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Declaration

This thesis has been composed by myself only and the work presented in this document is my own. No portion of the work in this thesis has been submitted for any other degree or qualification.

Signed:

Michael Batashvili

Abstract

This thesis set out to investigate the electrophysiological correlates of maths anxiety (MA). Research has shown that those with high MA (HMA) tend to have poorer accuracy and increased reaction time on maths based tasks and that high maths anxious individuals avoid situations where they might have to use maths. This can impact on their future by restricting their degree or job prospects. Previous research has identified the behavioural cognitive and psychological effects of MA and recently studies have begun to examine the associated underlying mechanisms in the brain. Chapter one outlines the background MA behavioural and measurement research before evaluating the neurophysiological methods used in cognitive neuroscience and the use of electroencephalography (EEG) in chapter two. Chapter three continues by outlining previous research concerning the neurophysiological processing of maths and number before evaluating relevant neurophysiological research concerning MA.

Four experimental studies are conducted, exploring the neurophysiological underpinnings of MA research using EEG. Each of these recruits 30 participants and measures of electro-cortical (Event Related Potentials (ERPs), Global Field Power, Frequency etc.) and questionnaire measures are implemented. The first study aimed to identify whether the behavioural effects of MA (poorer accuracy and increased reaction time) are consistent with ERP differences (component amplitude and latency differences) in the brain and to understand why these effects are experienced. This revealed no significant comparisons between ERP components and behavioural responses involving low and high maths anxious individuals, but this may have been due to the lack of an anxious response by using a verification task, rather than requiring calculation.

Study two introduces the measurement of gamma activity as a neurophysiological measure of anxiety and threat processing and brings three core areas of anxiety research together: Previous studies outline high anxiety in connection with gamma modulation, also showing gamma band activity is associated with the amygdala and finally, that the amygdala is responsible for the processing of threat perception and anxiety. This research has not been brought together when studying MA. Results produced similar ERP findings to the previous study but the introduction of gamma activity into the research provided the first differences between high and low MA (LMA) groups, showing significantly greater gamma activity levels in HMA individuals.

However, this study only used numerically-based tasks, thus the third study implemented a non-numerical condition to act as a control.

Study three replicates the findings showing a reduced level of gamma activity in high MA individuals for the non-numerical based task, however, this was also reduced for the simple maths task. It was theorised that it is more likely to be the initial threat perception that represents the anxious response and gamma activity increases.

To test this and remove any working memory demands, the fourth study implements the presentation of single digit observation (using single digit numbers and letters). Even though there was no demand on working memory, high maths anxious participants displayed similar levels of gamma activity as low maths anxious individuals during letter observation. However, they had significantly greater levels during the observation of number.

Findings suggest that HMA individuals may not only struggle with the processing of maths stimuli, but may have a threat-related response to the simple observation of numerical stimuli. This implies that HMA individuals consistently apply an avoidance technique due to a threat response associated with increased levels of gamma activity. The findings of the each study are finally discussed in terms of their contribution to the neurophysiological underpinnings of MA, the first exploration of this using gamma activity, future research and the extent that number anxiety may act as a precursor or *sine qua non* to MA.

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Chapter 1: Research introduction and overview of previous maths anxiety research

1.1 Research introduction

This thesis will explore the electrophysiological correlates of maths anxiety (MA). The first three chapters represent the introduction to the thesis as they collectively present the background to the research and why it is necessary. This includes a general background to the research area, methodology and specific background tailored to the neurophysiological research in MA.

In this chapter, an outline (and definitions) of what MA is will be presented. This will be followed by a detailed account of MA measurement, the behavioural, cognitive and psychological underpinnings and consequences of MA.

In chapter two, an explanation and evaluation of relevant neurophysiological measures, comparing their advantages and disadvantages will be conducted, followed by a detailed explanation of the current research methodology. The remainder of the chapter a detailed discussion of data acquisition and analysis principles applied in electrophysiological research, i.e. frequency analysis and Event Related Potentials (ERPs).

Chapter three evaluates research concerning the neurophysiological processing of maths and number in order to outline processing in non-high maths anxious populations. The chapter continues by outlining and evaluating current neurophysiological MA research noting the direction of the current body of work and ends with aims and hypotheses leading into the first study.

Chapters four, five, six and seven represent a series of empirical investigations studying the electrophysiological correlates of MA. The first study aimed to identify whether behavioural effects of MA (poorer accuracy and increased reaction time) relate to neurophysiological ERP effects (component amplitude fluctuations and latency shifts). This was conducted using a maths based verification task. The second study built on the previous and utilised the measurement of frequency analysis alongside ERP measurements using a calculation task. This was conducted to explore the contribution that gamma power had on the MA brain, finding differences between MA groups. This study found interesting results but had no non-numerical condition to identify if the effects in MA individuals were purely towards maths or all stimuli.

The third study confirmed the previous results by implementing a non-numerical control condition, indicating that MA individuals perceive maths as a threat. Finally, to evaluate the extent to which MA individuals perceive number as threatening, single digit number and letters were presented with no task demand.

Finally, Chapter eight is discussion and synthesis of the empirical findings in the previous body of work presented in this thesis. This chapter will discuss the relevance of the findings to the behavioural, cognitive and psychological processes of MA. This will be followed by an outline of the limitations of the research and will conclude with a detailed discussion of directions for future study.

1.2 What is maths anxiety?

1.2.1 Defining maths anxiety

MA is a form of trait anxiety that causes difficulty for some individuals when they perform maths or number related tasks. Indeed it is defined thus; "feelings of apprehension and tension concerning manipulation of numbers and completion of mathematical problems in various contexts" (Richardson & Suinn, 1972, p.551). General anxiety is defined as an aversive emotional state that occurs in threatening circumstances (Eysenck, 2013) that emerges when a goal is blocked by an event or object that the individual is unable to remove or alter (Derakshan & Eysenck, 2009). We can see that the shared anxious feelings experienced in anxiety disorders are experienced by those with high MA (HMA) when confronted with maths problems. However, there are discrete differences between general anxiety and MA. It has been shown that those with HMA show similar trait anxiety levels to those with low MA (LMA) (Young, Wu, & Menon, 2012), indicating that they are not generally anxious in everyday life. This means that their worry and tension is subject specific and only occurs when thinking about maths related subjects, rather than experiencing an ongoing anxiety towards various aspects of life (American Psychiatric Association, 2013).

Research into MA highlights a range of notable consequences of MA such as lower maths grades, maths and numerical knowledge and poorer performance on standardised maths tests than those who have LMA (Ashcraft & Krause, 2007). This can further result in the avoidance of jobs or degrees that may contain mathematical or numerical elements (Ashcraft, 2002; Beilock & Ramirez, 2011; Meece, Wigfield, & Eccles, 1990; Parsons & Bynner, 2005) or poorer performance in maths related-classes individuals do enrol on (Ashcraft & Kirk, 2001). However, these symptoms can also be triggered in everyday situations, for example, working out how much change you should be provided with after a purchase. This pattern of behaviour has been noted as similar to the developmental disorder dyscalculia, defined as congenital and persistent disability in achieving normal levels of arithmetical skills (Shalev, Manor, & Gross-Tsur, 2005). Furthermore, those with MA and/or dyscalculia have great difficulty in developing numerical ability and will often lag behind in math lessons (Butterworth, 2005). They also display similar symptoms including difficulties in mental calculation, number comparison and perceptual information (Kaufmann, 2002). Whilst dyscalculia can often be comorbid with MA (Rubinsten & Tannock, 2010), MA has been identified and measured solely as its own emotional reaction to the processing of maths.

It is noteworthy at this early stage that although the construct is referred to as MA, behavioural, cognitive and psychological research tasks use very simple arithmetic rather than mathematics. With MA studies consistently using these tasks alongside results displaying an anxious response, it might not necessarily be an anxiety towards maths rather; the anxious response is generated towards number. Indeed, the definition even states number above, leaving a mismatch in definition and research methodology.

1.3 Maths anxiety measurement

Researchers have devoted a considerable amount of time to developing scales for the measurement of MA. These have important uses, particularly in the identification of children who experience MA, and maths difficulties as a result of these anxieties at an early age. Indeed, a number of robust scales exist designed for children, such as the Maths Anxiety Rating Scale-Elementary (MARS-E; Suinn, Taylor, & Edwards, 1988) Math Anxiety Scale for Children (MASC; Chiu & Henry, 1990) and the Scale for Early Mathematics Anxiety (SEMA; Wu, Barth, Amin, Malcarne, & Menon, 2012). There are also those designed for adult populations, such as the Revised Maths Anxiety Rating Scale (RMARS; Plake & Parker, 1982), the Maths Anxiety Scale (MAS; Pajares & Urdan, 1996), Abbreviated Maths Anxiety Scale (AMAS; Hopko, Mahadevan, Bare, & Hunt, 2003) and Maths Anxiety Scale - UK (MAS-UK; Hunt, Clark-Carter, & Sheffield, 2011). For many years the most prominent scale used in MA research was the Maths Anxiety Rating Scale (MARS; Richardson & Suinn, 1972). This 98-item scale was developed in order to identify individuals with maths anxiety, provide normative data for comparisons of high and low maths anxious individuals, identify a structure for evaluating the levels of maths anxiety as a construct and finally, to assess the effectiveness of interventions to alleviate the consequences of MA. Richardson and Suinn's (1972) primary objective for constructing the MARS was to identify a population of individuals that acquired MA without a comorbidity with other forms of anxiety, such as test or trait anxiety. This showed Richardson and Suinn (1972) that it exists as a separate construct and should have an appropriate method of measurement. At the time there was only one scale that appeared to be measuring MA; the Number Anxiety Scale (Dreger and Aiken, 1957) adapted from the Taylor Manifest Anxiety Scale (Taylor, 1953) however, the scale had few numerically based items and a more comprehensive maths anxiety scale was needed, hence the development of the MARS.

The MARS uses brief descriptions of mathematically related situations used to produce levels of anxiety. It is comprised of a 5 point Likert scale (1 = Not at all, 2 = Slightly, 3 = A fair amount, 4 = Much, 5 = Very much) and defines a higher total score as a representation of HMA. Richardson and Suinn (1972) suggested that MA might have a hierarchical acquisition, i.e. individuals can be at different stages of maths anxiety, which would be assumed given the way scales are rated. However, through the use of cluster analysis, Batashvili (2012) identified 2 distinct clusters of individuals labelled either as high or low MA. The purpose of this was to identify clusters of individuals that possess similar characteristics (Aldenderfer & Blashfield, 1984; Everitt, Landau, & Leese, 2001). Out of 209 participants 63.6% were identified as low maths anxious and 26.4 were identified as high maths anxious. This displays that MA may not work on a gradual scale of acquisition but rather individuals are simply either high or low MA. If this was not the case, the cluster analysis would have likely identified multiple clusters. Through the use of cluster analysis, it is possible to accurately identify the differences between high and low maths anxious individuals, dependant on their scores for each item. This provides a unified way to differentiate between high and low maths anxious individuals, eliminating the need for arbitrary methods such as the quartile method and median split, which are frequently used across MA studies (e.g. Faust, 1996). Within their original psychometric tests, Richardson and Suinn (1972) recruited 397 students and showed a very high internal consistency (α = .97) and good test re-test reliability (.85) compared to other anxiety scales (Watson & Friend, 1969; Sarason, 1958).

The MARS has been used in many studies as a measure of MA in adults showing high MARS scores are associated with poor performance in maths based tasks. Similarly, MARS scores have been shown to decrease post intervention for those with MA (Richardson & Suinn, 1972; Suinn, Edie, & Spinelli, 1970; Suinn & Richardson, 1971) identifying its effective use as a diagnostic tool. However, due to the size of the 98-item scale its administration time is a potential disadvantage, (Alexander & Martray, 1989; Pajares & Urdan, 1996; Suinn & Winston, 2003) especially since shorter and more specific scales based on the MARS have been subsequently created. The MARS was seen as a particular hindrance when applying it in children or adolescent based populations, therefore more specific scales were applied.

An example of this is the Mathematics Anxiety Rating Scale – Elementary form (MARS-E: Suinn, Taylor, & Edwards, 1988). Suinn et al. (1988) asked elementary students (ages 9-12) to circle items that caused them to be nervous or anxious. Similar to the MARS, the MARS-E also uses a 5-point Likert system to identify how children feel towards certain mathematically based situations. Furthermore, with a growing body of evidence suggesting that MA acquisition may occur at a younger age (Ashcraft & Moore, 2009; Luo, Wang, & Luo, 2009), researchers still endeavour to create scales that are appropriate for even younger age groups. Wu et al. (2012) developed the SEMA to create a measure of MA for 7-9 year olds. They asked 162 children to complete the 20 item scale with the first 10 based on age appropriate mathematics and the anxiety related to solving these problems and the last 10 based on the anxiety associated with testing during the learning of these concepts. They also note that these situations were derived from items in the MARS and MARS-E. The results indicated this as a reliable measure of MA in 7-9 year olds.

There have also been more comprehensive and shorter scales that have been created for adults. Whilst compiling a shorter 30-item version of the MARS, Suinn and Winston (2003) noted that the formation of a new scale from the MARS needed two inclusion criteria. The first was that each item needed to be considered important in at least two previous studies replicating the MARS's (or similar scales) data. The second was that each item had to have had the highest factor loading in previous studies (Baloglu & Zelhart, 2007). These criteria would likely increase the construct validity as well as internal consistency for the new scale. With validity data showing a high internal consistency (.96) and a good test re-test reliability (.90) they concluded that the MARS 30-item scale was comparable to the original 98-item MARS with the advantage of shorter administration time.

The majority of MA scales tend to focus on the negative aspects of MA. This may seem sensible, but the unidimensional aspect of these scales limits the identification of positive consequences towards maths. The items in these scales remain similar to previous MA scales however, a few positive items are also included e.g. "enjoyment of mathematics" (Sandman, 1980). Bai *et al*. (2009) developed the revised maths anxiety scale (MAS-R), a 14-item scale with seven positive and seven negative items. They also used a 5-point Likert scale and reversed positive item scores so that the total score measured the level of MA. Psychometric testing identified the MAS-R as a valid tool for measuring MA. Multidimensional scales have an advantage in that by identifying the positive consequences of maths for high maths anxious individuals, treatment can focus on the purely negative consequences they have towards maths. For example, identifying a possible area of maths an individual deemed positive, using statements such as "it wouldn't bother me at all to take more math classes", enables an individual centred approach leaving more focus on the negative aspects (Bai et al., 2009).

The scales mentioned so far have been popular for use in western populations however; it is acknowledged that there is the need for individual MA scales for different populations. Whilst the MARS is English in language, it and most of its adaptations are designed using a North American population, which can affect the validity of using these scales in the UK. The MAS-UK (Hunt et al., 2011) was designed specifically for a UK population because no others existed. Hunt et al. (2011) note that although the majority of the statements in the MARS are transferable to a UK population, items based around sales tax or adding VAT to products provide language difficulties as it is uncommon to work out the VAT on everyday items in the UK (Hunt et al., 2011). To resolve this issue they created 10 original items based on discussions with British undergraduate participants. For example, an item based around a darts game was originally included (a recognisable British game). Similarly to Richardson and Suinn (1972), Hunt et al (2011) aimed to provide normative MA data for a UK population as all previous work had been based in North American and Canadian populations (Burns, 1998; Jackson & Leffingwell, 1999).

The use of MA scales to identify or measure levels of MA have enabled the identification of factors associated with the construct. The constant psychometric evaluations of the MARS and other scales have identified many factors within MA, the most crucial being, maths evaluation anxiety. This involves conducting a mathematical task whilst being watched or evaluated and as such is found to be the largest factor for many MA scales (Alexander & Martray, 1989;

Bessant, 1995; Hunt et al., 2011; Richardson & Suinn, 1972; Suinn & Winston, 2003). For example, a task such as writing an answer on the board in front of other individuals tends to induce a large amount of anxiety. Whilst this is noted as being similar to test anxiety (Dew & Galassi, 1983), maths anxious individuals exhibit anxiety in relation to what the test is made of (i.e. maths tasks), rather than the presence of a test situation (Beilock & Ramirez, 2011). Other factors commonly found within scales are social maths anxiety (Bessant, 1995; Hunt et al., 2011; Richardson & Suinn, 1972), based around everyday situations (e.g. calculating how much time you would need before going to work) or number anxiety (Dreger & Aiken, 1957; Kazelskis, 1998).

This section has identified many scales used for measuring MA but Hunt et al's. (2011) MAS-UK is the only one designed for a UK population and as such would be most appropriate for the following UK-based studies. In the context of the research presented here, this will be used to assess individual's levels of MA enabling a split into high and low maths anxious groups for comparisons in neurophysiological and behavioural effects. Before continuing to the neurophysiological measurements of MA, an understanding of the behavioural research and underpinnings needs to be outlined.

1.4 The Psychological and Behavioural Underpinnings and Consequences of Maths Anxiety

1.4.1 Underpinnings of Maths anxiety

Research has shown that MA arises during the manipulation of number or during the processing of maths based tasks (Ashcraft & Moore, 2009; Ashcraft, 2002; Richardson & Suinn, 1972) and has been theorised to begin at an early age (Baptist, Minnie, Buksner, Kaye, & Morgan, 2007; Krinzinger, Kaufmann, & Willmes, 2009; Petronzi, 2012). It's development can be due to poor early experiences with maths or a lack of parental/educational support or motivation (Geist, 2010). This can occur as teachers may have MA themselves and pass this on to students. An example is shown by Beilock, Gunderson, Ramirez, & Levine (2010) who tested female elementary maths teachers MA and female student's maths achievement at the beginning and end of a school year. They identified no relation between these after the first measurement but by the end of the school year the higher a teacher's MA score, the lower the maths achievement of female students. This identified one of the probable causes of MA development in children, which can impact on their arithmetic and calculation strategies later in life.

In primary education, those that have higher working memory tend to use retrieval strategies, rather than finger counting (Barrouillet & Lépine, 2005), but in turn can suffer from maths anxiety due to the reliance on working memory capacity (Ramirez, Gunderson, Levine, Beilock, 2013). As working memory is strained by anxious thoughts (Eysenck et al., 2007) it is likely that this will impair performance (Gerardo et al, 2013). This may suggest that to avoid using working memory resources, those who experience difficulties with maths may resort to using immature techniques such as finger counting, in order to establish mental number representations (Kaufmann, 2008).

Nevertheless, those with HMA tend to have poor maths competence in the first place therefore; maths tasks would cause an increase in stress and anxiety. Ashcraft and Kirk (2001) provide some support for this statement identifying that high maths anxious individuals do tend to be less motivated towards maths tasks than those with LMA however; there are multiple factors to consider.

It has been shown that just the anticipation of doing a form of maths can trigger negative effects in those with MA (Ashcraft & Kirk, 2001; Krinzinger et al., 2009) which leaves these individuals wanting to avoid maths-based situations. The classic technique of avoiding maths seen with those who have HMA (Hembree, 1990) will no doubt cause an on-going cycle of poor performance, resulting in more avoidance to counter stress or fear of failure. This is likely to cause poor performance rather than a low competence level and is adopted due to the perception of failure in maths based tasks. It is argued that high maths anxious individuals lack the necessary working memory resources needed by the phonological loop and central executive (Fürst & Hitch, 2000) to process the primary task i.e. maths. Working memory is known to have a limited capacity of attentional resources which are a necessary component within maths processing, including arithmetical fact retrieval and operation application (Eysenck et al., 2007). This has been shown to be related to attentional control theory (Eysenck, 2013), whereby high anxious individuals have intrusive anxious thoughts (Ford, Staples, Sheffield, & Vanono, 2005; Hunt, Clark-Carter, & Sheffield, 2014) or attentional bias towards a threat (Bar-Haim, Lamy, Pergamin, Bakermans-Kranenburg, & van IJzendoorn, 2007a), reducing necessary working memory resources.

