of inhibition efficiency on mathematics anxiety, which might be the result of unwanted thoughts during mathematical tasks. These unwanted thoughts might have a detrimental effect during the execution of mathematical tasks (Carey et al., 2016), but they might also have longitudinal effects. Indeed, as previously discussed (see chapter 5.4.2, page 209), a deficit in the inhibition efficiency would likely cause the individual to experience unwanted thoughts during the execution of different tasks, including mathematical tasks. In line with this interpretation, Hunt and colleagues (2014) assessed mathematics anxiety and the presence of intrusive thoughts during the execution of mathematical tasks in university students. The authors found a significant positive relationship between the number of intrusive thoughts experienced during the execution of the mathematical task, and mathematics anxiety ($r = .59$). These worrisome thoughts may work as a stressing stimulus, causing the person to dread the idea of having those thoughts again, hence developing anxiety for situations in which those thoughts might arise (i.e., developing mathematics anxiety). Although, this mechanism would not work concurrently, but more likely it would have longitudinal effects in the development of mathematics anxiety. This mechanism would be similar to the development of some cases of aviophobia, where fear of flying is often the result of intense worry around the idea of experiencing a panic attack while flying (Clark & Rock, 2016). Thus, future studies are warranted on the relationship between the presence of worrisome thoughts during mathematical tasks and the development of mathematics anxiety. These studies could, for example, be longitudinal studies that assess the presence of worrisome thoughts during the performance of mathematical tasks and investigate if the number of worrisome thoughts has a longitudinal relationship with the development of mathematics anxiety. Moreover, techniques like expressive writing seem to help reduce worry in individuals (Wolitzky-Taylor & Telch, 2010). The use of the expressive writing technique might help reduce the number of worrisome thoughts and the effect of this reduction might be assessed in relation to the development of mathematics anxiety.

6.5 Mathematics self-belief

I planned to assess the reciprocal relationships between mathematics anxiety and mathematics self-belief longitudinally. However, this was not possible with my dataset as the model fit indices were not adequate. Nevertheless, concurrent relationships between mathematics anxiety and mathematics self-belief suggest that in line with the literature (Jain & Dowson, 2009; Lee, 2009; Pajares & Graham, 1999; Pajares & Miller, 1994) the two factors share significant negative relationships. Moreover, concurrent analysis suggested mathematics self-belief as a more relevant predictor of mathematical performance than mathematics anxiety. This result suggests that mathematics anxiety might not be related to mathematical performance once the shared variance with mathematics self-belief is ruled out. However, concurrent relationships cannot inform on directionality. In this sense, the longitudinal analysis can be more informative. When looking at the longitudinal relationships between mathematics anxiety, mathematics self-belief, and mathematical performance, I observed that both mathematics anxiety and mathematics self-belief did not show longitudinal effects on the development of mathematical performance, whereas mathematical performance was a significant predictor of the development of both factors. Moreover, mathematics anxiety did not have a significant longitudinal effect on the development of mathematics self-belief. It is possible that the shared variance between these two factors may be due to both of them being the result of similar mechanisms which work in opposite ways. For example, on one side mathematics anxiety seems to be influenced by cognitive control. Cognitive control has also an effect on working memory, both verbal and visuo-spatial (Baddeley et al., 2015). In fact, verbal and visuo-spatial working memory were significantly positively related to inhibition efficiency (please see Appendix D.1). Verbal and visuo-spatial working memory might then influence mathematics self-belief. In fact, the longitudinal path analysis reported in Figure 5.7 suggested that verbal and visuo-spatial working memory had significant positive longitudinal relationships with mathematics self-belief. Future studies might want to assess the longitudinal relationships between mathematics anxiety and mathematics self-belief from an early age, while also including the longitudinal effect of the different working memory systems to assess each individual contribution.

Nevertheless, the findings from the concurrent relationships suggest that mathematics self-belief is an important and distinct factor that should be considered when assessing mathematics anxiety.

6.6 Limitations and open questions

In the present thesis, I discussed several underlying mechanisms that are likely to play a pivotal role in the development of mathematics anxiety and found that low mathematical performance, low inhibition efficiency, and high sensitivity to mathematical errors might be risk factors for the development of mathematics anxiety. However, the results of all my studies only explained a small part of the variance in mathematics anxiety, roughly one third. Future studies should, therefore, investigate the role of other factors that might be relevant in the development of mathematics anxiety, such as teaching methods and negative attitudes of parents (e.g., Mammarella et al., 2019).