Ashcraft and Kirk (2001) investigated the link specifically between MA and working memory and whether MA causes disruption in working memory. They recruited 66 undergraduate participants and distinguished high maths anxious individuals using the short Maths Anxiety Rating Scale (sMARS; Alexander & Martray, 1989). Participants were then asked to store an increased amount of words or digits to measure their working memory capacity, whilst processing simple verbal or arithmetic tasks. They identified that working memory capacity was negatively associated with MA. A series of follow-up studies identified that even a counting-like process is enough to trigger a maths anxious reaction rather than general arithmetic or calculation. They go on to support the above theory in that the result of a deficit in working memory is likely due to the inability to prevent working memory resources being allocated to intrusive thoughts. This also shows support that MA can be brought on by simple counting processes, as well as maths.

Furthermore, research has shown that a large inhibitor of performance for high maths anxious individuals is the amount of intrusive thoughts they are overwhelmed with. High maths anxious individuals report a substantial increase in the amount of intrusive thoughts experienced when processing maths (Hunt et al., 2014). These thoughts consume attentional resources needed for maths processing resulting in delayed and impaired performance. Eysenck et al. (2007) note that an increase in motivation is needed to combat these thoughts from overwhelming individuals. However, this then requires increased effort and can further impair performance if this is not achieved.

1.4.2 Performance and Behavioural Consequences of Maths Anxiety

Performance effects in maths anxious individuals have been studied extensively; including research into a range of maths tasks, removing anxiety inducing factors (such as evaluation and high task demand) and intervention based practices. This section will briefly outline key areas of this research.

Research has shown that those with HMA tend to do worse than those with LMA when performing a range of maths, including simple number tasks (Maloney, Waechter, Risko, & Fugelsang, 2012) to more complex tasks. This has been supported by a key study in MA and reaction time by Ashcraft & Faust (1994). They recruited 130 undergraduate students to complete a verification task using simple addition and multiplication, complex addition and mixed arithmetic. Participants were split in to four groups based on their level of MA identified by the MARS (Richardson & Suinn, 1972), with groups 1 – 4 ranging from low to high MA, respectively. They noted that those with LMA scores showed the fastest reaction time and highest accuracy and as MA scores increased (in groups 2 and 3) reaction time decreased. This indicates the effect MA has on the speed of mathematical processing for high maths anxious individuals. However, Ashcraft and Faust (1994) also noted that the very HMA group (4) had a similar reaction time to the LMA group (1) which contradicts the theory of MA causing a delay in processing. They noted that accuracy was worse for group 4 and theorised that they may have purposely sacrificed accuracy in order to answer faster as an avoidance technique. In other words, individuals with HMA were likely to have selected either true or false quickly to avoid processing the task and increasing levels of anxiety and threat.

It has also been shown that performance also increases when the evaluation element (a classic factor associated with MA) is removed from a maths task. Faust, Ashcraft, & Fleck (1996) asked participants to answer complex addition using pen and paper but removed any time constraint and found that the negative consequences of MA were absent. This was due to the low cognitive load participants experienced whilst using pen and paper i.e. calculating on the paper reduced the amount of WM resources normally in short supply for maths anxious individuals (Ashcraft & Moore, 2009; Ashcraft & Kirk, 2001; Beilock & Ramirez, 2011). Whilst the above studies have outlined the performance effects of MA, there is still a continuous theme that the tasks used here are not maths and are more arithmetically based, however some studies have alluded to the fact that anxiety towards number needs to be investigated.

Number anxiety is a particularly interesting factor associated with MA due to the little research involved and whether it contributes towards the formation of MA. Kazelskis (1998) supports this theory by stating "the manipulation of numbers could be the *sine qua non* of maths anxiety" (p.631). It has only been recently that research has begun to identify the theory of number anxiety as a possible prerequisite to MA. Maloney, Risko, Ansari, & Fugelsang, (2010) used an enumeration task whereby a number of squares (1-9) were presented to high and low maths anxious individuals. When 1-4 squares were presented they found that high and low maths anxious individuals enumerated equally as quick. However, when 5-9 squares were presented high maths anxious individuals took significantly longer, supporting the theory that those with HMA may also experience number anxiety. (Maloney, Ansari, & Fugelsang, 2011) further tested why number anxiety would have an impact on maths anxious individuals, whether it is through MA impacting on working memory or a numerical deficit. Participants were asked to state whether a number (1-4 or 6-9) was higher or lower than 5. This study manipulated the numerical distance effect (NDE) stating that the further away the number is from 5 (e.g. 1 or 9) it becomes easier to distinguish differences between it and the target number. Overall they identified a slower reaction time for high maths anxious individuals showing the NDE was higher than low maths anxious individuals. This can be expected due to the anxiety effect on working memory as it is in use keeping the standard (5) active whilst performing the task.

Therefore, in order to rule out working memory's role in the study, Maloney et al. (2010) conducted a follow up using a modified version of the low/high 5 task. Participants were instead presented with two stimuli on screen and were asked to press either the left or right end on the keyboard to correspond to which number they identified as being the largest. This showed a replication of the previous NDE results without the need for a target number. These findings raise some issues concerning the explanations for the relationship between MA and how MA manifests itself, as stated above. It is assumed that working memory is impaired due to the amount of resources consumed by anxious responses, which creates delay and performance issues when solving a maths based task. However, Maloney et al. (2011) note there is no research currently stating that numerical comparison is demanding of working memory resources. Therefore, it is theorised that those with HMA may have a low level deficit during numerical processing.

This is contradictory to previous research which notes that working memory capacity is not a consequence or precursor to MA. If this was the case then cognitive performance in other areas would also be affected (Ashcraft and Kirk, 2001). Other behavioural studies have shown the prominent effects of MA on even the most basic numerical processes including counting and simple addition (Ashcraft & Ridley, 2005; Maloney et al., 2010). Earlier research provides a contrasting explanations to the above based on intervention results. Hembree (1990) showed that tackling MA problems was less to do with improving mathematical skills and more about preventing the anxiety from overwhelming individuals. High maths anxious individuals who had been in treatment group showed higher maths achievement. If the first theory was correct and MA was brought about by low competence then interventions that tackled anxiety such as the one mentioned above, would be seen to have very little effect. Further research may be necessary to identify whether those with MA have a deficit in working memory, e.g. comparing neurophysiological responses between those with high and low MA to identify MA's effects on processing at a neuronal level.

1.5 Summary

In conclusion, this first chapter has outlined the definitions, measurement and behavioural effects of MA. It has identified a clear theme that the tasks and scales used in behavioural and cognitive MA research are more arithmetic or number based and given this, it could be called for a nomenclature or definition shift to include aspects of anxiety towards number or arithmetic. The chapter has also explained the underpinnings of MA and its effects on maths performance but does not expand on the neurophysiological mechanisms that control this. Ashcraft (2002) notes that maths processing research has become increasingly associated with cognitive neuroscience, providing the ability to understand how MA affects brain activity during maths processing. The remainder of this thesis will identify the neurophysiological effects of MA and identify the electrophysiological correlates associated with this construct. To accomplish this, an understanding of the neurophysiological methods used in cognitive neuroscience research is required. The next chapter outlines current neurophysiological measures that are used to investigate the underlying mechanisms of MA and will evaluate multiple measures of brain activity as well as the analysis methods associated with them. This will then prepare the subsequent chapter (chapter 3) for providing a substantial literature review of relevant neurophysiological maths and number processing research, as well as recent research concerning the neurophysiological aspects of MA.

Chapter 2: Neurophysiological methodologies

2.1: Introduction

The previous chapter summarised the construct of MA and research to date noting the thesis' direction towards neurophysiological methods. However, to provide a review of the neurophysiological research concerning MA, an understanding of methods used in cognitive neuroscience needs to be evaluated. This chapter will explain relevant neurophysiological measures (fMRI, MEG and EEG), then compare their advantages and disadvantages before explaining the current research methodology. This will be followed by a detailed discussion of data acquisition and analysis principles applied in electrophysiological research, i.e. frequency analysis and Event Related Potentials (ERPs). This will enable the following chapter to provide a literature review of relevant neurophysiological maths and number processing research, as well as recent research concerning the neurophysiological aspects of MA.

2.2: Measures in cognitive neuroscience

The most frequently used imaging measures in neurophysiological research include functional Magnetic Resonance Imaging (fMRI), Magnetoencephalography (MEG) and Electroencephalography (EEG). The following sections will outline the features of each of these methods, before evaluating the relative advantages and disadvantages of these methods in section 2.2.4. Emphasis will be made on the latter sections as it forms the basis of the empirical work in this thesis.

Before outlining these, some definitions need to be clarified in order to understand the terms used in neurophysiological research. One of the main comparisons between these methods is resolution and neurophysiological measures are typically defined as having good spatial resolution, temporal resolution or both. Spatial resolution defines the accuracy of locating where an event is occurs for example, identifying fluctuations of activity in specific brain structures. Temporal resolution defines the accuracy of identifying when an event occurs for example; the time (or latency) a physiological process occurs in the brain associated with cognitive function. Another term used frequently is dipoles which are more prominent in MEG and EEG as they are elicited through neuronal activity. A dipole occurs when multiple neurons collectively fire and comprises a positive and negative electrical charge separated by a small distance. The following sections will outline neurophysiological measures with reference to these terms.

2.2.1: functional Magnetic Resonance Imaging

fMRI is an imaging method that can identify areas of activation through changes in blood flow, specifically when an area of the brain is engaged (see Raichle, 2009, for a review). It has been used frequently to identify areas of processing within the brain due to its excellent spatial resolution, meaning it can easily discriminate between locations in the brain. This measures the amount of distortion to local magnetic fields (Arthurs & Boniface, 2002) caused by deoxyhaemoglobin in red blood cells. This gives an indication of the amount of deoxyhaemoglobin in the blood which is transferred from oxyhaemoglobin when neurons consume oxygen. The actual measurement is referred to as blood oxygen-level-dependent contrast (BOLD; Ogawa, Lee, Kay, & Tank, 1990). When an increase in activity is required in a region of the brain, neurons consume oxygen and the amount of deoxyhaemoglobin increases slightly, which reduces BOLD signal. The consumption of oxygen prompts an increase in blood flow to the affected region, which then increases BOLD signal. This is the component that is measured by fMRI (Arthurs & Boniface, 2002). The final stage of this measurement occurs when neuron firing decreases in the specific area, which decreases blood flow and oxygen levels (Lopes Da Silva & van Rotterdam, 2012). This process permits researchers to investigate changes in brain activity within regions and structures in response to a task. The excellent spatial resolution of around 1 millimetre allows accurate measurement and identification of structures in the brain from multiple angles (Lopes Da Silva & van Rotterdam, 2012).

2.2.2: Magnetoencephalography

MEG is another popular imaging method and is considered to be a more precise technique in observing temporal resolution with some spatial advantages. When neurons fire, electrical fields and magnetic fields are produced simultaneously (Lopes Da Silva & van Rotterdam, 2012). MEG functions by using between two and three hundred Superconducting Quantum Interference Devices (SQUIDs) to measure these magnetic fields. These allow accurate latency perception of neurophysiological processes to identify when they occur alongside cognitive function (Hari, Levänen, & Raij, 2000).

This method is useful as it is unaffected by layers above the brain e.g. the skull and meninges. This permits the transducers (that pick up magnetic activity) to be further away from the scalp, as magnetic fields do not disappear in free space (Lopes Da Silva & van Rotterdam, 2012). MEG also has the advantage of good temporal resolution, which refers to the precision of measurement in time, i.e. excellent temporal resolution permits the recording of multiple data points every second. Because magnetic fields are not disrupted by layers within or outside the brain, it is assumed that MEG also has good spatial resolution and can identify some dipoles within the sulci of the brain (Cohen & Cuffin, 1983), however this has been disputed and will be discussed in section 2.2.4.

2.2.3: Electroencephalography

The human EEG was discovered in 1929 by German psychiatrist Hans Berger, providing a new neurological diagnostic tool (Tudor, Tudor, & Tudor, 2005). This method is used to record the oscillations (cycles per second) of electrical brain potentials, measured in hertz (Hz), from electrodes placed at the scalp i.e. one Hz is equal to one cycle per second. The majority of electrical output, recorded from the scalp, originates in the cerebral cortex of the brain which transmits activity through the billions of synapses covering it. This transmission occurs when an action potential is created through neurotransmitters passing through synapses. The neuronal connection from this process generates an electrical current to transfer the signal from one neuron to the next neuron or pyramidal cell (specific form of neuron found in the cortex, amygdala and hippocampus; Branco & Häusser, 2011) and so on. To record this activity electrodes are placed on the scalp in an array conforming to the 10-20 system, devised by Jasper (1958) and typically use between 32 and 256 electrodes per cap. The internationally recognised 10-20 system refers to the placement distance of electrodes, being either 10% or 20% spaced away from the edges of the scalp. This was created in order to allow comparisons across laboratories.

Each electrode can acquire synaptic activity from between one hundred million and one billion neurons (Nunez & Srinivasan, 2006) and the activity at each electrode is amplified and recorded simultaneously for offline analysis. However, EEG is only useful when certain conditions are met at a neuronal level: In order for the activity to be detected, large groups of neurons need to be aligned and firing in the same direction whilst emitting electrical activity in phase (Nunez & Srinivasan, 2006). This usually occurs when an area of the brain is stimulated enough to be identified by the EEG electrodes. Whilst this appears to be a hindrance in comparison to other methods, it requires sampling at high frequencies (often 1000 Hz) which enables EEG's excellent temporal resolution. This inevitably means that the EEG system can record processing as it happens with instant timing, which translates to excellent temporal resolution. Whilst this is extremely useful for latency and amplitude analysis of electrical activity, EEG does have limitations concerning spatial resolution, i.e. accurately locating where the source is localised to. Recent technological developments have begun to allow EEG source localisation, as well as EEG's compatibility with other measures of brain activity (e.g. fMRI).

2.2.4 Comparing fMRI, MEG and EEG

This section will compare and evaluate the three neurophysiological methods outlined above to identify the most appropriate for use in the current research. As stated above, fMRI has excellent spatial resolution (due to the visible movement of blood unaffected by outer layers of the brain), enabling the accurate location of structures in the brain. However, fMRI's poor temporal resolution results in a delay between activation in brain structures and the precise viewing and measurement of when this happens (Huster, Debener, Eichele, & Herrmann, 2012). This becomes an issue when trying to identify when a cognitive process has occurred (e.g. in response to a stimulus), as the measurement will be several seconds delayed, due to the slower haemodynamic response.

It has been argued that MEG, whilst having poorer spatial resolution than fMRI, has a better spatial resolution that EEG (Cohen & Cuffin, 1983) as magnetic fields are uninhibited by skull and other tissues, whereas electrical fields deteriorate through these. However, EEG electrodes are typically two times closer to the scalp than MEG coils and depending on location, MEG measurements can fall by 50% of expected maxima, which can be open to misinterpretation. To combat this and accurately identify a source of activity, it recommended that both EEG and MEG are used together (Lopes Da Silva & van Rotterdam, 2012).

MEG provides a good temporal resolution much like EEG and is largely unaffected by the outer layers of the brain, enabling a useful representation of cognitive processes however, MEG processing can struggle when dipoles emerge at a deeper level in the brain. EEG, whilst having poorer spatial resolution, has excellent temporal resolution which enables the ability to assess the timing of specific cognitive processes in the brain. EEG also provides a good indication of shallow and deep dipoles as a part of ERP analysis (see section 2.4.2), which allows assumptions to be made about how regions in the brain are involved in specific processing (Mosher, Spencer, Leahy, & Lewis, 1993). In other words, EEG sees more of the brain but cannot localise activity easily, whereas MEG sees less of the brain but can localise somewhat better. Because localisation is not the focus or question in this body of research, it is more appropriate to use EEG.

EEG was used in this thesis due to its ability to measure brain activity instantly in response to cognitive processing, which permits the recording of such activity with excellent temporal resolution. Locations in the brain affected by MA have been observed (outlined in chapter 3) but a complete picture of the electrophysiological processes associated with the typical delay and poorer performance seen in high maths anxious individuals, is lacking. Using this method it is possible to fill the gaps in this research area.

In summary, the sections above has outlined the basic principles of fMRI, MEG and EEG however, to explore EEG's advantages further, an understanding of analysis methods needs to be achieved. Examples used in cognitive neuroscience research include the identification of differences in response to stimuli, through either the breakdown of raw EEG activity into bands using frequency analysis or using event related potentials (ERPs).

2.3: The Current Methodology

The following sections will outline typical analysis methods in EEG research which will be applied in the thesis' empirical studies. This will include breaking down raw EEG using frequency analysis and ERP analysis. These will be discussed in turn, firstly outlining frequency analysis and the breakdown of individual bands of activity before moving on to ERP analysis and the relevant components and their associated functions.

2.3.1: Frequency Analysis

Raw EEG activity is comprised of rhythmic activity or frequencies bands (measured in Hz), which are often broken down to identify their relation to psychological function, usually conducted by noting the most prominent frequency. These have been defined and named over years of research to include prominent frequency bands, such as delta, theta, alpha, beta and gamma. In order to separate the overall EEG activity into these bands, Fast Fourier Transform (FFT) analyses are performed, to measure the estimated power of the different frequencies. This enables the interpretation of behavioural or psychological functions that influence their prominence (Cacioppo & Tassinary, 1990). The calculation requires a specific number of data points, often converted from the original measurement (using a spline fit), to be sampled at the power of 2 e.g. 64, 128, 256, 512, etc. (Porges & Bohrer, 1990). When used with the *Nyquist* formula, this method states that the identified frequency is equivalent to half of its sample frequency (Nunez & Srinivasan, 2006). For example, if the highest observable frequency in a particular timeframe (or epoch) is 20Hz, a minimum sampling rate of 40Hz is needed to record the entirety of this frequency (Ray, 1990). An issue can occur as higher frequencies are needed for recording (e.g. gamma band activity), whereby the sampling rate becomes too high to perform this. To understand psychological phenomena associated with frequency bands, it is important to identify each band's contribution to behavioural effects. An outline of the common EEG frequency bands and their associated cognitive functions are discussed below.

Delta (δ)

Delta (δ) activity encompasses low frequency (0.5-4Hz) and is typically absent during wakefulness (in adults) as it is one of the dominant frequency bands in raw EEG during sleep. This band is visibly identified in new-borns (awake) until 2 years of age and can also appear when vascular lesions and brain tumours are present. Lower power of delta can be identified in the normal adult brain but this occurs through FFT analyses to access clearer representations, rather than observing raw EEG. For example, using a frequency analysis, Grillon & Buchsbaum, (1986) identified delta activity in awake individuals during changes in light intensity. Other examples of research show manipulations of delta during word fluency tasks (Tucker, Dawson, Roth, & Penland, 1985), mental calculation (Harmony et al., 1996) and more recently, susceptibility to depression (Lotrich & Germain, 2015; Meerwijk, Ford, & Weiss, 2015). Cacioppo and Tassinary (1990) state that it may be beneficial to separate the different methods of observation (FFT and visually observing raw EEG) when comparing delta's differing psychophysiological processes.

Theta (θ)

Theta activity (4-8 Hz), initially identified by Grey Walter (1953), was originally associated with pleasure, whereby theta was shown to be mutually exclusive to the experience of pleasure. Later research also showed rudimentary associations with REM sleep, problem solving, hypnosis and meditation (see Schacter, 1977, for a review). More recently, theta activity has been identified in children aged between 1 and 6 (Orekhova, Stroganova, Posikera, & Elam, 2006) and in adults it is assumed to represent sleep, sleep deprivation (Bernardi et al., 2015) and some forms of problem solving (Rütsche, Hauser, Jäncke, & Grabner, 2015).

Alpha (α)

Alpha activity (8-12 Hz) was the first to be identified by Hans Berger (inventor of the human EEG) and is typically elicited in raw EEG in the occipital lobe when the individual has their eyes closed but are awake. When eyes are open the most prominent band shifts from alpha to beta activity, which led alpha to be associated with relaxed levels of consciousness and awareness (Cacioppo & Tassinary, 1990). Recent explanations of alpha activity's role state that it focuses on network communication as well as a mechanism underlying the functional role of other bands of activity (see Bazanova & Vernon, 2014, for a review).

Beta (β)

Beta activity (12-30 Hz) was also introduced by Hans Berger and can be divided into low (12-20 Hz) and high (20-30 Hz) beta. This band is physiologically associated with motor control or tensing but is also linked to states of anxiety, stress or active concentration (Baumeister, Barthel, Geiss, & Weiss, 2008). Furthermore, beta activity is also seen when movement has to be resisted or stopped (Zhang, Chen, Bressler, & Ding, 2008) thus, it is seen often during tasks where performance or time measures may be taken.

Gamma (γ)

Gamma activity (30-100 Hz) has recently received more attention due to its association with cognitive processes and assumption that it is involved in memory (see Herrmann, Fründ, & Lenz, 2010, for a review). Originally, this band was not explored in detail because of the increase in activity from non-cerebral sources (or artefacts) e.g. muscle movement. Artefacts are typically associated with higher frequency bands however, the gamma band is now noted as being associated with various processes, including threat responses (Maratos, Senior, Mogg, Bradley, & Rippon, 2012), memory (Jensen, Kaiser, & Lachaux, 2007) working memory and attention (Keil et al., 2001; Müller, Keil, Gruber, & Elbert, 1999; Oya, Kawasaki, Howard, & Adolphs, 2002; Tallon-Baudry, Bertrand, Hénaff, Isnard, & Fischer, 2005; S. F. Taylor, Liberzon, & Koeppe, 2000).

It may be considered useful to break down raw EEG into individual frequencies in order to identify the largest contributor and therefore, possible psychological and physiological processes. However, no one band contributes to EEG activity at one given time. This means that multiple frequency bands could be contributing to a cognitive process even though other bands may be more prominent.

It may be more useful to identify ERP components which are constructed by multiple frequency bands and associated with cognitive processes in the brain. For example, to compare a negative behavioural effect of MA (reaction time) to neurophysiological activity (component latency), it would be useful to identify when processing occurs in ERPs post-stimulus presentation. This section will continue by evaluating ERPs, another analysis method for understanding correlates between brain activity and behavioural processes. The method will be explained before providing examples of typical ERP components.

2.3.2: Event Related Potentials

Another commonly used method of EEG analysis is breaking down data to identify the cognitive function at specific (time locked) points. First identified by Davis, Davis, Loomis, Harvey, & Hobart (1939), ERPs are used as a method to capture time-locked EEG activity (Sur & Sinha, 2009) and are one of the most practised analysis methods in cognitive neuroscience (Coles, Gratton, & Fabiani, 1990). ERPs are comprised of voltage fluctuations in time-locked EEG, of which changes are representative of psychological processes, such as sensory, cognitive or motor (Coles et al., 1990; Luck, 2005). This encompasses an average of a certain period of time (or latency) during the processing of a relevant, constant, stimulus. In ERP studies a visual or auditory stimulus is typically presented to a participant whilst EEG activity is recorded. An average ERP can be taken encompassing milliseconds (ms) prior to the stimulus presentation (e.g. 100ms) and for a period of time afterwards depending on the study design (e.g. 800ms). For example, if shapes and numbers are presented to participants multiple times, the researcher may take an average every time a shape was presented and every time a number was presented. This 900ms average will enable the researcher to compare and contrast the averaged ERPs for all shapes against all numbers, across participants and electrode locations. This average waveform will contain multiple components (a specific duration encompassing the peak or trough in a waveform) identified through amplitude, measured in millivolts (mv) and latency in ms.

These components tend to be identified through the observation of positive and negative peaks that vary in amplitude, polarity and latency however; these peaks and troughs can often be arbitrarily assumed to represent human brain processes (Luck & Kappenman, 2012). In fact, it is wrong to assume complete understanding of what the peaks represent. Instead, by using *a priori* assumptions based on previous research, correlates can be observed between components and behavioural or psychological responses. For example, a typical study employing a checkerboard paradigm, where the squares are inverted regularly, shows a definitive P100/P1 component. This is the first positive component occurring around 100ms, post stimulus presentation, which would be elicited during each reversal (Odom et al., 2004). Through replications of these findings, showing a similar P1 component eliciting in similar spatial and temporal locations, it is assumed that this represents contrast perception. Earlier ERP components tend to be indicative of the physical parameters of the presented stimulus (e.g. contrast perception; Afra, Cecchini, Pasqua, Albert, & Schoenen, 1998), whereas those that are generated later (post 100ms) tend to be linked to information processing and retrieval (Sur & Sinha, 2009). These components often represent mental processes including recognition and the processing of stimuli and are normally labelled by their latency within the ERP for example, the P1 (as stated above). It should be noted that whilst components are labelled based on their position in the ERP, latencies can be varied. For example, some components elicit earlier if a quick response is required or attention modulates the processing of the stimulus (Luck, Woodman, & Vogel, 2000).

To understand the typical functions of ERP components in relation to cognition, examples of those relevant to visual maths processing (P1, N1, P3 and N400) are outlined below.

The P1 Component

The P1 component is the first positive component that typically elicits between 70-100ms post-stimulus onset and is displayed across the posterior occipital region (Luck & Kappenman, 2012). The P1 has been shown to fluctuate in amplitude based on contrast differences, in that higher luminance increases the amplitude of the P1 (Johannes, Münte, Heinze, & Mangun, 1995). For example, Johannes et al. (1995) presented participants with high and low luminance at left or right stimulus locations and told them to attend to either the right or left field. They noted that brighter luminance resulted in larger P1 components and an earlier occipital N1 component. This is also seen in checkerboard pattern reversal studies (e.g. Afra et al., 1998) whereby, the luminosity changes elicit a P1 component around 100ms after every reversal.

The N1 Component

The N1 is a negative component mainly elicited in parietal regions (between 160-190ms post stimulus onset) following a P1. This has been shown to represent pattern recognition and discrimination (Vogel & Luck, 2000), including the identification of visual stimuli (Hillyard, Vogel, & Luck, 1998; Mangun & Buck, 1998). Research has noted that an increase in amplitude for the N1 component shows a requirement for performance improvements (Hillyard et al., 1998). This implies that the N1 component plays a role in discrimination of visual stimuli and preparation for task performance.

The P300 Component

The P300 or P3 (elicited at around 300ms) has been presented in a number of research areas including memory (Azizian & Polich, 2007; Curran & Cleary, 2003; Guo, Duan, Li, & Paller, 2006), ageing (Polich, 1997), biological factors (Polich & Kok, 1995) and attention (Polich, 2007). The P300 has been shown to be sensitive to the amount of attentional resources available, typically identified in dual task paradigms where an increase to the P300 is elicited when task difficulty increases in the primary task. However, if the primary task is easier, the P300 will increase for the secondary task (Kramer, Wickens, & Donchin, 1985). This identifies the P300's role in task performance and its susceptibility for manipulation by attention. This may represent the neurophysiological processing equivalent to the behaviour described by the attentional control theory (Eysenck et al., 2007), whereby individuals struggle to allocate necessary attentional resources to the task at hand due to their consumption during an anxious state.

The N400 Component

Finally, the N400 (observed between 250-550ms) is typically studied within word processing research and semantic significance in verification tasks. For example, Kutas & Van Pettens (1994) found that when presenting the sentence "he spread the bread with butter/cream", the word 'cream' elicits a higher N400 amplitude as the sentence context predicts the semantic features of the word 'butter' instead. They note that 'cream' would be more difficult to retrieve in this context, hence the higher N400. This component has also been shown in maths-based tasks, where incorrect answers provided during verification or probe tasks have shown higher N400 amplitudes (Niedeggen & Rösler, 1999; Niedeggen, Rösler, & Jost, 1999) identifying that the processing involved in retrieving an incorrect answer requires more attentional resources.

2.4: Conclusion

The aim of this chapter was to provide an understanding of methods used in cognitive neuroscience. This chapter has outlined and evaluated multiple neurophysiological methods to measure brain activity. It has also contrasted each measure and highlighted the use of EEG and relevant analysis methods that will be used in this body of research. Whilst EEG has limitations it is still one of the predominant, well-established methods practised in cognitive neuroscience. Chapter one and the current chapter have focused on the behavioural, cognitive and psychological effects of MA and neurophysiological methods used in cognitive neuroscience. Before conducting empirical research into the electrophysiological correlates of MA, there is a clear need for a review of current neurophysiological research concerning MA to identify previous temporal and spatial findings. However, it is first important to outline relevant research concerning the processing of maths and number. The following chapter will highlight baseline maths and number processing in non-high maths anxious populations in order to compare and contrast processing to typical MA neurophysiological processing, when faced with maths tasks. Chapter three will then continue to outline and evaluate current research concerning the neurophysiological effects of MA using the multiple measures evaluated in this chapter. This will lead into the need for this body of research. The way in which data is acquired, processed and analysed will be outlined in each method section of the empirical chapters (4, 5, 6 and 7).

Chapter 3: Neurophysiological research in maths, number and maths anxiety

3.1 Introduction

The previous chapter outlined and evaluated the relevant neurophysiological measures used to identify mechanisms of brain activity, concluding that EEG was the most appropriate for the research questions posed. Before presenting the empirical work conducted for this thesis, previous research focusing on the neurophysiological correlates of maths and number processing and maths anxiety will be evaluated.

This chapter will first explore and evaluate research concerning the neurophysiological processing of maths and number in order to outline processing in non-high maths anxious populations. The chapter will then evaluate the neurophysiological research concerning MA conducted thus far to outline the gaps in research, the direction of the current thesis and end with aims and hypotheses leading into the first study.

3.2 Neurophysiological correlates of maths processing

Maths processing has been widely studied using multiple neurophysiological methods. This section will outline key studies noting latency and location of brain activity involved in maths processing.

To identify ERP component correlates during maths processing, Zhou et al. (2006) recorded EEG using 64 electrodes from 18 undergraduates. They presented each individual with simple multiplication, addition and subtraction and asked them verify whether the succeeding answer was either correct or incorrect. They identified that significant operation effects were seen during the N300 peaking at 320ms, whereby multiplication elicited a larger N300 than addition and subtraction. Zhou et al. (2006) note that due to the retrieval of the answer (one of three stages within processing) different strategies were used depending on the arithmetic operation required. Furthermore, the retrieval tended to occur between 200 and 400ms, consistent with the N300 component. The N300 may have been identified due to the different fact retrieval or calculation processes needed between the three operations. For example, increased amplitudes are likely to manifest in parieto-occipital regions bilaterally when applying strategies during addition and subtraction (De Smedt, Grabner, & Studer, 2009), whereas multiplication typically shows greater activation in the left parietal (angular gyrus) region (Grabner et al., 2009). Zhou et al. (2006) note that when comparing addition and multiplication problems (matched for size and difficulty) there was a similar N300 effect showing little difference across operation, identifying that the N300 is not specific for similarly processed mathematical operations (Seitz & Schumann-Hengsteler, 2002). A similar finding was observed by Zhou et al. (2009) where a strong N300 was found in left anterior (frontal lobe) regions of the brain for multiplication problems. This has identified a possible component of interest however; the multiple task demands may have caused the N300 to elicit and due to the use of specific stimuli sets in the first study (using addition and multiplication), N300 differences are not expected.

Minor adjustments in task demand can also produce differences in ERP components. Prieto-Corona et al. (2010) recorded EEG from 31 electrodes whilst presenting a single digit multiplication verification task to a group of 16 male children and 18 male adults. They were required to specify whether the answer presented was correct or incorrect using a mouse press. Prieto-Corona et al. (2010) identified an N400 effect in both adults and children, with children displaying roughly a 400ms delay in central and parietal regions. Delayed latencies can occur in children, compared to adults, in P300 and N400 components due to physiological immaturity (Atchley et al., 2006; Polich, Ladish, & Burns, 1990). Whilst the latency period is different, they are still representative of the component and its function. Prieto-Corona et al. (2010) further noted that the N400 component was higher for incorrect than for correct answers and that this may occur because the representation individuals have of the current equation fails to fit the answer presented, therefore eliciting a stronger N400. However, the N400 is one of many components involved in the processing of maths which researchers have identified.

Peng, Chen, & Wei (2011) explored latency and amplitudes of ERP components during mental arithmetic processing. They asked eight participants to perform 2 by 3 digit subtraction, with a choice of two answers and a fixation (+) presented before and after each stimulus and prior to the study. Peng et al. (2011) identified specific components at prefrontal, temporal and parieto-occipital regions. These were identified as a P1 (at 60-90ms onset and 100-130ms peak), N1 (100-150ms peak), P2 (150-250ms evoked), P300 (250-350 evoked) and a N400 (unspecified). This presents useful information for the analysis of specific ERP components associated with mental arithmetic. In critique of this, the use of a mathematical operation (+) as the fixation for each stimulus could have affected results; it is possible that viewing this could act as a confounding variable and delay component latency. This confound could have primed participants such that accuracy may have decreased (being that the task centred on subtraction). Furthermore, it is possible that this confusion could have offset the latency of components causing a delay and mislabelling of components. Nevertheless, the components identified above provide a good basis for comparison of amplitude and latencies across groups.

Zhang et al. (2012) also recorded EEG from 64 electrodes and used ERPs to examine how adults process common fractions to look at mathematical processing. They recruited 17 participants to take part in a numerical distance effect (NDE) task using fractions and required participants to state whether a fraction was higher or lower than the target fraction (⅕). The simple condition used the numerator 1 and denominators ranged from 1-9, except the fraction '⅕' which was used as a target. The complex condition involved a randomisation of those same common fractions but also included 8 decimal fractions (e.g. 0.05, 0.25,0.40 etc.; Zhang et al., 2012). They identified a distance effect in the component P3, which was observed over all frontal central and parietal electrodes, showing contrast to previous maths research (e.g. Dehaene, 1996; Hyde & Spelke, 2009). They also identified a larger N2 over the left frontal region during the complex condition. They concluded that the N2 is associated with cognitive control (Folstein & Van Petten, 2008), as the complex condition was more demanding of this and the larger N2 is likely due to the switching of cognitive processes between identifying whether common fractions were higher or lower and whether decimal fractions were higher or lower (in the complex condition). They note that two processes are required for each e.g. componential processing for the fractions and holistic processing when componential processing is too difficult, i.e. for decimals (Zhang et al., 2012). This provides further evidence of more complex mathematical processing and the components associated with it. However, up to now there have been no paradigms designed specifically to look at arithmetical processing whilst aiming to exclude parallel occurring non-numerical processing in the brain.

Avancini, Soltész, & Szűcs (2015) aimed to tease apart the overlapping processes in the brain during arithmetical processing in order to solely identify the neurophysiological underpinnings of arithmetic using ERPs. They presented 24 participants with single digit addends (e.g. 3+4) with a probe of one or two digits (e.g. 9) whilst recording EEG from nine electrodes. Participants were asked to calculate the answer and then decide whether the actual result was odd or even. The response required was whether the parity of the probe was the same (odd or even) as the correct sum, using a button press. They also presented 10% of stimuli in a red font, rather than black to elicit ERP differences for stimuli of an unexpected nature. The multiple presentations of different stimuli enabled the identification of differences across arithmetical processing. They identified that incorrect probes to the sum increased N400 and P3b amplitude as opposed to correct results (supporting previous ERP effects; Kutas & Federmeier, 2009; Niedeggen & Rösler, 1999), as well as increased reaction time and decreased accuracy for incorrect results. Avancini et al. (2015) state that even though this was task irrelevant, semantic processing still occurred for arithmetical fact retrieval. The red stimulus properties were also found to elicit delayed latency (11ms) as well as an increased behavioural reaction time response (20ms), suggesting that this detection occurs when processing arithmetic correctness, which supports this as one of the non-numerical processes that can occur alongside numerical processing. They conclude by noting that this is a novel paradigm to investigate arithmetical verification processing by being able to dissociate the overlapping temporal mechanisms between numerical and non-numerical processing where previous EEG and fMRI studies have not. They suggest that this paradigm allow for clearer interpretation of data providing a method to isolate single processes involved in arithmetic problem solving. However, whilst it is useful to isolate the processing directly involved in arithmetic verification, it should be of importance to include components associated with early stimulus parameters. Particularly, in MA research it would be of use to note how the maths anxious brain might hinder or interfere with early ERP components that influence the processing of basic stimulus parameters, such as contrast perception (P1) and early stimulus recognition (N1). These components may be involved in the processes that promote poorer accuracy and increased reaction time in high maths anxious individuals, therefore including them in analysis could be beneficial.

In summary, the above research has outlined typical ERP components involved in complex and simple maths processing. These have displayed positive components including P1, P2, P300, and negative components including N1, N2, N300 and N400. Whilst these are useful and contribute to knowledge about non-high maths anxious individual's maths processing it is also necessary to investigate possible components involved in the processing of number. MA is theorised to originate from poor early maths education (see chapter 1), which involves numeracy and basic number facts. With this in mind, the processing of number could still generate anxious thoughts in adults with HMA and therefore, it would be beneficial to investigate neurophysiological research concerning non-high maths anxious individual's number processing in order to provide a comparison when investigating high maths anxious individuals. Similarly, typical MA scales and behavioural tasks tend to apply arithmetic or numerically based questions rather than maths. Indeed, if these have measured number anxiety instead of MA then baseline number processing needs to be investigated.

3.3 Neurophysiological correlates of number processing

This section will investigate the neurophysiological correlates of number processing. This will enable an understanding of typical numerical processing when confronted with number based tasks that differ from the more complex maths tasks stated above. This will later enable the identification and comparison of appropriate locations and latencies to use when investigating MA's contribution to brain activity.

Dehaene (1996) provides a detailed view of number processing using ERPs, identifying multiple components involved. The study presented participants with either single digit numbers (e.g. 8) or a verbal format (e.g. EIGHT) and had to identify if the number was larger or smaller than 5 (NDE task). Dehaene identified a P1 component at 104ms in temporal, parietal and occipital regions bilaterally and noted this as a component associated with nonspecific visual processing, supported by visual evoked potential research (Luck, Woodman, & Vogel, 2000; Van Voorhis & Hillyard, 1977). The second component identified was the N1, which peaked in similar areas to the P1 but amplitude was lateralised higher in the left hemisphere, identifying that this component marked the beginning of number recognition (Dehaene, 1996). This can be shown during the third component detected, P2p (second positive peak in parietal region), where the identification of whether the stimulus was higher or lower came into effect. Dehaene (1996) identified this by noting that the size of the verbal numbers presented (word length effect) modulated the transition from N1-P2p and the P2p's amplitude. The final component identified was the P3 which is likely linked to the response participants had to give. Dehaene (1996) states that the P3 tends to occur post sensory/cognitive processing therefore, this is likely due to the response to the task including motor pre-emption. This study therefore highlights the components involved in observation, recognition, and retrieval of arithmetic facts whilst responding to specific number tasks.