The main limitation of the results presented in this work is that they come from observational studies based on concurrent and longitudinal analyses designs. Because, except for the mathematical or non-mathematical session manipulation, no other active manipulation of independent variables or covariates was involved, the conclusions reached from this work need to be corroborated by experimental designs. For example, the finding that mathematics anxiety did affect mathematical performance neither longitudinally nor online could be further tested by actively manipulating mathematics anxiety. One possible future study, for example, could be to use expressive writing to lower mathematics anxiety and then to assess whether this affects concurrent mathematical performance. It would also be interesting to use expressive writing to manipulate mathematics anxiety in a longitudinal design to assess whether this affects the later development of mathematics anxiety and mathematical performance. For example, a randomized control trial could require the participants to be divided into two different groups: an experimental group, in which the participants are exposed to expressive writing, and a control group in which the participants are asked to write about their previous day. The experimental manipulation could be continued for various years, and the participants could be tested regularly from primary school until at least secondary school. After the intervention, the researcher could assess if mathematics anxiety decreased. In case mathematics anxiety decreased, researchers could then assess the effect that this decrease had on mathematical performance. Importantly, this effect could be assessed concurrently (i.e., the online effect) and also longitudinally. This type of study, by combining an empirical design with a longitudinal design, would allow a clearer and more precise answer to the directionality of the relationship between mathematics anxiety and mathematical performance over time.

Another important limitation involves the sample of my adult studies. Having such a specific sample composed only of academically successful participants does not allow to draw conclusions about the wider population and might have biased some of the results. Future investigations with more representative adult samples are therefore warranted.

An open question of this study is the importance of an individuals' history regarding mathematical performance. As discussed before, a history of poor mathematical performance might cause the development of mathematics anxiety, whereas a history of good mathematical performance might be the foundation for developing good levels of mathematics self-belief.

Future studies should, therefore, assess longitudinal relationships between these two factors from an early age (possibly from preschool) to at least secondary school, in order to observe the direction of the relationship between them. The earlier mathematics anxiety can be measured the better, however, to the best of my knowledge, there are no available tasks that can reliably assess mathematics anxiety in preschool children. Hence, researchers that would like to assess mathematics anxiety in such young children would need to first develop a reliable and valid measure. The reason why the longitudinal study should ideally start in preschool is in order to assess the reasons that cause the genesis of mathematics anxiety it would be best to start the study before mathematics anxiety has been developed. Assessing the relationship between mathematics anxiety and mathematical performance before the start of formal schooling would give us information on how these two constructs develop from the very beginning and show which other factors might be relevant in their development. Moreover, the relationships between mathematics anxiety and mathematical performance might not be stable during the different stages of development (e.g., Hembree, 1990). This would mean that a longitudinal study that carries on until secondary school would allow us to assess the presence and the development of the relationships between mathematics anxiety and mathematical performance and to observe if the size or the direction of the relationship changes during specific developmental stages (e.g., the start of primary school, change from primary to secondary school, etc.) or not.

6.7 Conclusion

The findings presented in this thesis suggest that having a lower efficiency of the inhibition processes may represent a risk factor for the development of mathematics anxiety. More specifically, poor inhibition efficiency may cause the presence of worrisome thoughts before and during the execution of mathematical tasks (although I did not assess the presence of worrisome thoughts in my studies, so this is speculation based on previous research; e.g., Hunt et al., 2014). The presence of these thoughts might, in turn, cause the fear of having them again in the future, hence causing the development of mathematics anxiety. Poor inhibition efficiency may also be associated with poorer mathematical performance, and a history of mathematical difficulties is likely to play a role in the development of mathematics anxiety. Future studies should consider the adoption of longitudinal and especially experimental designs in order to investigate these predictions and study the relationship between mathematical development, mathematics anxiety, and inhibition efficiency in younger children to be able to give more definite answers about the directionality and the development of these relationships.