A further study conducted by Wang et al. (2007) observed number recognition using an ERP paradigm. They recruited 16 right handed undergraduate students and showed them either a 2 digit number (target stimuli, e.g. 49) or a single digit number and a letter (non-target stimuli, e.g. 7T) whilst recording EEG from 128 electrodes. Participants were instructed to press a button with their dominant hand when target stimuli appeared. Further tasks also included simple subtraction and complex arithmetic. They report a P100 across frontal, central and parietal regions (unchanged throughout each task), indicating a visual evoked potential, as well as an N120 discovered in occipital regions linking this to visual processing. They also identified a P300 in all scalp locations and note that amplitude did not change across locations, except in frontal and temporal regions when the tasks were increasingly difficult. Wang et al. (2007) suggest that between the N120 and P300 components, number recognition occurs, supported by Hillyard & Müntes (1984). Due to the physical reaction (button press) occurring at 430ms (130ms after the P300), the P300 must represent the termination of cognitive processing (also supported by Dehaene, 1996). Wang et al. (2007) note that the P300 was larger in the left parietal than in the right parietal region, suggesting that the left parietal lobe plays an important role. However, at this point motor processing activity could have contributed to this i.e. as cognitive processing stopped, anticipation of pressing the button (leading to motor processing) may have started (Dehaene, 1996). Due to the necessity of participants answering with their dominant hand, left hemispheric activity via the sensorimotor cortex would have increased (Rogers, Carew, & Meyerand, 2004) generating increased amplitude in the observed electrodes, acting as a confound here. Similar research has also been conducted without the use of numerical or alphabetical stimuli, likely to avoid the involvement of semantic context (Andres, Olivier, & Badets, 2008).

Hyde & Spelke (2009) recruited 57 adult participants and asked them to watch a display of dots whilst EEG was recorded from 128 electrodes. Stimuli were split into both small-number blocks containing dots of 1, 2 or 3 and large-number blocks containing 8, 16 or 24 dots over a number of trials. Participants were informed to pay close attention to stimuli as related questions would be asked after the trial. They identified an N1 over posterior regions suggesting the processing of numbers and noted that small-number blocks produced a larger N1 magnitude, identifying a different method of processing than for larger numbers. However, they state that the larger N1 magnitude between number groups may have been due to the differences in dot size between the small and large number blocks. In order to eliminate this possible effect they conducted a second experiment, replicating the first design, but displayed all stimuli in one block (1, 2, 3, 8, 16 and 24) and equated the item size across all images. Again, it was found that early N1 increases continued with smaller numbers, confirming their earlier results. In both studies they also identified a P2p which increased over small ratio changes (e.g. between 1 and 2) rather than larger ratio changes. They suggest that this may occur because adults automatically compare numerosities in the large number range without being asked. This is supported by participants later reporting that they did not realise the study was about number and believed it to be about spatial arrangement of the stimuli. These results replicate previous findings in comparison of number quantities (Dehaene, 1996) as well as detecting lateralisation of activation, in parietal regions using fMRI (Ansari, Dhital, & Siong, 2006).

In another study Hyde and Spelke (2011) presented participants with small or large numbers of shapes and informed them to pay attention as they would be asked questions about the task afterwards, whilst EEG was recorded from 128 electrodes. They manipulated the number of shapes (circles) and shape change (to squares) whilst using ERPs to identify peaks associated with number processing. A common component, the N1, occurring in posterior regions was identified and described as a reflection of attention at the desired areas in the brain occurring at 173 ms for small numbers. Further research in this area has identified the N1 as an important component in number processing. Again, this provides useful information about relevant components associated with number processing however, an indication of where this occurs using a method with increased spatial resolution is also beneficial.

Previous research has compared the processing of both letter and numerical strings which is of use for comparing the foundation of math processing (number) with a non-numerical control task. Using fMRI for greater spatial resolution, Park, Hebrank, Polk, & Park (2012), identified differences across hemispheres (lateralisation) between the processing of letter and number strings. They found that there was high activation in both the bilateral visual cortex (responsible for visual processing) and sensorimotor cortex (responsible for sensory and motor function) however; letter processing seemed to lateralize towards left ventral visual cortex and number processing towards right. This provides an initial understanding of where numerical and alphabetical processing may localise within the brain. Furthermore, these results are supported by previous fMRI and MEG studies and provide an understanding of where these processes may occur (Chochon, Cohen, Moortele, & Dehaene, 1999; Liu et al., 2010; Pinel, Dehaene, Rivière, & LeBihan, 2001a). Similarly, Goswami (2004) notes that research has confirmed that bilateral intraparietal areas activate when participants perform tasks such as number comparison, involving either Arabic numerals, sets of dots or number words (Dehaene et al., 1998; Park et al., 2012). However, as stated previously, due to fMRI's poor temporal resolution it is not possible to identify the latency of processes that occur in the brain during processing of number.

It could be argued that the above research is less relevant than studies involving children as they are at the stage when MA can develop, during numerical task education. Although it is important to determine the processes and components in adolescents and children at ages where they are likely to acquire MA, it has been identified that mathematical processing mechanisms in adults are similar to the processing shown by children as young as 5 (Temple & Posner, 1998). Temple and Posner identified that when testing a NDE task, using either Arabic numerals or dot patterns, similar voltage signatures between adults (mean age = 23) and 5 year olds were present at around 200ms, however it was identified that reaction time was around three times slower for children. This highlights that adult research could elicit similar activity signatures and may even be imperative to the processing of mathematical cognition in children.

In conclusion, it has been outlined that the seemingly simple task of answering a numerical or maths problem involves different neurophysiological processes occurring in multiple regions of the brain, including arithmetic fact retrieval, number recognition and motor processing. This research suggests that central, temporal, parietal and occipital regions contribute to the processing of numerical stimuli, bilaterally. Furthermore, previous research using ERPs identified typical components used in the perception, recognition and processing of numerical stimuli including; P1 (contrast perception), N1 (recognition of stimuli), P2 (processing of basic stimuli), P300 (processing of more complex stimuli) and N400 (comprehending task difficulty). This information provides *a priori* assumptions of possible ERP components expected in future analyses.

This section has outlined and evaluated relevant research investigating maths and number processing in non-high maths anxious populations. This was included to identify processing in these individuals in comparison to those with HMA. Only recently has neurophysiological methods been applied to the study of MA and at present, studies are limited (Young et al., 2012). Young et al. (2012) note that although the cognitive and behavioural aspects of MA have been studied across different age groups, almost nothing is known about the neurophysiological underpinnings of MA. The following section will outline the current neurophysiological research concerning MA.

3.4 Current neurophysiological research concerning maths anxiety

The previous chapters and sections have evaluated behavioural MA research as well as the neurophysiological aspects of maths and number processing. As described previously, with the rise of neurophysiological research, it would be of interest to identify processes involved in MA (Ashcraft, 2002). This research area has been investigated more recently in order to explore the neurophysiological processes of MA using multiple methods; including fMRI and EEG. This section will describe and evaluate maths and number anxiety aspects within neurophysiological research thus far. This will also pay particular attention to methodology used in current research, especially concerning the assignment of individuals to MA groups

In one of the first studies to explore this, Sheffield & Hunt (2006) presented 27 participants, with a variety of MA scores (identified using the MARS), with a complex addition verification task whilst recording EEG from 7 electrodes. Correlations were used to identify relationships between MA and errors during the task and simple linear regressions were conducted to identify how ERP amplitudes at each electrode location and latency correlated with MA. They identified higher positive ERP (unspecified) amplitudes for high maths anxious participants when a carry operation was presented and noted that the stimuli were likely to be perceived as threatening, explaining the greater activation. Furthermore, high maths anxious participants had greater frontal activation during arithmetic tasks and differences were observed in parietal areas (known for contributing to maths processing). They conclude by stating that the carry operation is likely to affect high maths anxious participants more, due to the increased demand on working memory. Furthermore, worry could pre-empt maths processing, inhibiting the resources needed for the primary task. Failure to inhibit the worrisome thoughts then detrimentally affects performance, as seen in previous research (Ashcraft & Kirk, 2001; Eysenck et al., 2007). This study aimed to set a foundation for maths anxiety research using electro-cortical methods by exploring brain activity of those with HMA however, it also had some serious flaws: Sheffield & Hunt (2006) note that differences were seen across frontal and parietal sites, but used only seven electrodes. This is clearly not enough to gain a reasonable coverage of regions and could result in omitted data, being that the more electrode sites used, the greater the accuracy of potentials (Handy, 2005). With this in mind, it is hard to imagine significant findings showing any real effects due to the lack of data across the scalp. This study was one of the first to explore MA's effect on brain activity. Since this initial study, only a few MA ERP studies have been conducted, with larger arrays of electrodes applied providing more reliable data.

Jones, Childers, & Jiang (2012) contributed to this area by testing MA differences using ERPs, in an applied setting i.e. implementing a shopping decision making task. Thirty eight participants, 19 low and 20 high maths anxious individuals, were asked to choose to evaluate the prices presented to them and either buy or not buy an item depending on whether they thought the offered promotion would give them a ‘better deal’. High maths anxious individuals were defined by having a score around 32 or 1.5 standard deviations (SDs) or greater than the average sample mean. A total of 50 items were used and in promotion tasks, discounts were applied (such as 20% off). Researchers used the abbreviated math anxiety scale (Hopko et al., 2003) twice with a week in between to substantiate initial scores. Stimulus groups were presented to participants in blocks of promotion or non-promotion whilst activity was recorded from 32 electrodes. Jones et al. (2012) note that under promotion situations high maths anxious individuals rely on assumption rather than using a memory search to identify if the price or promotion is acceptable, in an effort to avoid doing maths. They note that the greater P3 experienced by high maths anxious individuals is likely representative of emotional and motivational factors due to the rapid response needed. However, for those with LMA this is more like the typical P300, representing decision making in working out the correct answer. They conclude by identifying that high maths anxious individuals deduce that mathematical processing, when no promotion is associated, means a bad price but a good price under promotional trials. This shows the classic avoidance technique found in those with HMA (Ashcraft and Faust, 1994) resulting in a faster reaction time but reduced accuracy.

Whilst this research provides an insight into MA ERP processing and relates to realistic situations, it leaves some aspects untouched. Firstly, this work focuses solely on buying and price comparison which lacks contribution as to why MA may occur. Secondly, buying is only one aspect that maths anxious individuals struggle with; using simpler maths based stimuli outside of a shopping context would be more beneficial at this early stage of research. For example, the MAS-UK contains only two items related to buying, involving working out a shopping bill and the change a cashier should give you after paying. There are other aspects of this construct that focus on evaluation, social/every day and observational anxiety. It is pertinent to first focus on the basic underlying principles of MA before the specific associated situations. Furthermore, it is also of use to understand the spatial locations of where MA affects individuals in specific brain regions to localise temporal processing more efficiently.

In order to examine the neural basis for the formation of MA, Young et al. (2012), analysed fMRI data in 46 seven to nine year old children, using the SEMA to assess different levels of MA. Simple (single digit) addition and subtraction verification stimuli were presented and participants were informed to identify correct or incorrect answers. They found that high maths anxious individuals had an increase in activity in the right, hemispheric amygdala, signifying the processing of fearful stimuli and negative emotions in conjunction with lower accuracy levels (Young et al., 2012). This is consistent by research on the activity of the amygdala and its response to fearful stimuli (Bzdok, Laird, Zilles, Fox, & Eickhoff, 2012), further supporting the theory that MA is not just a deficit and that fear and anxiety plays a large role in its development. This also supports Sheffield & Hunt's (2006) study stating that maths based stimuli are considered threatening and could further contribute to the avoidance effects seen in behavioural research (Ashcraft, 2002; Beilock & Ramirez, 2011; Meece et al., 1990; Parsons & Bynner, 2005).

Whilst it is important to consider MA as “feelings of tension and apprehension when performing maths tasks” (Ashcraft, 2002, p.1), recent research has also identified that avoidance of maths (by those with HMA) may be due to the anticipation of, rather than conducting, maths tasks. Lyons & Beilock (2012) presented 32 participants with difficult word and maths tasks. For example, a word task may have involved identifying a real word e.g. reversing the string ‘yrestym’ generates ‘mystery’, where participants would respond ‘no’ as yrestym is not an English word. Maths tasks involved using equations such as (a*b)2c=d, with numbers rather than letters. They presented these in blocks whilst neural activity was recorded using fMRI and identified that the higher an individual’s MA, the higher activity was in regions associated with threat detection, including pain (e.g. dorso-posterior insula within the central region). They concluded that the activity was not linked maths itself; rather the anticipation caused activation in pain networks. They go on to say that this could identify a possible neural mechanism as to why high maths anxious individuals avoid maths related situations, which can then lead to the avoidance of career paths and classes situated around this topic. It is likely that that a combination of perceived failure (Chinn, 2012) and anticipated pain (Lyons & Beilock, 2012) contributes to this avoidance. Whilst this is important and adds towards MA neurophysiological research, it does not explain how the underlying brain mechanisms relate to the increased reaction time and decreased accuracy seen in those with HMA.

Research measuring EEG activity between high and low MA groups using a NDE task (Suárez-Pellicioni, Núñez-Peña, & Colomé, 2013a) has attempted to understand this further. Suárez-Pellicioni et al. (2013) presented high and low maths anxious participants (based on sMARS scores; Alexander & Martray, 1989) with a simple addition, verification task where some answers were severely incorrect. MA groups were identified using the quartile method where low maths anxious individuals consisted of 13 participants scoring below the first quartile and high maths anxious individuals consisted of 13 participants above the third quartile on the sMARS. Participants were asked to respond with either a correct or incorrect button press whilst EEG recordings were acquired from 31 electrodes. They found that high maths anxious individuals exhibited more errors for large split problems (furthest from correct answer) than low maths anxious individuals, which indicates that MA affects simple maths processing efficiency. They note through investigating the P3b and P600 potentials that high maths anxious individuals have difficulty inhibiting the processing of irrelevant information. A number further away from the answer would normally promote a quicker reaction as it serves as irrelevant and easier to recognise as such, for example, a wrong answer of 212 from the problem 19+25= would be easier to refute than 49. Nevertheless, high maths anxious individuals show an increase in working memory resources needed for processing the problem and therefore, provide a slower reaction time for simple tasks.

This shows support for theories of threat detection and attentional bias in relation to the (perceived) threat inducing stimuli (212) whereby, it would induce an anxious response regardless of the distance from the true answer (Bar-Haim et al., 2007a). Suárez-Pellicioni et al. (2013) note that the P3b typically indicates cognitive demand during task processing e.g. higher task demand corresponds to a higher P3b amplitude and the longer it takes to evaluate stimuli, the more delayed the latency. Similarly, they note differences in the P600 potential stating that it modulates based on correct or incorrect answers. This support the behavioural results suggesting high maths anxious individuals invest increased processing in large split solutions than low maths anxious individuals, resulting in poorer accuracy and increased reaction time. This is additional evidence for the attentional control theory (Eysenck et al., 2007) in that when more attention is given to irrelevant information, less resources are available for the primary task, resulting in reduced performance overall. This is further supported by research indicating that high anxiety promotes inefficient search strategies (Janelle, 2002).

Recent research has also suggested that a deficit may exist in high maths anxious individuals but that this is part of attentional control branch relating to the central executive in working memory. Suárez-Pellicioni, Nuñez-Peña, & Colomé (2014) used the sMARS to classify high and low maths anxious individuals (17 in each group) in an ERP stroop study. Participants groups were identified using the quartile method again, whereby low maths anxious individuals were those that scored below the first quartile and high maths anxious above the third quartile. To measure how high maths anxious individuals process conflicting stimuli, participants were presented with pairs of Arabic numerals of different size and were required to state the greater of the two numerals, whilst avoiding differences in physical size. Findings showed slower reaction time in high maths anxious individuals than those with LMA, supporting previous behavioural research however; there were no significant ERP differences at the monitored components (N450 and Conflict-SP; linked to conflict detection). However, when they investigated conflict adaptation, by analysing the effect of the previous trial's congruence in current interference, they noted that high maths anxious individuals showed attention control only when conflict was encountered (e.g. a smaller sized number with a greater numerical value), whereas high maths anxious individuals exerted this throughout. From this they theorise that, due to the reactive way that high maths anxious individuals use attentional control, it leaves them more susceptible to distraction, hence the increase in reaction time.

The above two studies matched participants based on arithmetic performance with differences only on the sMARS however, using the quartile method to split participant groups is fairly arbitrary. It would be more useful to apply a method that groups individuals based on their responses, such as cluster analysis. Whilst the above two studies also provide support for previous research it lacks ecological validity and generalisation to an applicable setting, for example, high maths anxious individuals are less likely to encounter these tasks in education settings. To explore this further, it would be of use to construct a verification task to explore the minimal levels at which high maths anxious individuals may perceive maths as threatening.

3.5 Summary

In conclusion, this chapter has outlined previous research concerning the neurophysiological correlates of maths and number processing in non-high maths anxious individuals to compare to those with HMA. It has also outlined up to date relevant research concerning the neurophysiological effects of MA, using multiple methods including fMRI and EEG. Table 3.1 outlines the key studies in neurophysiological MA research highlighting the methods used to measure neurophysiological and behavioural effects of MA. It also highlights the arbitrary nature that MA groups are identified in MA research i.e. using quartile or median split methods. Also, the tasks used to measure MA are still typically numerically or arithmetically based, rather than involving maths problems. With these in mind, it is evident that there are gaps in current research that need to be explored in further depth.

Table 3.1:

Summary of relevant neurophysiological MA research.

Author	N	MA identification	Neurophysiological Method	Task
Sheffield & Hunt (2007)	27 (N/A)	MARS (N/A)	EEG, ERPs (7 Electrodes)	Addition Verification
Jones, Childers, & Jiang (2012)	38 (19 LMA, 20 HMA)	AMAS (score around 32 or 1.5 SD or greater than the average sample mean)	EEG, ERPs (32 Electrodes)	Evaluate prices in promotional situations
Young et al. (2012)	46 (23 LMA, 23 HMA)	SEMA (Median split)	fMRI	Simple addition and subtraction verification
Lyons & Beilock (2012)	28 (14 LMA, 14 HMA)	sMARS (in keeping with published norms)	fMRI	Word and maths task
Suárez-Pellicioni, Núñez-Peña, & Colomé, 2013)	26 (13 LMA, 13 HMA)	sMARS (quartile method)	EEG, ERPs (31 Electrodes)	NDE simple addition verification
Suárez-Pellicioni, Nuñez-Peña, & Colomé (2014)	34 (17 LMA, 17 HMA)	sMARS (quartile method)	EEG, ERPs (64 Electrodes)	Numerical stroop

One critique is that participants have mostly been arbitrarily assigned to groups based on outdated norms or instructions lacking in evidence that participant groups are alike. Inferential statistical methods to classify participants based on their responses, such as cluster analysis, would highlight participant groups based on statistical analyses rather than using the highest and lowest quarter of participants. The flawed quartile method doesn't look at differences across participants i.e. if all participants were classified as low maths anxious in a population; the quartile method would still say the higher scorers (not necessarily high in MA) were high maths anxious. Cluster analysis will be applied in this body of work to combat arbitrary placement of participants.