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Appendix A - Supplementary material for Chapter 2

Appendix A.1: Letter Span task

Level 1

F	R
H	J

Level 2

Y	J	F
Z	M	H

Level 3

F	R	W	M
W	Z	Y	J

Level 4

W	Y	Q	R	M
Y	J	H	W	F

Level 5

Q	W	Y	R	J	M
R	M	Y	H	J	W

Level 6

R	Z	F	J	M	W	Y
M	Y	H	R	W	Z	Q

Level 7

Z	Y	H	F	Q	M	J	W
R	J	M	Q	Y	F	H	Z

Complete Set:

F H J M Q R W Y Z

Appendix A.2: Listening Span task

Instructions:

(Read Aloud): "Now you'll hear a series of phrases, and for every phrase you'll have to say whether it's TRUE or FALSE. At the end of the set of phrases, you'll have to remind me of the last word of each phrase in the same order as they were presented" (it's important to ask to respect the order; however, if they can't follow the order, ask them to repeat the ones that they remember instead of having them not saying anything).

Examples:

Ex. Level 2

1) Hens are four legged animals (F)
2) Fables are tales of imagination (T)

A: animals, imagination

Ex. Level 3

1) In the morning you can eat biscuits with milk and tea (T)
2) When it is sunny, people walk around with an umbrella (F)
3) Seals are animals that live both in water and on land (F)

A: tea, umbrella, land

Trial Begins

2A

1) Chocolate is eaten on spaghetti (F)

2) Dogs are domestic animals like cats (T)

A: spaghetti, cats

2B

1) Cows have four legs and a tail (T)

2) Seawater contains salt (T)

A: tail, salt

3A

1) In the mountains you often need to use scarfs and gloves (T)

2) Glasses are used to hear sounds better (F)

3) Christmas is a holiday (T)

A: gloves, better, holiday

3B

1) Butter and Jam can be spread on bread (T)

2) Bicycles are faster than cars and airplanes (F)

3) Fishing rods are used to catch butterflies (F)

A: bread, airplanes, butterflies

4A

1) A and B are the two first letters of the alphabet (T)
2) Houses are built with wool and cotton (F)
3) Hunters kill animals with a rifle (T)
4) Africa is a cold country that is situated close to the North Pole (F)

A: alphabet, cotton, rifle, Pole

4B

1) At the zoo you can admire famous paintings (F)
2) At dawn the sun is high in the sky (F)
3) In the evening we lie in our bed under the blankets (T)
4) Airplanes take off from the ground and fly through the clouds (T)

A: paintings, sky, blankets, clouds

5A

1) During spring flowers blossom in the fields (T)
2) Fishes breastfeed their babies for up to three months (F)
3) At the Pole it is very hot and it's where eagles fly (F)
4) The hen is a mammal that lives in the sea (F)
5) Cars are transportation devices (T)

A: fields, months, fly, sea, devices

5B

1) In summer you wear scarfs and sweaters (F)

2) Spring and summer are two seasons (T)

3) The cat is a mammal that hunts rats (T)

4) The record player is a device that is used to watch pictures (F)

5) The scissor is used to cut the paper (T)

A: sweaters, seasons, rats, pictures, paper

Only from middle school and after add level 6

6A

1) Egyptians built grandiose and solid monuments that are called pyramids (T)

2) The key is used to open doors, and is slipped into the lock (T)

3) Christopher Columbus was a great and famous navigator (T)

4) The river is a stream of water that often comes from the mountains (T)

5) The day is composed of twenty-four hours (T)

6) Of some fruits, like the banana, you eat only the skin (F)

A: pyramids, lock, navigator, mountains, hours, skin

6B

1) Times tables are a set of letters that you need to learn by heart (F)

2) In winter birds dig their den underground (F)

3) Felt tips are used to colour drawings (T)

4) Masts have leaves and branches (F)

5) In the radio we can see the most famous actors (F)

6) You go to the swimming pool to play soccer (F)

A: heart, underground, drawings, branches, actors, soccer

Appendix A.3: AMAS

AMAS Hopko et al. 2003

Please rate your feelings when you are in the different activities on a scale from **one** (if you have no bad feelings during that situation) to **five** (you have the worst feelings. E.g., the most fear, the most tension, the most anxiety, the most worry, or the most nervousness).