The above research also shows that fMRI methods are excellent at identifying spatial locations of where maths processing occurs but does not identify how these processes occur temporally, whereas EEG can do this. Studies in MA have also been conducted using EEG and ERPs, but tasks have either relied on incorrect answer processing, NDEs or comparing promotional prices. These have contributed to the exploration of MA effects in the brain but do not identify how this relates to the typical behavioural effects seen in high maths anxious individuals, for example, consistently poorer accuracy and increased reaction time.

This current research aims to address these issues by identifying how the behavioural effects relate to the underlying neurophysiological processes. For example, is the delay in providing an answer to a maths problem related to the latency of specific ERP components, hindering reaction time in high maths anxious individuals? It is therefore predicted that differences in amplitude and latency of ERP components will occur between high and low maths anxious individuals. This first study aims to identify the electrophysiological correlates of MA and its behavioural effects, outlined in Chapter 1, which has not been explored fully up to now. The following empirical chapters will continue to explore the neurophysiological correlates of MA. This also acknowledges that high anxiety levels experienced by those with HMA is likely to be more comparable to anxiety towards number or arithmetic over maths, based on the multiple tasks and scales that observe this.

Chapter 4: Exploring the electrophysiological correlates of maths anxiety

4.1: Introduction

The previous chapters have presented an overview of behavioural MA research, neurophysiological methodologies in cognitive neuroscience and a literature review evaluating neurophysiological maths and number research and current neurophysiological research concerning MA. This first exploratory study aims to address the gap identified in the literature review, concerning the latency and amplitude in electrophysiological correlates of MA and the need to map these effects to typical behavioural effects. Furthermore, as an exploratory study, this initial research aims to determine an appropriate processing and analysis methodology, addressing previous pitfalls and highlighting the future direction of this research area moving forward.

As stated in chapter one, behavioural research has continuously shown high maths anxious individuals struggle with maths processing and often have an increased reaction time when responding to maths (Ashcraft & Kirk, 2001; Ashcraft & Krause, 2007; Ashcraft & Moore, 2009; Faust et al., 1996) and simple numerical tasks (Maloney et al., 2011). It is theorised that there may be a deficit in working memory resulting in poorer accuracy and increased reaction time (Maloney et al., 2011), which has led a rise in exploration of how MA affects maths processing in the brain.

Chapter three notes that MA researchers have applied multiple methods to observe the neurophysiological processes involved in those with HMA, typically using fMRI to localise these. This has also been explored considering the anticipation of maths in high maths anxious individuals (Lyons & Beilock, 2011), as well as the activation of pain pathways (Lyons & Beilock, 2012). Whilst fMRI is excellent for identifying spatial locations for these processes, more sensitive methods can be used to analyse latency and amplitude variances. A method with excellent temporal resolution enables the identification of latency and amplitude at the same time as cognitive processing, whilst fMRI displays this with a several second delay. This severely inhibits the ability to detect processes as they happen. Indeed, it has been suggested that the use of other measures (other than fMRI) in combination with reaction time and accuracy data should be conducted in order to catalogue the timing of cognitive processes in anxious populations (Bar-Haim, Lamy, Pergamin, Bakermans-Kranenburg, & van IJzendoorn, 2007b).

Whilst there is a growing body of electrophysiological research concerning general anxiety disorders (for example, Moscovitch et al., 2011; Schmidt et al., 2012) and maths processing (for example, Fernández et al., 1995; Heine, Tamm, Wissmann, & Jacobs, 2011; Ku, Hong, Gao, & Gao, 2010) there is very little concerning MA specifically. The few in this area have focused on perception of price comparison (Jones et al., 2012) or the processing of incorrect answers (Sheffield & Hunt, 2007; Suárez-Pellicioni et al., 2013a). The present study and subsequent research aims to identify the underlying processes affecting these differences between high and low maths anxious adults, being that it affects their career and educational prospects (Ashcraft, 2002).

EEG methods are used for multiple reasons; firstly, to ascertain whether specific levels of activity in high maths anxious individuals (reduced/increased amplitude in selective regions) are comparable with poorer accuracy on these tasks. Secondly, to identify whether increased reaction time for high maths anxious individuals is comparable with delay or increased latency in electrical brain activity, compared to low maths anxious individuals. It can be assumed that complex maths tasks will not affect the processing of low maths anxious individuals to the same extent as high maths anxious individuals. Those with LMA will likely apply certain strategies to decrease reaction time, for example, adding the last one column digits in an addition sum to perceive whether the answer's last digit matched. It may be that high maths anxious individuals cannot apply this technique due to threat perception and attentional bias, as shown in previous general anxiety research (Bar-Haim et al., 2007b; Cisler & Koster, 2010; Derakshan & Eysenck, 2009; Derryberry & Reed, 1998; Janelle, 2002; Mogg, Bradley, & Hallowell, 1994; Rinck, Becker, Kellermann, & Roth, 2003; Yiend & Mathews, 2001).

The aim of this initial exploratory study was predominantly to identify whether the behavioural MA effects (reduced accuracy and increased reaction time) and neurophysiological (amplitude and latency differences) MA effects were consistent. This study had 3 objectives; (a) to compare latency differences between high and low maths anxious participants, (b) to compare amplitude differences between these MA groups, and (c) to evaluate whether these correlates map on to current behavioural research and theory.

In summary, it hypothesised that there will be significant main effects and interactions identifying the neurophysiological correlates between accuracy and amplitude, as well as reaction time and latency of ERP components. This is theorised to shed some light on the electrophysiological correlates of MA and how they differ between groups of individuals. Differences are hypothesised to elicit in *a priori* established components; P1, N1, P3 and N400 (see chapter 3). Specifically, it is hypothesised that ERP components will differ in amplitude between MA groups in relation to accuracy and that reaction time differences will appear in line in ERP component latency differences.

4.2: Method

4.2.1: Design:

The study employed a 2 (high/low MA groups) × 2 (addition/multiplication stimuli) × 3 (anterior/centre/posterior electrodes) × 3 (left/midline/right electrodes) mixed design. The between subjects independent variable (IV) was MA group and within subjects IVs included stimulus set, horizontal and vertical electrode layout. Electrical activity at electrodes acted as the dependent variable (DV).

MA scores (see section 4.2.2) and state-trait anxiety inventory (STAI: Spielberger, Gorsuch, & Lushene, 1970) scores were taken for participant selection and also in controlling for the effects of anxiety. This was implemented to observe correlations between the two measures and identify if MA exists solely, or as part of an overarching anxiety, forming part of the exploration of MA.

Secondly, *A priori* assumptions, based on previous maths research, were made for specific ERP components. A Global field power (GFP; see section 4.3.3.1) analysis was applied to ERP data to provide a global view of differences in processing. This technique assisted in refining the already theorised component latency windows. To gain a perspective across all the groups and conditions, it was conducted using an average of all participants however, to accomplish objective (a) it was clear that a comparison of latencies between high and low maths anxious participants first needed to be conducted. This was achieved by creating an average of all high and low maths anxious participants separately, applying the GFP analysis to each group and finally, identifying any differences between groups.

All 70 electrodes (including a reference, ground, 2 mastoid, 2 horizontal and 2 vertical electro-oculogram electrodes) were utilised for data acquisition and a key nine electrodes were used for analysis (T7, Cz, T8, P5, Pz, P6, O1, Oz, O2, see table 4.1). These were employed based on previous neurophysiological maths research identifying maths processing in temporal and parietal regions in adults (Barnea-Goraly, Eliez, Menon, Bammer, & Reiss, 2005; Eliez et al., 2001; Kiefer & Dehaene, 1997; Ku et al., 2010; Pinel & Dehaene, 2010; Schmithorst & Brown, 2004; Tang et al., 2006a) and children (Davis et al., 2009; Heine et al., 2011; Hyde & Spelke, 2011; Simos et al., 2008). A pilot study was conducted prior to testing to ensure stimulus presentation, lighting and procedure was adequate and followed in an appropriate manner.

Table 4.1

Layout of horizontal and vertical electrodes.

		Vertical		
		Left	Midline	Right
Horizontal	Anterior	T7	Cz	T8
	Centre	P5	Pz	P6
	Posterior	O1	Oz	O2

4.2.2: Participant Selection

A MA questionnaire and cluster analysis was used to identify and define high and low maths anxious groups for recruitment in the study. Three-hundred and six participants were recruited from the University of Derby, post-lecture, and were asked to complete the MAS-UK (Hunt et al., 2011). The MAS-UK was designed for a UK population due to the fact that there are few scales specifically intended for measuring MA in the UK and current scales used in MA research are generally designed for a North American population. Participants gave written consent and completed the MAS-UK which consisted of 23 statements answered by a five point Likert-scale about how anxious participants would feel in certain math based situations. A total MA score was calculated by assigning a value, 1 to 5, for every item (1 being ‘not at all’ to 5 being ‘very much anxious’), with the sum of these values providing the total MA score. High scores indicate high levels of MA and lower scores indicate low levels of MA. Participants were debriefed after completing the scale. This scale has been confirmed as an adequate scale to measure MA based on previously conducted factor analyses (Batashvili, 2012).

Participants were asked to complete the questionnaire pack containing the consent form, scale and debrief (see appendix ii). They were told that they may be selected for the second part of the study which involved EEG recording but were not told how they would be selected, omitted in order to avoid demand characteristic confounds. Data was collected and input into SPSS for analysis. It is not possible or relevant to measure statistical power of a cluster analysis (used to identify participant groups) much like other psychometric measures e.g. factor analysis. To distinguish a relevant sample size, the same parameters were implemented that guide adequate sampling in factor analysis. For example, Comrey & Lee, (1992) suggest that 300 participants provides a good sample size, whilst others argue that lower samples are adequate (see MacCallum, Widaman, Zhang, & Hong, 1999, for a review of factor analysis sample size). This supported the sample size adequacy above.

4.2.3: Cluster analysis

A cluster analysis was run on MAS-UK data to identify clusters of participants that possessed similar characteristics (Aldenderfer & Blashfield, 1984; Everitt, Landau, & Leese, 2001). Each individual began as a single cluster then, based on responses to several variables (Burns & Burns, 2008), analogous clusters formed their own larger clusters. An ANOVA approach was used to assess the distance between clusters, calculated through observation of the increase in the error sum of squares after two clusters combine. The analysis chose a cluster path most likely to minimise this increase (Everitt et al., 2001). The model fit is tightest to the data when the error sum of squares is at its smallest therefore, clusters continued to merge based on this principal until a number of distinct clusters remained (Clatworthy, Buick, Hankins, Weinman, & Horne, 2005). This provides a statistical representation of groups rather than using arbitrary methods, such as a median split or quartile cut-off points (see Batashvili, 2012, for a review).

A hierarchical cluster analysis indicated two clusters whereby the first was responsible for 78.8% of cases (N=241) and contained those who scored low on the MAS-UK indicating a LMA cluster. The second had 21.2% of the total sample (N=65) and contained those who scored high on the MAS-UK indicating a HMA cluster. The results provided clusters of high and low maths anxious participants however, in order to distinctly invite those with the highest and lowest levels of MA, participants were systematically selected, with scores up to 40 and down to 65, for the EEG phase of the study.

Eligible participants (based on the above criteria) were invited via email to participate in the EEG phase of the research. Thirty individuals participated, consisting of 15 HMA and 15 LMA, 10 males and 20 females (Mean age = 26.23, SD = 6.94). Participants reported normal or corrected to normal vision, were all right handed, and had not been diagnosed with dyslexia. The sample size selected for this study was informed by previous research in this area. Within ERP studies, sample sizes tend to be particularly low due to the amount of data acquired from each participant, for example, Sheffield & Hunt, (2007) gained a total of 27 participants and Suárez-Pellicioni et al. (2013) used 26. Therefore, it was deemed adequate to use 30 participants for the current research.

4.2.4: Materials and Equipment

Participants were asked to complete a consent form and then the STAI (see appendices iv, v & vi). This scale includes 40 statements describing different feelings and emotions (20 related to the individual's current feelings and 20 relating to how the individual generally feels). Participants were required to answer on a Likert scale ranging from 1 (not at all/almost never) to 4 (very much so/almost always). This scale was employed to identify whether MA correlated with state and trait anxiety and therefore, existed independently or as part of an overarching anxiety.

In order to follow previous research in this area (e.g., Prieto-Corona et al., 2010; Rousselle & Noël, 2008; Zhou et al., 2006), complex maths tasks were presented to participants in a verification style format, so as not to overload working memory by providing multiple answers. In order to compare neurophysiological and behavioural data, stimuli similar to those used in previous MA research were presented to participants. This included both complex addition and multiplication problems with either a correct or incorrect answer presented afterwards (Faust et al., 1996; Kellogg, Hopko, & Ashcraft, 1999a). These were applied based on stimuli used in previous behavioural MA research (Ashcraft & Kirk, 2001; Ashcraft & Krause, 2007; Faust et al., 1996) as well as their use in neurophysiological maths processing research (Davis et al., 2009; De Smedt et al., 2009; Fernández et al., 1995; Jost, Hennighausen, & Rösler, 2004; Kawashima et al., 2004; Tang et al., 2006a; Zhang et al., 2012; Zhou et al., 2006). Answers were also presented alongside problems in order to avoid keeping the problem in short-term memory as a target whilst calculating. This would have otherwise increased the amount of working memory resources allocated to the task, decreasing the amount left for the primary task. Due to multiplication answers being considerably larger than addition answers, production of the solutions may have involved higher levels of processing for multiplication (Zhou et al 2009). Researchers have noted that the use of verbal production tasks involve tongue and muscle movement which add artefacts to EEG recordings (e.g., Galfano et al., 2004; Niedeggen and Rosler, 1999; Szücs and Csépe, 2004) however, the use of verification helps to minimise these problem as much as possible. The task used the standard, rather than delayed verification parameters. Zhou et al. (2009) note that in the standard verification task, when operands and answers are simultaneously presented, plausibility judgement may be used by participants (e.g., Campbell and Tarling, 1996; Lemaire and Fayol, 1995) for example, the further an answer is from the correct response, the easier it becomes to distinguish. To minimise this, false answers were always very close to the true answers (plus or minus 1-10) ensuring that the correct answer was not clearly identifiable at first glance.

Two hundred maths equations; 100 complex two by two digit addition (e.g. 24+35=59) and 100 complex two by one digit multiplication (e.g. 23×3=68) were presented to participants in a random order to avoid complacency with conditions. ERP methods were used so a large number of stimuli were presented in each condition as large number of trials are needed to provide an adequate signal-to-noise ratio (at least 60; Huffmeijer, Bakermans-Kranenburg, Alink, & van IJzendoorn, 2014). Complex addition tasks were defined by using double digit addition and the need to implement a carry operation (Faust et al., 1996; Wu, Amin, Barth, Malcarne, & Menon, 2012). Complex multiplication was defined by using a one by two digit problem (Tronsky, 2005). Multiplication problems with 0 and 1 as a single digit operand (e.g. 23×1) were not used as they would act as simple rule-based problems (LeFevre et al., 1996).

NeuroScan SynAmps² was used to acquire and process EEG and ERP data (Neurosoft, Inc. Sterling, USA). This system consisted of a 70 channel amplifier and head box, PC, an isolator (to separate any mains electricity from all attached equipment) and compatible NeuroScan software. One of the advantages of this was the active noise cancelation which enables accurate recording of EEG data. Finally, a 64 channel Quik-Cap with Silver-Silver Chloride Sintered electrodes was used to acquire data. All electrodes in the cap were arranged according to the international 10-20 electrode placement standards. An outline of the electrode positions including analysis sites are shown in figure 4.1.

4.2.5: Procedure

Participants were emailed with the required information (see appendix iii) and asked to arrive at the university at a mutually agreed time. The researcher explained the consent (see appendix iv) and study procedure, including timing of the study.

Participants were seated in a dimly lit room whilst black stimuli (font size 64) were presented on a white background. Luminance levels were measured from the visual display unit (90.0 candela per square metre (cd/m^2)) distanced at 72cm at eye height with the centre of the screen.

This was mainly to ensure that light changes did not affect ERP components, for example, light changes can indirectly increase the amplitude of the P300 (Polich & Kok, 1995). Participants were sat in a comfortable chair at eye height to the centre of the screen. They were asked to verify if answers, presented with stimuli, were correct or incorrect and to answer with their dominant hand by pressing either the first or second button on a button box. Each stimulus was presented for 2000ms with a response window of 5000 followed by a fixation with a duration of 500ms. Inter trial intervals were pseudo randomised between 500ms and 2000ms to avoid habituation.

A small area of skin on the back of participant's hand was used to test for any allergic reaction to either the electrolyte gel (used to bridge the gap between the scalp and the cap) or alcohol rub (used to reduce sebum layer and improve impedances). Participant's heads were then measured from naison to inion, ear to ear and head circumference to allow appropriate fitting of the cap. Participants were asked to brush their scalp with a hairbrush in order to break down the sebum layer and aid reduction of impedance. An alcohol rub was applied to cotton wool and run through participant's scalp, at vertical and horizontal elctrooculogram (VEOG and HEOG) eye positions and mastoid locations to also reduce impedance. The upper forehead served as a ground, two channels were placed at the outer canthi of both eyes to record the horizontal electro-oculogram (HEOG), and another two channels above and below the left eye for vertical electro-oculogram (VEOG), using adhesive electrode collars. Neuroscan Quik-Gel conductive gel was placed into a 5ml syringe with a blunt applicator/needle attached. Each electrode was filled whilst holding it in place to avoid bridging of the gel solution to multiple electrodes. Small cotton tipped applicators were used to lower impedance at each electrode site. Impedances were kept below 15 kiloohms (kΩ) but were typically less than 5kΩ and the sampling rate was 1000Hz. Participants were informed when the study would begin and that they should try to remain fairly still whilst focusing on the task. Data was recorded using NeuroScan Acquire and then transferred to the Edit PC for offline processing.