	No bad feelings	Somewh at bad	Fearful, tense or nervous	Very bad feelings	Worst feelings
	1	2	3	4	5
Having to use the tables in the back of a math book.					
Thinking about an upcoming math test 1 day before.					
Watching a teacher work an algebraic equation on the blackboard.					
Taking an examination in a math course.					
Being given a homework assignment of many difficult problems that is due the next class meeting.					
Listening to a lecture in math class.					
Listening to another student explain a math formula.					
Being given a "pop" quix in math class.					
Starting a new chapter in a math book.					

Appendix A.4: Simple Calculations

Calculations

In this task you will be asked to do some simple calculations.

There are three sections:

Section 1: Addition
Section 2: Subtraction
Section 3: Multiplication

Each section consists of fifty questions, including two examples. You will be given a certain amount of time per section (between 15 seconds and 2 minutes) to complete as many questions as possible, whilst remaining as accurate as possible. Don't worry if you don't complete all the questions before time is finished.

The questions will look like this:

Section 1: Addition A
Please ADD the number in column A and the number in column B. Answer as many questions as you can in FIFTEEN SECONDS, whilst remaining as accurate as possible.

	A		*B*		*Answer*
Example Q1.	*2*	+	*3*	=	*5*
Example Q2.	*3*	+	*3*	=	*6*
Q3	*2*	+	*4*	=	
Q4	*9*	+	*6*	=	

Please write your answers in the box provided, and write any workings out you might need on the answer sheet.

DO NOT TURN OVER
Please wait for the experimenter before turning the page. 1

Section 1: Addition A

In this task please **ADD** the number in column A and the number in column B. Answer as many questions as you can in **15 SECONDS**, whilst remaining as accurate as possible.

	A		B		Answer
Example Q1.	*2*	+	*3*	=	***5***
Example Q2.	*3*	+	*4*	=	***7***
Q3	2	+	9	=	
Q4	4	+	8	=	
Q5	2	+	4	=	
Q6	7	+	2	=	
Q7	6	+	8	=	
Q8	7	+	3	=	
Q9	2	+	6	=	
Q10	7	+	4	=	
Q11	8	+	2	=	
Q12	6	+	9	=	
Q13	7	+	6	=	
Q14	3	+	6	=	
Q15	4	+	9	=	
Q16	3	+	8	=	
Q17	9	+	7	=	
Q18	6	+	4	=	
Q19	7	+	8	=	
Q20	9	+	3	=	
Q21	8	+	9	=	
Q22	14	+	7	=	
Q23	22	+	6	=	
Q24	23	+	8	=	
Q25	12	+	7	=	

Please wait for the experimenter before turning the page.

Section 1: Addition B

In this task please ADD the number in column A and the number in column B. Answer as many questions as you can in **45 SECONDS**, whilst remaining as accurate as possible.

	A		B		Answer
Q26	2	+	24	=	
Q27	18	+	6	=	
Q28	9	+	13	=	
Q29	3	+	29	=	
Q30	24	+	3	=	
Q31	14	+	32	=	
Q32	33	+	62	=	
Q33	22	+	36	=	
Q34	44	+	53	=	
Q35	32	+	24	=	
Q36	22	+	49	=	
Q37	27	+	24	=	
Q38	18	+	19	=	
Q39	24	+	36	=	
Q40	29	+	16	=	
Q41	19	+	27	=	
Q42	14	+	17	=	
Q43	29	+	38	=	
Q44	52	+	94	=	
Q45	83	+	87	=	
Q46	34	+	77	=	
Q47	89	+	98	=	
Q48	58	+	99	=	
Q49	76	+	68	=	
Q50	136	+	184	=	

Please wait for the experimenter before turning the page.

Section 2: Subtraction A

In this task please **SUBTRACT** the number in column B from the number in column A. Answer as many questions as you can in **15 SECONDS**, whilst remaining as accurate as possible.

	A		B		Answer
Example Q1.	*3*	-	*2*	=	*1*
Example Q2.	*3*	-	*3*	=	*0*
Q3	4	-	3	=	
Q4	7	-	3	=	
Q5	7	-	4	=	
Q6	8	-	7	=	
Q7	6	-	4	=	
Q8	9	-	8	=	
Q9	8	-	3	=	
Q10	9	-	2	=	
Q11	6	-	2	=	
Q12	9	-	3	=	
Q13	9	-	7	=	
Q14	7	-	2	=	
Q15	8	-	4	=	
Q16	9	-	6	=	
Q17	7	-	6	=	
Q18	6	-	3	=	
Q19	8	-	6	=	
Q20	9	-	4	=	
Q21	16	-	2	=	
Q22	14	-	7	=	
Q23	22	-	6	=	
Q24	12	-	7	=	
Q25	23	-	8	=	

Please wait for the experimenter before turning the page.