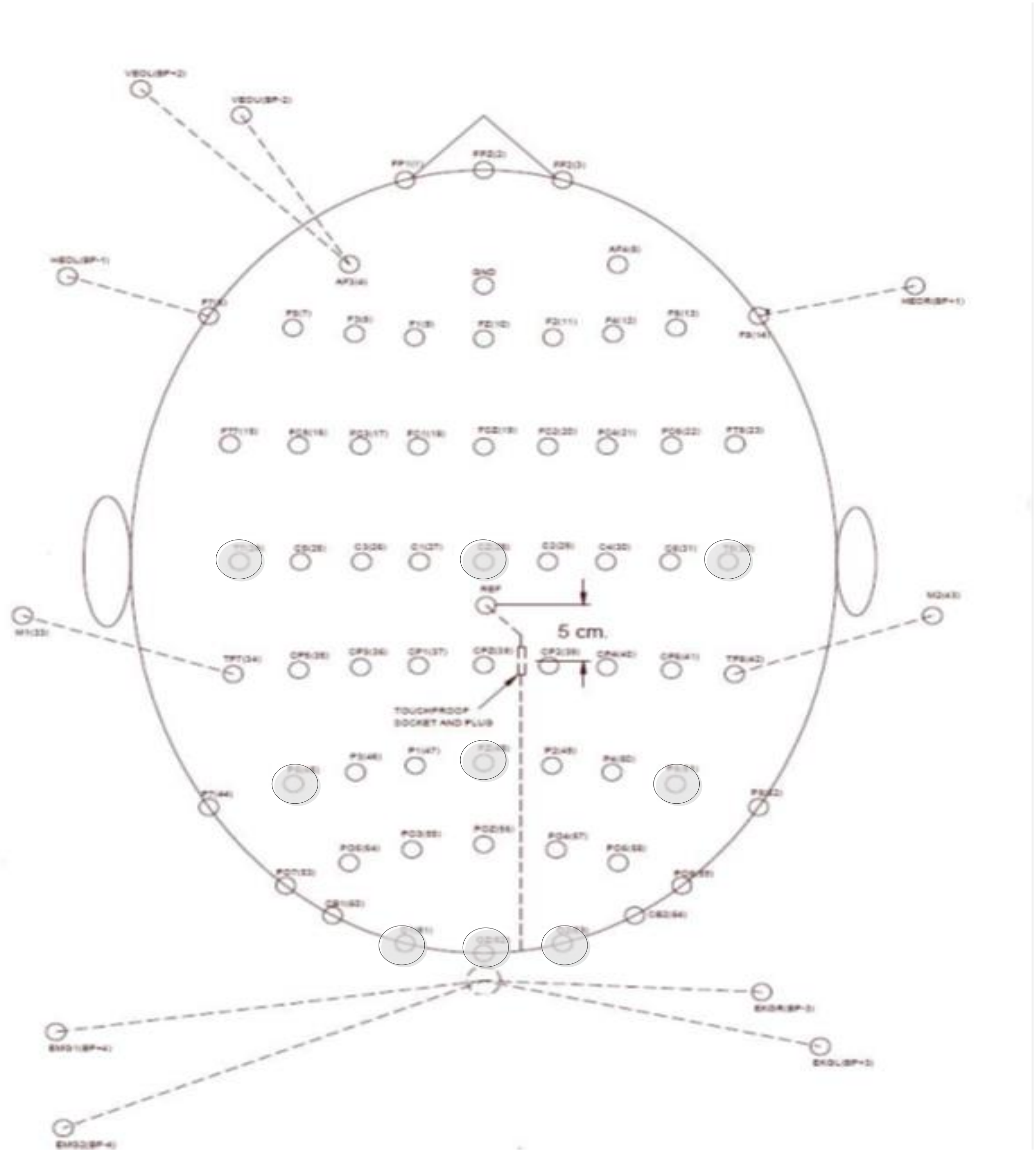

Figure 4.1: Neuroscan Synamps 64 channel Quik-Caps Electrode layout with sites used for analysis highlighted

4.3: Results

4.3.1: Analytical strategy

The results are split into two stages: The first (section 4.3.2) comprises behavioural data including MA and state and trait anxiety correlations, accuracy and reaction time. A Spearman's rho correlation was conducted to analyse correlations between MAS-UK scores and STAI scores to identify whether MA exists solely or as a factor in an overarching anxiety. Mixed factorial ANOVAs were also used to measure differences in accuracy and reaction time across MA groups and conditions. This was conducted to identify whether the behavioural effects (reduced accuracy and increased reaction time), typically found in high maths anxious individuals, occurred in this study.

The second stage (section 4.3.3) comprises ERP data preparation, processing and analysis: Based on *a priori* assumptions from previous research, four components (P1, N1, P3 and N400) were each analysed using a mixed factorial ANOVA to identify significant interactions and main effects between condition, MA group and horizontal and vertical electrodes.

4.3.2: Analysis of correlation, accuracy and reaction time data

Correlations

Data showed significant kurtosis therefore, a Spearman's rho correlation was used to look at the relationship between MAS-UK and STAI scores. There was a weak, positive but non-significant correlation between MA and state anxiety scores (r(28)=.26, p=.164) and MA and trait anxiety scores (r(28)=.27, p=.149). The lack of a significant relationship supports that MA is not correlated to state and trait anxiety scores.

Accuracy and Reaction time

Data was screened prior to analysis and was found to be normally distributed. Two 2 (High/Low MA) × 2 (addition/multiplication stimuli) mixed factorial ANOVAs were run to identify any interactions between accuracy and reaction time for responses.

Accuracy

There was a significant main effect of stimulus type ($F_{(1,28)}$ = 125.86, p<.001 η^2=.82), such that accuracy for addition was significantly higher than multiplication. There was also a significant main effect of MA ($F_{(1,28)}$ = 15.25, p=.001 η^2=.03), such that those with HMA had significantly poorer accuracy overall than those with LMA. There was no significant interaction between MA and stimulus type ($F_{(1,28)}$ = .48, p=.493 η^2=.003).

Reaction time

There was no significant main effect of stimulus type ($F_{(1,28)}$ = 1.42, p=.243, η^2=.04) however, there was a significant main effect of MA ($F_{(1,28)}$ = 16.39, p<.001 η^2=.36), such that those with HMA took significantly longer to answer than those with LMA. There was no significant interaction between MA and stimulus type ($F_{(1,28)}$ = 2.49, p=.126, η^2=.08).

Table 4.2:

Mean (SD) accuracy and reaction time scores between high and low MA groups.

	Maths Anxiety Group			
	Stimulus Type	**High**	**Low**	**Total**
Accuracy	Addition	59.40 (22.43)	84.53 (16.42)	71.97 (23.17)
	Multiplication	41.73 (16.96)	64.53 (12.40)	53.13 (18.64)
Reaction Time (ms)	Addition	3562 (496)	2578 (719)	3070 (787)
	Multiplication	3539 (621)	2747 (636)	3143 (737)

In summary, accuracy was higher overall for addition and high maths anxious groups performed significantly poorer overall. Reaction time was not significantly different for addition or multiplication and high maths anxious individuals performed significantly slower than low maths anxious individuals.

4.3.3: ERP processing and analysis

4.3.3.1 ERP preparation and processing

NeuroScan Edit (Version 4.5) was used to process the data offline. The following explains the data processing procedure, conducted using a BATCH file written by the researcher (see appendix vii for an example), for each individual and condition. Data was first re-referenced from a central reference to the linked mastoids, to conform to Luck's (2005) three key factors (see appendix i for reference site justification) and previous maths processing research (Heine et al., 2011; Paulsen, Woldorff, & Brannon, 2010; Prieto-Corona et al., 2010; Wang et al., 2007; Zhang et al., 2012; Zhou et al., 2006). The positive trigger threshold for ocular artefacts was set to 10% with the minimum number of sweeps required to construct an averaged VEOG artefact being 30. The duration of the average artefacts was 400ms. After the correction of ocular artefacts, data was filtered with a band pass (zero-phase, 24 dB/octave), then epoched to an appropriate length, (800ms in total) to encompass relevant ERP components, with all epochs containing a 100ms pre-stimulus interval serving as the baseline correction period. EEG was then baseline-corrected and epochs exceeding a range of −75 to +75 mV (at all channels excluding HEOG, VEOG and mastoid electrodes) were rejected as artefacts. These were also verified manually to identify any anomalies in the data unrecognised by the artefact rejection process. The remaining trials were averaged for each condition.

Global field power (GFP) was used specifically to classify the average strength of electrical activity over the scalp (Yamada et al., 2004) This method functions by measuring the standard deviation (SD) from each electrode to every other electrode and reporting the differences across the latency. Whilst this is not a perfect method, as electrodes do not span the whole head or the shape of a brain, this is the most impartial method of identifying maxima and minima as it is not influenced by condition or group. The results present how the "field strength of a map series varies over time, and its maximum value in a predetermined time window can be used in order to determine evoked component latency" (Skrandies, 1995, p.4). This enabled validation of *a priori* assumptions concerning predetermined ERP components. To accurately identify maxima, all ERPs (between conditions and groups) were averaged together to create an overall, average ERP of the group. This was conducted so that bias was eliminated towards any condition or participant group. GFP analysis was then conducted on this average to identify peaks across the latency. There was no observable latency difference between groups or conditions therefore, the onset and offset of these peaks were used as the parameters when analysing mean amplitude on each individual ERP across participants and conditions. The global field power calculation is outlined below (Lehmann & Skrandies, 1984):

$$GFP = \sqrt{\frac{1}{2n} \sum_{i=1}^{n} \sum_{j=1}^{n} \left(U_i - U_j\right)^2}$$

To analyse amplitude of components, the onset and offset was taken and the amplitude within this area was averaged. This method is supported by previous research (Picton et al., 2000) however, since defining the onset and offset of individual components is subjective, *a priori* assumptions and GFP were used to inform identification of components based on research outlined in chapter 3. This presented the emergence of four components; with P1 identified between 54-97ms, N1 at 98-198ms, P3 at 204-250ms and N400 at 280-350ms (see figure 4.2), which are in line with previous research (see chapter 2.3.2).

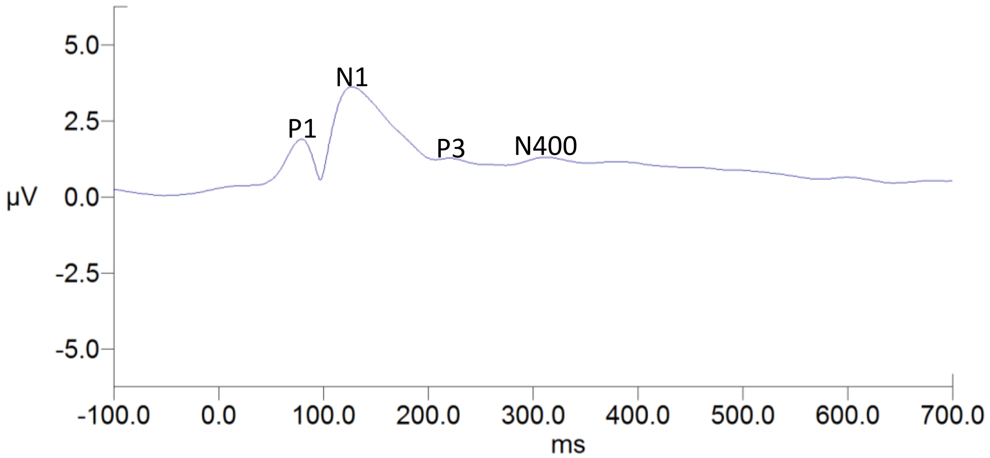

Figure 4.2: Positive peaks in GFP analysis representative of components and latencies across average epoch

Component windows were extracted from relevant electrodes acting as the DVs (T7, Cz, T8, P5, Pz, P6, O1, Oz, O2) and four 2 (High/Low MA group) × 2 (addition/multiplication stimuli) × 3 (anterior/centre/posterior electrodes) × 3 (left/midline/right electrodes) mixed factorial ANOVAs were used to identify any interactions and main effects. These were conducted separately for the four components. All ANOVAs included the Greenhouse-Geisser correction to ensure type I error rates were not inflated (Greenhouse & Geisser, 1959) being that neurophysiological data is rarely homogenous.

Motor interference

To ensure that motor processing (using the button box to answer tasks) did not interfere with analysis of maths processing, reaction times were explored and compared to previous research. Signs of motor processing (readiness potentials) were identified at around 800ms prior to movement in early research (Kornhuber & Deecke, 1965) and have subsequently been identified closer to movement depending on experimental design. These potentials have been found as early as 400ms before processing, if the movement is paced by the individual at a rate of 5 seconds or longer (Shibasaki & Hallett, 2006). However, due to the earliest response average of 2662ms (LMA group) and an averaged epoch of 700ms (post-stimulus onset), readiness potentials would not interfere with components associated with maths processing. The earliest identification of these potentials would be, on average, at 1800ms onwards post-stimulus onset, which permitted the analysis of ERP component amplitudes.

4.3.3.2 ERP amplitude analysis

This section will state each component analysis identifying and tabulating main effects and interactions. Alongside summaries, topographical maps are used illustrating positive inflections highlighted in red and negative in blue. Translucent shapes highlight the dipoles averaged over component latencies.

P1 Component Amplitude Analysis

The results display the findings of the P1 amplitude, explaining the overall analysis, interactions and finally, main effects (see table 4.3).

Table 4.3:

*P1 ANOVA F values, degrees of freedom, significance levels and effect size (Ƞ²) for amplitude interactions and main effects.**

Interaction / Main Effect	**ANOVA**			
	F	***df***	***p***	***Ƞ²***
Horizontal x Vertical x Stim x MA	.32	2.67,74.73	.787	8.40×10^{-5}
Horizontal x Vertical x Stim	.79	2.67,78.27	.492	2.02×10^{-4}
Vertical x Stim x MA	.11	1.76,49.16	.866	4.82×10^{-5}
Horizontal x Stim x MA	.98	1.46,40.88	.362	4.62×10^{-4}
Horizontal x Vertical x MA	.91	3.36,94.16	.451	.002
Vertical x Stim	.09	1.75, 50.85	.896	3.40×10^{-5}
Horizontal x Stim	1.77	1.44,41.85	.190	8.38×10^{-4}
Horizontal x Vertical	14.72	3.36,97.47	<.001	.03
Stim x MA	5.68	1,28	.024	.009
Vertical x MA	1.02	1.90, 53.32	.355	.005
Horizontal x MA	.46	1.36,38.13	.560	.004
Vertical	24.56	1.87, 54.70	<.001	.14
Horizontal	15.29	1.39, 40.30	<.001	.15
Stim	3.59	1,29	.356	.03
MA	.79	1,28	.383	.001

*significant main effects and interactions are highlighted.

The 3×3×2×2 model showed no significant interaction between horizontal, vertical electrodes, stimulus type and MA group. There was no significant interaction between stimulus type, horizontal and vertical electrodes. Similarly, there was no significant interaction between horizontal, vertical electrodes and maths anxiety group. There was no significant interaction between maths anxiety group, stimulus type and horizontal electrodes or between maths anxiety group, stimulus type and vertical electrodes.

There was a significant interaction found between maths anxiety group and stimulus type, such that those with HMA exhibited a lower P1 amplitude (Mean = -1.24, SD = 1.33) than those with LMA (Mean = -.43, SD = 1.31) during addition processing. However, there was no significant interaction between maths anxiety group and horizontal electrodes and maths anxiety group and vertical electrodes. It was also found that there was no significant interaction between stimulus type and horizontal electrodes and stimulus type and vertical electrodes.

There was a significant interaction of horizontal and vertical electrodes, whereby higher P1 amplitudes were found in posterior left (Mean = .90, SD = 2.16) and right (Mean = .28, SD = 2.67) regions than anterior midline (*see figure 4.3*). There was no significant main effect of maths anxiety groups or stimulus type. However, there was a significant main effect of horizontal electrodes, whereby higher P1 amplitudes were exhibited at posterior (Mean = .26, SD = 2.35) than at centre (Mean = -.81, SD = 2.61) and anterior (Mean = -1.71, SD = 1.62) sites (see figure 4.3). There was also a significant main effect of vertical electrodes such that higher amplitudes were exhibited at right (Mean = -.13, SD = 2.00) and left (Mean = -.31, SD = 2.41) electrodes than at midline sites (Mean = -1.82, SD = 2.31) (see figure 4.3).

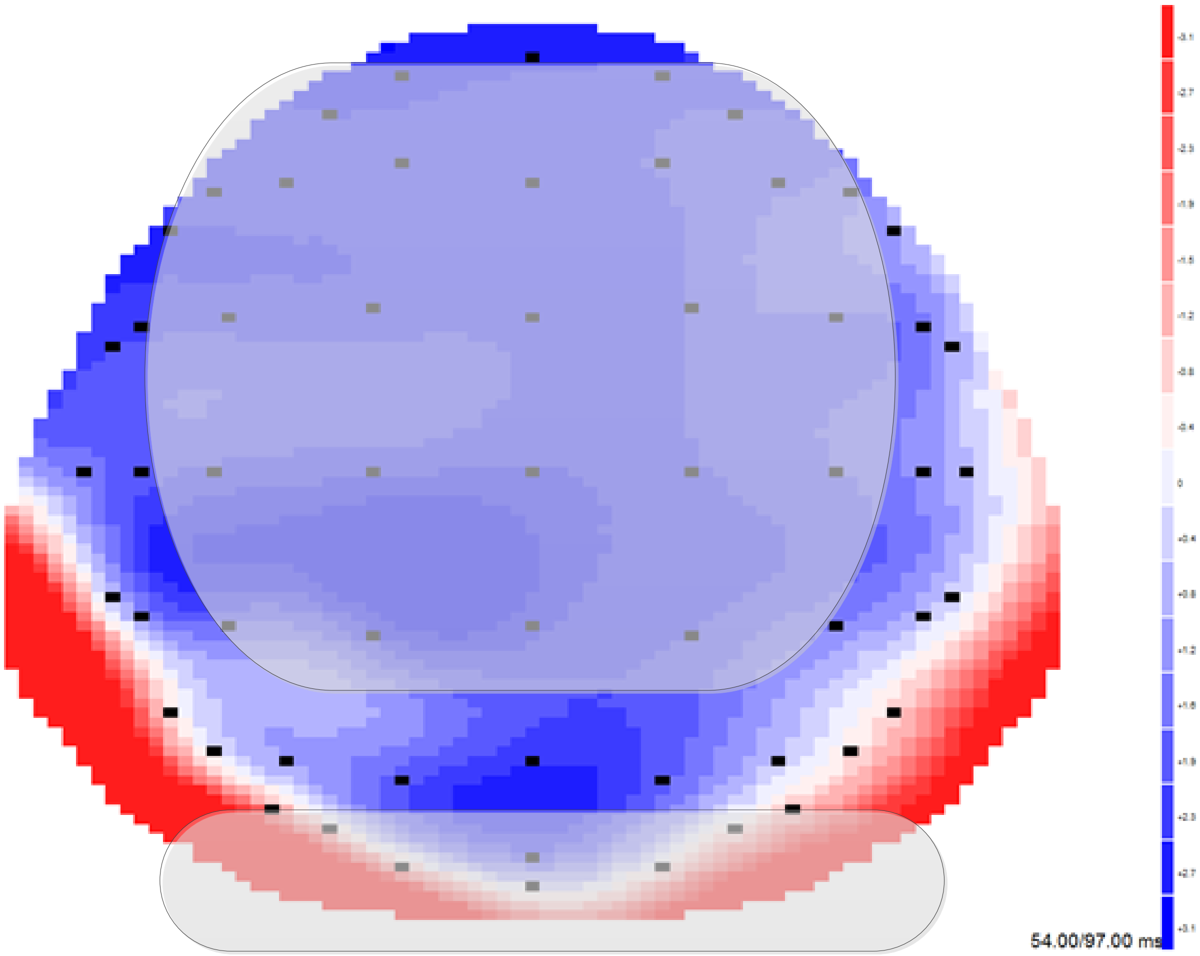

Figure 4.3: Topographic map of electrodes showing differences between horizontal and vertical sites at P1 component (54-97ms)

N1 Component Amplitude Analysis

The results display the findings of the N1 amplitude, explaining the overall analysis, interactions and finally, main effects (see table 4.4).

Table 4.4:

N1 ANOVA F values, degrees of freedom, significance levels and effect size for amplitude interactions and main effects.

Interaction / Main Effect	**ANOVA**			
	F	***df***	***p***	η^2
Horizontal x Vertical x Stim x MA	.62	2.86, 80.01	.599	9.72×10^{-5}
Horizontal x Vertical x Stim	2.69	2.85, 82.61	.054	4.19×10^{-5}
Vertical x Stim x MA	1.64	1.44,40.21	.210	4.88×10^{-4}
Horizontal x Stim x MA	.12	1.62,45.36	.850	1.88×10^{-5}
Horizontal x Vertical x MA	.93	3.45,96.71	.439	4.19×10^{-4}
Vertical x Stim	1.81	1.41, 40.91	.184	5.51×10^{-4}
Horizontal x Stim	.16	1.17, 46.93	.804	2.55×10^{-5}
Horizontal x Vertical	14.80	3.45,100.01	<.001	.03
Stim x MA	4.45	1,28	.044	.003
Vertical x MA	1.33	1.99,55.61	.219	8.41×10^{-4}
Horizontal x MA	1.49	1.36,38.05	.237	.01
Vertical	33.43	1.99, 57.65	<.001	.12
Horizontal	42.07	1.34, 38.97	<.001	.37
Stim	.29	1,29	.594	2.37×10^{-4}
MA	1.43	1,28	.242	.04

The 3×3×2×2 model showed no significant interaction between horizontal, vertical electrodes, stimulus type and maths anxiety group. There no significant interaction between stimulus type, horizontal and vertical electrodes or between horizontal, vertical electrodes and maths anxiety group. There was also no significant interaction between maths anxiety group, stimulus type and horizontal electrodes. Equally, there was no significant interaction between maths anxiety group, stimulus type and vertical electrodes.

There was no significant interaction between maths anxiety group and horizontal electrodes and maths anxiety group and vertical electrodes. There was also no significant interaction between stimulus type and horizontal electrodes and stimulus type and vertical electrodes. There was a significant interaction between maths anxiety group and stimulus type, such that N1 amplitudes were higher for those with LMA, particularly during multiplication (Mean = -.27, SD = 3.01) than those with HMA (Mean = .73, SD = 2.79). Those with HMA also showed a higher N1 amplitude for addition (Mean = .53, SD = 2.84) than for multiplication (Mean = .73, SD = 2.79).

There was also a significant interaction of horizontal and vertical electrodes, whereby a higher N1 amplitude was identified at left and right posterior regions than anterior midline (see table 4.5). Figure 4.5 outlines ERP differences between MA groups across all electrodes and the full ERP latency (-100 – 700ms).

Table 4.5:

N1 mean amplitude (mv) and standard deviation depicting the interaction between horizontal and vertical electrodes.

	Vertical Electrodes		
Horizontal Electrodes	Left	Midline	Right
Anterior	1.85 (1.48)	3.86 (2.66)	0.87 (1.64)
Centre	-0.11 (2.56)	1.22 (2.83)	-1.26 (2.12)
Posterior	-1.57 (2.63)	-0.87 (2.38)	-1.56 (2.31)

There was no overall significant main effect of maths anxiety groups or stimulus type however, there was a significant main effect of horizontal electrodes such that a higher N1 amplitude was exhibited at posterior electrodes (mean = -1.33, SD = 2.45) than at centre (mean = -.05, SD = 2.70) and anterior sites (mean = 2.19, SD = 2.35). There was also a significant main effect of vertical electrodes such that a higher N1 amplitude was exhibited in right (mean = -.66, SD = 2.30) and left (mean = .05, SD = 2.67) regions than at midline sites (mean = 1.40, SD = 3.26) (see figure 4.4).

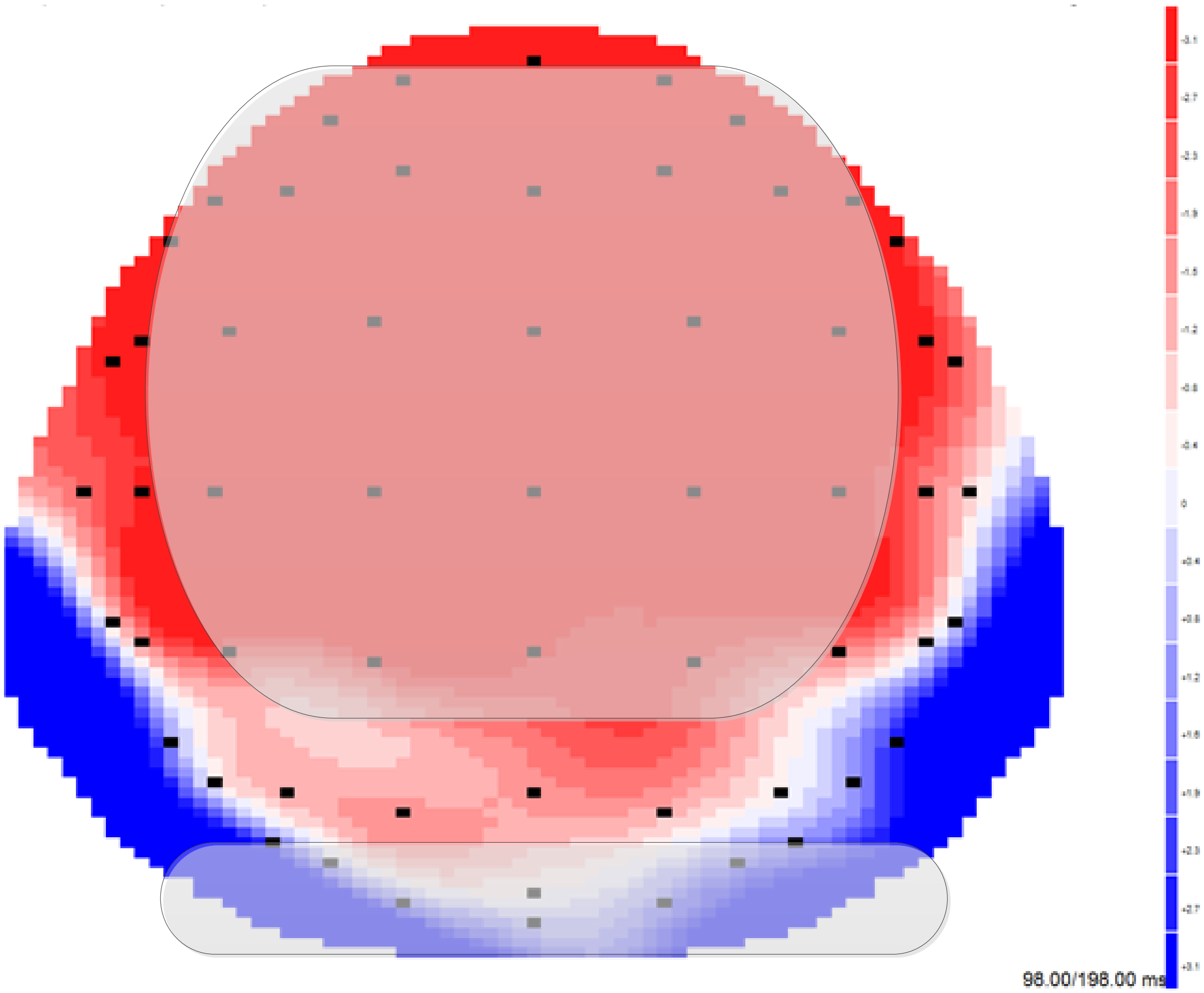

Figure 4.4: Topographic map of electrodes showing the differences between horizontal and vertical sites used for the N1 component (98-198ms)

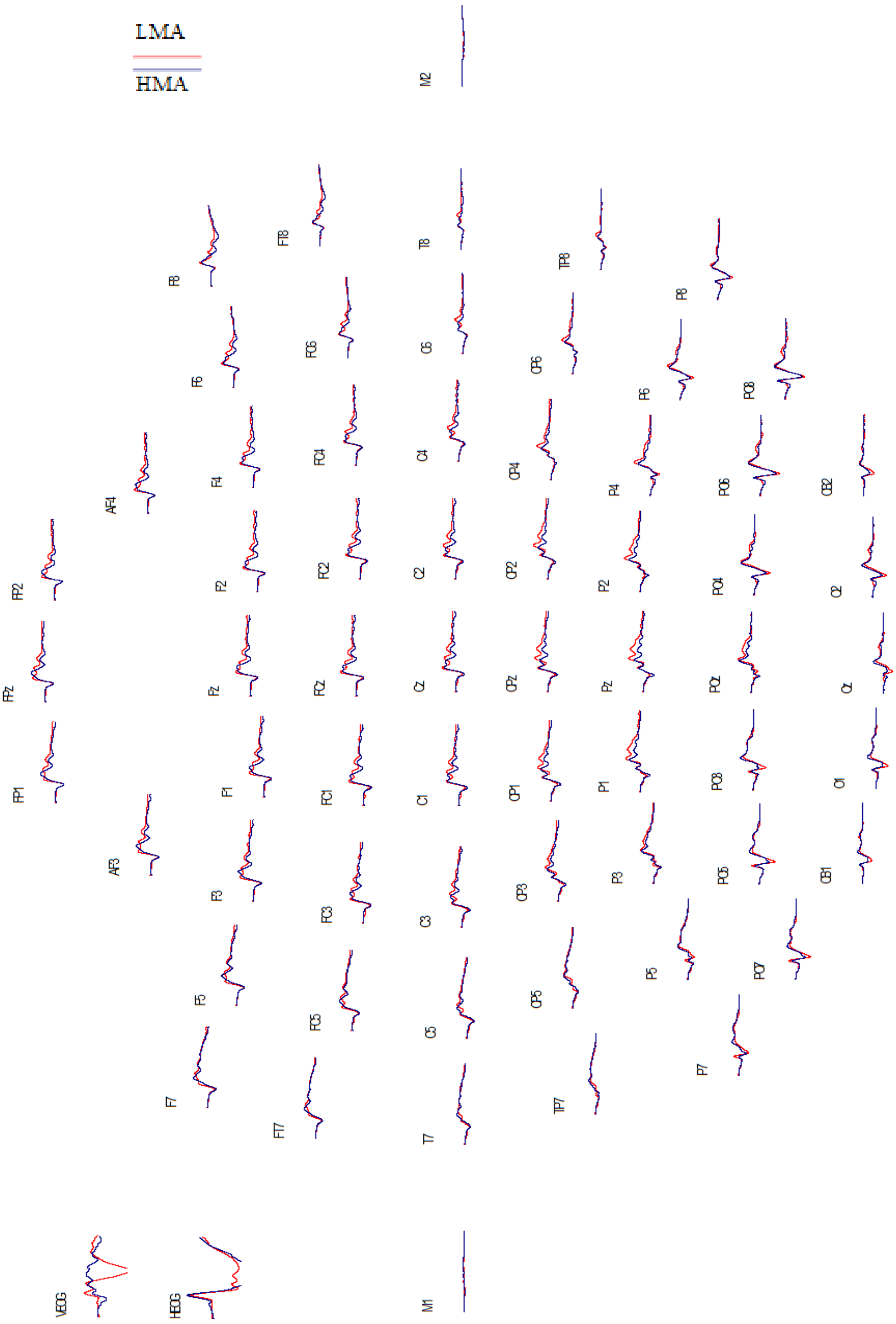

Figure 4.5: Scalp ERP differences across all electrode sites between high and low MA groups from -100ms (pre-stimulus onset) to 700ms (post-stimulus onset).

P3 Component Amplitude Analysis

The results display the findings of the P3 amplitude, explaining the overall analysis, interactions and finally, main effects (see table 4.6).

Table 4.6:

P3 ANOVA F values, degrees of freedom, significance levels and effect size for amplitude interactions and main effects.

Interaction / Main Effect	**ANOVA**			
	F	***df***	***p***	***η²***
Horizontal x Vertical x Stim x MA	.30	2.77, 77.52	.877	8.01×10^{-5}
Horizontal x Vertical x Stim	1.75	2.78, 80.66	.002	.001
Vertical x Stim x MA	.33	1.54,43.18	.665	1.49×10^{-4}
Horizontal x Stim x MA	.23	1.55,43.25	.735	5.39×10^{-5}
Horizontal x Vertical x MA	3.31	2.76,77.35	.028	.01
Vertical x Stim	1.62	1.54, 44.67	.212	7.21×10^{-4}
Horizontal x Stim	5.88	1.51, 45.00	.009	.001
Horizontal x Vertical	19.34	2.74,79.32	<.001	.08
Stim x MA	.82	1,28	.374	.001
Vertical x MA	5.44	1.80, 50.49	.009	.02
Horizontal x MA	2.00	1.33, 37.13	.144	.02
Vertical	1.15	1.73, 50.25	.319	.10
Horizontal	7.56	1.34, 38.90	.005	.10
Stim	1.81	1,29	.190	.003
MA	.36	1,28	.556	.01

The 3×3×2×2 analysis showed no significant interaction between horizontal, vertical electrodes, stimulus type and maths anxiety group. There was a significant interaction between stimulus type, horizontal and vertical electrodes, such that the higher P3 amplitudes were shown in right posterior electrodes during multiplication (see table 4.7). There was also a significant interaction between horizontal, vertical electrodes and maths anxiety group, such that those with LMA exhibited a higher P3 amplitude in left anterior electrodes than those with HMA (see table 4.8). There was no significant interaction between maths anxiety group, stimulus type and horizontal electrodes. There was no significant interaction between maths anxiety group, stimulus type and vertical electrodes.

Table 4.7:

P3 mean amplitude (mv) and standard deviation depicting the interaction between horizontal electrodes, vertical electrodes and stimulus type.

		Stimulus Type	
Horizontal	**Vertical**	**Addition**	**Multiplication**
Anterior	Left	3.70 (2.04)	3.09 (1.97)
	Midline	4.00 (3.14)	3.30 (3.10)
	Right	1.13 (2.53)	1.16 (2.36)
Central	Left	4.42 (3.07)	4.25 (3.04)
	Midline	4.87 (3.50)	4.21 (3.70)
	Right	5.22 (3.33)	4.91 (3.45)
Posterior	Left	2.89 (3.23)	3.02 (3.46)
	Midline	3.28 (3.11)	3.25 (3.44)
	Right	3.95 (3.38)	3.78 (3.60)

Table 4.8:

P3 mean amplitude (mv) and standard deviation depicting the interaction between horizontal electrodes, vertical electrodes and MA group.

		MA group	
Horizontal	**Vertical**	**High**	**Low**
Anterior	Left	3.35 (2.04)	3.45 (2.02)
	Midline	2.49 (2.69)	4.81 (3.11)
	Right	.48 (2.18)	4.82 (2.51)
Central	Left	4.63 (2.44)	4.04 (3.54)
	Midline	3.22 (3.52)	5.86 (3.20)
	Right	4.81 (2.89)	5.32 (3.82)
Posterior	Left	3.34 (2.83)	2.57 (3.76)
	Midline	3.57 (2.90)	2.96 (3.59)
	Right	4.11 (3.43)	3.62 (3.54)

There was no significant interaction between maths anxiety group and horizontal electrodes however, there was a significant interaction between maths anxiety group and vertical electrodes, such that those with LMA had a significantly higher P3 amplitude (mean = 4.55, SD = 3.48) at midline electrodes than those with HMA (mean = 3.09, SD = 3.05). It was also found that there was a significant interaction between stimulus type and horizontal electrodes, such that higher P3 components were identified in anterior electrodes for addition (mean = 2.95, SD = 2.89) than for multiplication (mean = 2.51, SD = 2.68). There was no significant interaction between stimulus type and vertical electrodes.

There was a significant interaction between horizontal and vertical electrodes. Higher P3 amplitudes were identified at centre electrodes (parietal region) in left hemisphere as well as parietal sites in both hemispheres (see table 4.9). However, there was no significant interaction between maths anxiety group and stimulus type. Similarly, there was no overall significant main effect of maths anxiety groups or stimulus type. There was a significant main effect of horizontal electrodes, such that a higher P3 amplitude was exhibited at centre electrodes (mean = 4.65, SD = 3.33) than at posterior (mean = 3.36, SD = 3.35) and anterior sites (mean = 2.73, SD = 2.78). There was no significant main effect of vertical electrodes.

Table 4.9:

P3 mean amplitude (mv) and standard deviation depicting the interaction between horizontal and vertical electrodes.

	Vertical Electrodes		
Horizontal Electrodes	Left	Midline	Right
Anterior	3.65 (3.11)	1.15 (2.43)	4.33 (3.03)
Centre	4.54 (3.59)	5.07 (3.37)	2.95 (3.32)
Posterior	3.27 (3.25)	3.86 (3.47)	3.10 (1.97)

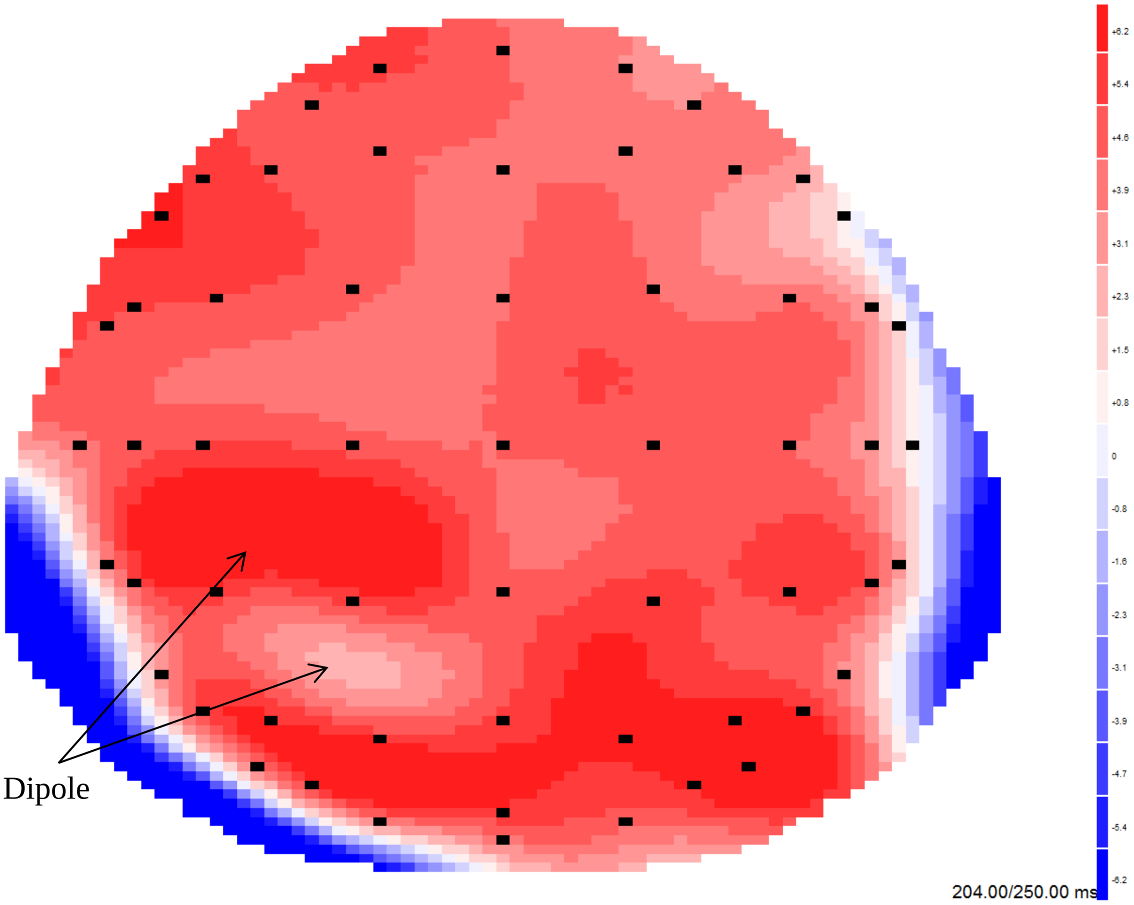

Figure 4.6: Topographic map of electrodes showing the differences between horizontal and vertical sites (204-250ms) used for the P3 component, specifically highlighting a dipole in the left hemisphere.