Section 2: Subtraction B

In this task please **SUBTRACT** the number in column B **FROM** the number in column A. Answer as many questions as you can in **45 SECONDS**, whilst remaining as accurate as possible.

	A		B		Answer
Q26	28	-	16	=	
Q27	94	-	73	=	
Q28	49	-	23	=	
Q29	36	-	22	=	
Q30	79	-	22	=	
Q31	57	-	24	=	
Q32	69	-	18	=	
Q33	36	-	24	=	
Q34	29	-	16	=	
Q35	77	-	34	=	
Q36	64	-	16	=	
Q37	42	-	14	=	
Q38	32	-	16	=	
Q39	52	-	34	=	
Q40	62	-	33	=	
Q41	47	-	19	=	
Q42	53	-	19	=	
Q43	48	-	29	=	
Q44	94	-	52	=	
Q45	87	-	53	=	
Q46	67	-	24	=	
Q47	98	-	69	=	
Q48	99	-	58	=	
Q49	76	-	58	=	
Q50	184	-	136	=	

Please wait for the experimenter before turning the page.

Section 3: Multiplication A

In this task please **MULTIPLY** the number in column A with the number in column B. Answer as many questions as you can in **20 SECONDS**, whilst remaining as accurate as possible.

	A		B		Answer
Example Q1.	2	x	2	=	*4*
Example Q2.	2	x	3	=	*6*
Q3	3	x	3	=	
Q4	4	x	3	=	
Q5	2	x	4	=	
Q6	3	x	7	=	
Q7	4	x	4	=	
Q8	2	x	7	=	
Q9	9	x	2	=	
Q10	3	x	8	=	
Q11	2	x	6	=	
Q12	4	x	8	=	
Q13	3	x	6	=	
Q14	7	x	4	=	
Q15	4	x	6	=	
Q16	3	x	9	=	
Q17	6	x	6	=	
Q18	8	x	7	=	
Q19	4	x	9	=	
Q20	8	x	8	=	
Q21	6	x	9	=	
Q22	7	x	7	=	
Q23	9	x	9	=	
Q24	7	x	6	=	
Q25	8	x	9	=	

Please wait for the experimenter before turning the page.

Section 3: Multiplication B

In this task please **MULTIPLY** the number in column A with the number in column B. Answer as many questions as you can in **2 MINUTES**, whilst remaining as accurate as possible.

	A		B		Answer
Q26	6	x	8	=	
Q27	9	x	7	=	
Q28	11	x	4	=	
Q29	2	x	12	=	
Q30	13	x	3	=	
Q31	6	x	11	=	
Q32	12	x	8	=	
Q33	16	x	3	=	
Q34	7	x	12	=	
Q35	29	x	3	=	
Q36	14	x	8	=	
Q37	9	x	16	=	
Q38	9	x	13	=	
Q39	8	x	27	=	
Q40	26	x	4	=	
Q41	43	x	8	=	
Q42	7	x	58	=	
Q43	68	x	6	=	
Q44	4	x	81	=	
Q45	9	x	72	=	
Q46	16	x	17	=	
Q47	27	x	19	=	
Q48	13	x	34	=	
Q49	28	x	27	=	
Q50	22	x	44	=	

End of task.
Please tell the examiner when you are finished.

Appendix A.5: GAD-7

GAD-7 Spitzer et al. 2006

Over the last 2 weeks, how often have you been bothered by the following problems?

Part. No.

	Not at all	Several days	More than half the days	Nearly every day
Feeling nervous, anxious or on edge				
Not being able to stop or control worrying				
Worrying too much about different things				
Trouble relaxing				
Being so restless that it is hard to sit still				
Becoming easily annoyed or irritable				
Feeling afraid as if something awful might happen				

Appendix A.6: Working memory descriptive statistics

Table A.1. Descriptive statistics of working memory measures divided by group and session

		Low mathematics anxiety (N = 17)		High mathematics anxiety (N = 15)	
Condition	Measure	Min - Max	Mean (SD)	Min - Max	Mean (SD)
Non-mathematical	Verbal working memory	6 - 14	9.82 (2.16)	6 - 11	8.40 (1.40)
	Visuospatial working memory	8 - 14	11.35 (1.96)	7 - 14	10.00 (1.96)
	Working memory capacity	25 - 40	33.65 (4.02)	20 - 36	30.07 (5.19)
	Intrusions	0 - 4	1.35 (1.22)	0 - 6	1.67 (1.84)
Mathematical	Verbal working memory	6 - 12	9.41 (1.73)	6 - 11	8.47 (1.55)
	Visuospatial working memory	8 - 14	10.71 (1.80)	8 - 12	9.87 (1.25)
	Working memory capacity	26 - 40	33.29 (4.40)	18 - 39	28.60 (6.94)
	Intrusions	0 - 4	1.12 (1.17)	0 - 6	2.13 (2.17)

Appendix B - Supplementary material for Chapter 3

Appendix B.1: Correlation matrix

Table B.1. Correlation matrix of Study 2.

Measure	1	2	3	4	5	6	7	8	9	10
1. Mathematics anxiety	-	-0.22	.27*	.36**	-.18	-.04	-.09	.07	-.16	-.02
2. Mathematical performance		-	-.20	-.08	.20	.19	.18	.14	.73***	.31*
3. State anxiety			-	.64***	< .01	-.19	-.13	-.10	.15	-.19
4. Trait anxiety				-	.19	-.10	-.01	-.13	.02	.04
5. Verbal working memory					-	-.03	.37**	.04	.20	.38**
6. Visuospatial working memory						-	.25	.22	.30*	.28*
7. Working memory capacity Listening span							-	.45**	.19	.30*
8. Working memory capacity Reading span								-	.14	.36*
9. Arithmetical fluency									-	.28*
10. Reasoning ability										-

Legend:
*: p < .05;
**: p < .01;
***: p < .001.

Appendix C - Supplementary material for Chapter 4

Appendix C.1: Correlation matrix

Table C.1. Correlation matrix. All correlations reported are partial correlations after partialling out the effect of trait anxiety.

	1	2	3	4	5	6	7	8	9	10
1. Mathematical performance	-	.72***	.37***	-.25**	.21**	.14	.39***	.14	.39***	.34***
2. Arithmetical fluency		-	.26***	-.23**	.11	.12	.33***	.18*	.36***	.39***
3. Conceptual understanding			-	-.15a	.17*	.24**	.40***	.07	-.42***	.14
4. Mathematics anxiety				-	-.06	.02	-.14	-.02	-.12	-.54***
5. Verbal working memory					-	.02	.26**	-.05	.20*	-.01
6. Visuo-spatial working memory						-	.24**	-.17*	.19*	-.02
7. No of Correct Responses Go/No-go							-	-.22**	.67***	.23**
8. Go RTs								-	.30***	-.02
9. Inhibition efficiency									-	.19*
10. Mathematics self-belief										-

Legend:
* p = .05
** p = .01
*** p = .001
a. p = .059

Appendix D - Supplementary material for Chapter 5

Appendix D.1: Correlation matrix

Table D.1. Correlation matrix

Measure	1	2	3	4	5	6	7	8	9
1. T1 Mathematical performance	-	.84***	-.34***	-.33***	.40***	.37***	.27**	.16	.42***
2. T2 Mathematical performance		-	-.36***	-.38***	.36***	.42***	.26**	.19*	.38***
3. T1 Mathematics anxiety			-	.51***	-.63***	-.44***	-.11	-.05	-.14
4. T2 Mathematics anxiety				-	-.37***	-.63***	-.14	.05	-.28**
5. T1 MSB					-	.52***	.03	.04	.22*
6. T2 MSB						-	.17*	.17*	.21*
7. Verbal working memory							-	.07	.26**
8. Visuo-spatial working memory								-	.20*
9. Inhibition efficiency									-

Legend:
MSB: Mathematics Self-Beliefs
*: $p < .05$
**: $p < .01$
***: $p < .001$