N400 Component Amplitude Analysis

The results display the findings of the N400 amplitude, explaining the overall analysis, interactions and finally, main effects (see table 4.10).

Table 4.10:

N400 ANOVA F values, degrees of freedom, significance levels and effect size for amplitude interactions and main effects.

Interaction / Main Effect	**ANOVA**			
	F	***df***	***p***	η^2
Horizontal x Vertical x Stim x MA	.33	2.73, 76.32	.787	8.81×10^{-5}
Horizontal x Vertical x Stim	.72	2.75, 80.01	.530	1.90×10^{-3}
Vertical x Stim x MA	.20	1.78,46.70	.794	8.39×10^{-5}
Horizontal x Stim x MA	.12	1.63,45.60	.843	5.44×10^{-5}
Horizontal x Vertical x MA	4.06	3.11,87.18	.009	.01
Vertical x Stim	1.93	1.77,51.36	.154	7.87×10^{-4}
Horizontal x Stim	.50	1.63,47.22	.569	2.16×10^{-4}
Horizontal x Vertical	16.71	2.83,82.12	<.001	.07
Stim x MA	4.16	1,28	.051	.01
Vertical x MA	3.93	1.84, 51.49	.029	.03
Horizontal x MA	.52	1.39,38.79	.532	.004
Vertical	17.85	1.86,53.97	<.001	.13
Horizontal	14.22	1.42, 41.12	<.001	.11
Stim	1.49	1,29	.233	.05
MA	1.00	1,28	.326	.002

The 3×3×2×2 analysis showed no significant interaction between horizontal, vertical electrodes, stimulus type and maths anxiety group. There was no significant interaction between stimulus type, horizontal and vertical electrodes. However, there was a significant interaction between horizontal, vertical electrodes and maths anxiety group, such that those with HMA exhibited higher N400 amplitudes in central and midline electrodes than those with LMA (see table 4.11). There was no significant interaction between maths anxiety group, stimulus type and horizontal electrodes or between maths anxiety group, stimulus type and vertical electrodes.

Table 4.11

N400 mean (SD) amplitude (mV) depicting the interaction between horizontal electrodes, vertical electrodes and MA group.

		MA group	
Horizontal	**Vertical**	**High**	**Low**
Anterior	Left	2.83 (2.03)	2.88 (1.92)
	Midline	2.32 (2.79)	3.82 (2.31)
	Right	-.33 (1.80)	.20 (1.90)
Central	Left	3.49 (1.63)	3.70 (2.01)
	Midline	2.47 (3.20)	5.32 (3.17)
	Right	2.25 (1.98)	2.16 (2.21)
Posterior	Left	1.66 (1.88)	1.73 (2.21)
	Midline	1.39 (1.72)	1.89 (2.16)
	Right	1.24 (2.00)	1.65 (2.29)

There was no significant interaction between maths anxiety group and horizontal electrodes however; there was a significant interaction between maths anxiety group and vertical electrodes. Those with HMA had a significantly higher N400 amplitude at midline electrodes (Mean = 2.06, SD = 2.66) than those with LMA (Mean = 3.68, SD = 2.92). There was no significant interaction between stimulus type and horizontal electrodes and stimulus type and vertical electrodes.

There was a significant interaction between horizontal and vertical electrodes such that higher N400 amplitudes were identified at anterior and posterior sites in the right hemisphere (see table 4.12). There was no significant interaction between maths anxiety group and stimulus type. There was no overall significant main effect of maths anxiety groups or stimulus type. There was a significant main effect of horizontal electrodes such that a higher N400 amplitude was exhibited at anterior (mean = 1.95, SD = 2.60) and centre sites (mean = 1.59, SD = 2.04) than at centre electrodes (mean = 3.20, SD = 2.65). There was also a significant main effect of vertical electrodes, such that higher N400 amplitudes were exhibited at midline sites (mean = 1.20, SD = 2.23) than at right (mean = 2.72, SD = 2.08) and left (mean = 2.87, SD = 2.90) sites.

Table 4.12:

N400 mean amplitude (mv) and standard deviation depicting the interaction between horizontal and vertical electrodes.

	Vertical Electrodes		
Horizontal Electrodes	Left	Midline	Right
Anterior	2.85 (1.96)	3.06 (2.65)	-.06 (1.86)
Centre	3.60 (1.82)	3.90 (3.47)	2.21 (2.08)
Posterior	1.70 (2.03)	1.63 (1.96)	1.45 (2.14)

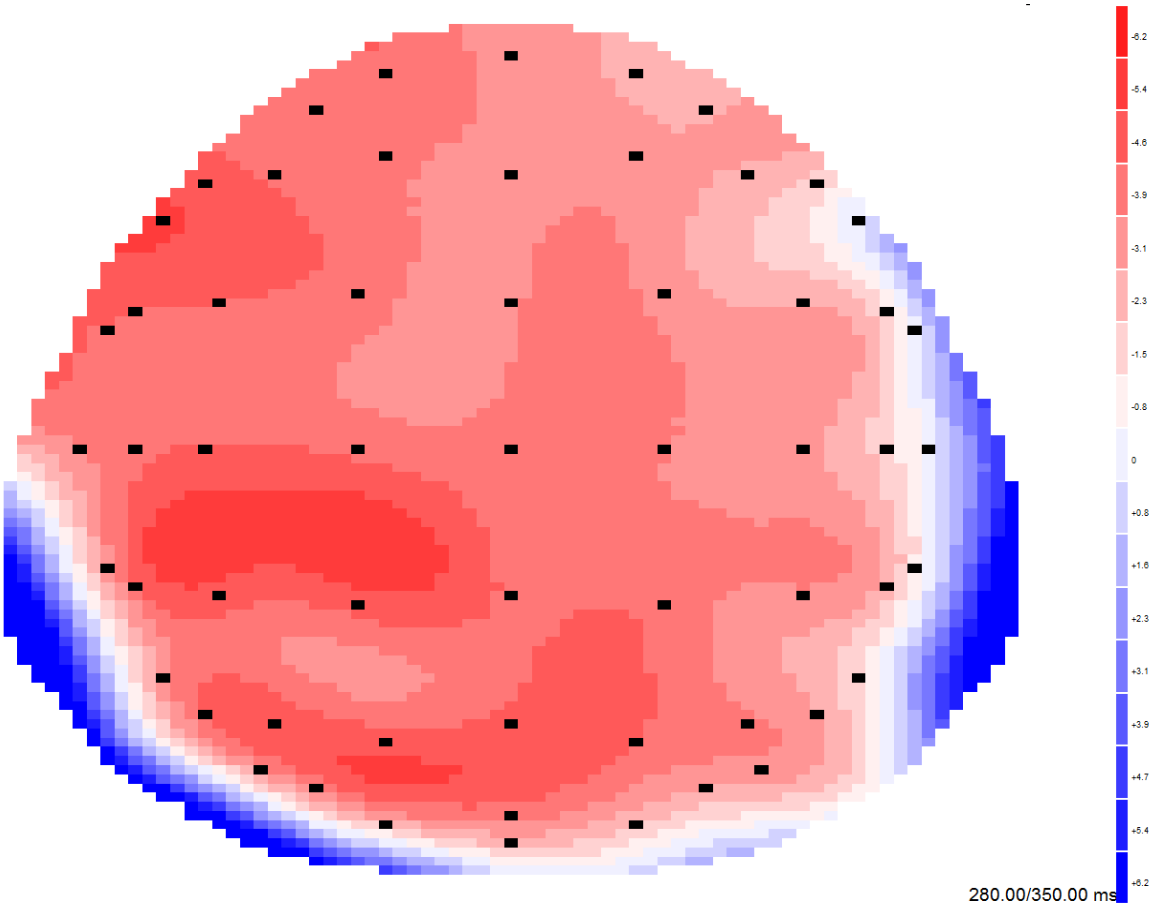

Figure 4.7: Topographic map of electrodes showing the differences between horizontal and vertical sites used for the N400 component.

4.3.4: Summary

To conclude, this seciton will highlight and summarise the significant ERP findings for each component. The summary will include significant main effects and interactions, not inlcuding main effects of horizontal and vertical electrodes and interactions between horizontal and vertical electrodes. This will be ommitted due to their clear findings on where components spatially appear, which is inline with previous research (see section 4.4).

The P1 showed a significant interaction between maths anxiety group and stimulus type, such that those with HMA exhibited a smaller P1 component than those with LMA, during addition processing. The N1 component also identified a significant interaction between maths anxiety group and stimulus type, such that amplitude was higher for those with LMA, particularly during multiplication.

The P3 component showed a significant interaction between stimulus type, horizontal and vertical electrodes, such that higher P3 amplitudes were shown in right posterior electrodes during multiplication. There was also a significant interaction between horizontal, vertical electrodes and maths anxiety group, such that low maths anxious individuals exhibited a higher P3 amplitude in left anterior electrodes than high maths anxious individuals. There was a significant interaction between maths anxiety group and vertical electrodes, such that those with LMA had a significantly higher P3 amplitude at midline electrodes than those with HMA. There was also a significant interaction between stimulus type and horizontal electrodes, such that higher P3 amplitudes were identified in anterior electrodes for addition than for multiplication.

Finally, the N400 component analysis showed a significant interaction between horizontal, vertical electrodes and maths anxiety group, such that those with HMA exhibited a higher N400 amplitude in central and midline electrodes than those with LMA. There was also a significant interaction between maths anxiety group and vertical electrodes; those with HMA had a significantly higher N400 amplitude at midline electrodes than those with LMA.

4.4: Discussion

The study set out to investigate latency and amplitude differences between high and low MA participants and to evaluate whether these correlates map on to current behavioural research and theory. It was predicted that there would be evidence of neurophysiological and behavioural correlates between accuracy and amplitude as well as reaction time and latency between MA groups. The above analyses generated results that set a foundation for the research in this thesis allowing the discussion below to evaluate the effectiveness of the methods used to obtain these. The neurophysiological data will be explained subsequent to the behavioural aspects discussed below:

4.4.1 Behavioural results

Correlations were run between MA and state and trait anxiety scores in order to identify if MA existed as a factor of an overarching anxiety or whether it exists solely. There was no significant relationship between MA and state and trait anxiety which supports that MA exists as a separate construct.

The behavioural results identified that overall, participants had higher accuracy for addition than multiplication. This can be assumed as addition is seen as easier than multiplication. This is likely due to addition being learnt prior to multiplication (in primary education) as the need to process multiples relies on number based rules in addition, which may make it seem easier. As expected, those with HMA had significantly poorer accuracy over those with LMA. Theories for this will be discussed alongside neurophysiological results.

Overall, it was found that those with HMA took significantly longer to answer than LMA individuals. This supports theories stating that high maths anxious individuals take longer to answer maths tasks as there is a the lack of memory resources available, due to combatting anxious thoughts (Eysenck et al., 2007). These results further support previous behavioural research concerning maths processing in high maths anxious individuals (Ashcraft & Faust, 1994; Ashcraft & Kirk, 2001; Ashcraft & Krause, 2007; Faust et al., 1996; Hopko, Ashcraft, Gute, Ruggiero, & Lewis, 1998). This will also be discussed alongside neurophysiological results.

4.4.2 Neurophysiological Results

This section will outline each analysed component and each significant interaction and main effect. These will be discussed using theory and previous research to explain and interpret the results.

It was predicted that ERP latencies would show differences in line with reaction time differences between MA groups. As seen in section 4.3.3.1 there were no differences in ERP component latencies. This may be because ERP latencies are not consistent with reaction time differences. Alternatively, the task may have been too simple to generate these differences. Nevertheless, the lack of latency differences permitted the amplitude analysis to proceed.

4.4.2.1 P1 Component Analysis

Significant main effects and interactions across horizontal and vertical electrodes were found within the P1 amplitude analysis. This was identified as higher in posterior left and right electrodes and is supported by previous research identifying the P1 within the occipital region (Odom et al., 2004). The significant interaction between stimulus type and MA showed a higher P1 amplitude for high maths anxious individuals than low maths anxious individuals. The P1 is typically elicited for checkerboard or similar high contrast flashing tasks (Odom et al., 2004) and due to the study being presented in black and white, this component is in accordance. Similarly, the high amplitude of the P1 shown here can be expected due to the demand of a quick response (Vogel & Luck, 2000). Knowing that the study would present mathematical stimuli, high maths anxious participants may have exhibited anticipation effects therefore, exhibiting a lower P1 component: Due to intrusive anxious thoughts occupying working memory, there are less working memory resources available to give full attention to what is presented (Eysenck et al., 2007).

The P1 results also showed an interaction between MA and the two stimuli types, whereby high maths anxious individuals displayed a smaller P1 than low maths anxious individuals, during addition only. Whilst addition can be seen as easier (judging from the accuracy results) recognition of the stimuli would not take place until at least the N1 component. As the P1 component is representative of contrast perception, the discrepancy is likely due to the length of the stimuli. For example, addition stimuli contained 2 two-digit addends surrounding a plus symbol followed by an equals symbol and answer (e.g. 24 + 42 = 66) whereas multiplication stimuli consisted of 1 two-digit multiplier and 1 one-digit multiplier surrounding a multiplication symbol followed by an equals symbol e.g. (24 x 4 = 96). The extra digit in addition stimuli may have contributed to a lower P1 component in high maths anxious individuals because it may be more difficult to attend to more digits whilst trying to combat intrusive thoughts. As the P1 elicits in response to stimuli parameters (Sur & Sinha, 2009) the above theory fits however, being that recognition hadn’t taken place at this stage, it is unlikely that high maths anxious individuals consciously perceived this as more threatening. Whilst there were no latency differences between components, providing no neurophysiological explanation for the increase in reaction time, the P1 fluctuation in high maths anxious individuals may have contributed to reduced accuracy. The early reduction of the P1 component may have begun an effect that would continue into the following component responsible for recognition of stimuli, eventually resulting in poorer accuracy.

4.4.2.2 N1 Component Analysis

The N1 component also showed significant interactions and main effects at horizontal and vertical electrodes, whereby the component was specifically localised at posterior left and right (parietal occipital regions). This is consistent with previous research examining the N1's typical localisation and latency (Bokura, Yamaguchi, & Kobayashi, 2001; Wang & Suemitsu, 2007). The interaction also noted that higher N1 amplitudes were presented at right parietal regions than left and midline sites. The higher amplitude at right electrodes is in line with previous research supporting this localisation to the right hemisphere during maths stimuli presentation (Szűcs & Csépe, 2005a).

Similar to the P1 findings, interactions were also found between stimulus type and MA; low maths anxious individuals elicited a higher N1 amplitude for multiplication than high maths anxious individuals. Again, this is likely due to the extra digit within addition problems. The higher N1 amplitude for high maths anxious individuals in addition is likely to reflect the vigilance towards a physically larger maths task and therefore, threat. This is supported by previous threat research noting anxious individuals experience attentional bias towards a threatening stimulus (Rinck et al., 2003) and due to the larger span of addition stimuli a higher N1 amplitude was generated than for multiplication. Whilst multiplication is arguably more complicated, the N1 also fluctuates based on stimuli parameters (Sur & Sinha, 2009). It is unlikely that high maths anxious individual's consciously perceived addition as being the most difficult, but rather the largest stimulus is initially observed as the most threatening. Observing the effects of MA on accuracy, it is likely that reduction of resources for recognition contributes to the poorer performance by high maths anxious individuals.

4.4.2.3 P3 Component Analysis

The P3 component presented significant main effects and interactions between horizontal and vertical electrodes, whereby higher P3 amplitudes were experienced at central, left sites and parietal sites across hemispheres. Significantly higher P3 amplitudes were also present in left temporal and midline, central regions than at right anterior electrodes. This was also seen in the interaction between stimulus type, horizontal and vertical electrodes, particularly for addition. Tang et al. (2006) note that individuals from western cultures employ language based processing during maths tasks primarily based in the left hemisphere (perisylvian cortex). This could be identified within left parietal and temporal regions as language techniques could have been employed by high maths anxious individuals to avoid processing tasks, using visuospatial methods instead. This is outlined by the interaction between MA groups, vertical and horizontal electrodes showing higher processing for high maths anxious individuals in left, centre electrodes than low maths anxious individuals who experienced higher P3 amplitudes in midline and right centre sites. Taking maths out of a numerical context and into language may soften the anxious, intrusive interferences experienced by high maths anxious individuals. Similarly, research has identified that most models of anxiety disorders have flawed visuospatial attentional processing when threat-relevant information occurs (Weierich, Treat, & Hollingworth, 2008), providing support for this subconscious technique and the increase in left hemispheric activation for high maths anxious individuals. Electrodes also elicited higher amplitudes for addition overall, which is consistent with theory noting the perceived complexity of addition (observing it as a physically larger problem due to extra digit span) and therefore, excess levels of processing required.

The discrepancy in hemispheres could also be explained by the significant interaction between vertical electrodes and MA group. Low maths anxious participants elicited higher P3 amplitudes at midline and right electrodes, supporting previous research concerning complex calculation (such as multiplication) eliciting higher activation in the right hemisphere (Kiefer & Dehaene, 1997). However, high maths anxious individuals experienced more subdued processing in the right hemisphere. This could be another indication of combatting intrusive thoughts (Ford et al., 2005; Hunt et al., 2014) leaving little working memory resources for the task at hand (Eysenck et al., 2007) as well as relying on language processing increasingly at left sites.

The above interaction also identifies higher amplitudes for high maths anxious individuals in left electrodes and whilst this may not be related to specific maths processing, previous research has indicated that left hemispheric activation is elicited during anxious states (in high trait anxious individuals), particularly when viewing negative stimuli (Derryberry & Reed, 1998; Heller, Nitschke, Etienne, & Miller, 1997; Wu et al., 1991). This could be supported by Tang et al.'s (2006) research that high maths anxious individuals may rely more language processes for mental calculation, rather than those with LMA, who may not rely on this as heavily. Support for the above theory can be seen in the significant interaction between MA group, horizontal and vertical electrodes. Low maths anxious participants have higher amplitudes across right and midline electrodes in anterior and centre electrodes, whereas high maths anxious participants elicit higher left hemispheric amplitudes across anterior, centre and posterior electrodes. These discrepancies likely identify the differences between the MA group's maths processing strategies but do not yet fully explain how this relates to the behavioural differences in accuracy and reaction time.

4.4.2.4 N400 Component Analysis

Significant interactions between horizontal and vertical electrodes were also found at the N400 component whereby, higher amplitudes were elicited at midline electrodes followed by left, with lower amplitudes in the right hemisphere. This occurred predominantly across central-parietal regions. The significant interaction between MA group and vertical electrodes also showed that low maths anxious participants elicited significantly higher amplitudes at midline than high maths anxious participants. As the N400 is manipulated by task difficulty (Atchley & Kwasny, 2003; Jost et al., 2004), it can be assumed that low maths anxious individuals were uninhibited in providing higher levels of working memory resources to verify complex answers, whereas high maths anxious individuals will have had fewer resources available due to anxiety (possibly due to anticipation of the presented stimuli (Lyons & Beilock, 2012)). These results are supported by the interaction between MA group, horizontal and vertical electrodes showing higher amplitudes overall for low maths anxious individuals but significantly at centre midline electrodes, within the parietal region.

Similar horizontal and vertical main effects and interactions were experienced for the N400 component, again with a higher N400 amplitude at posterior right electrodes overall. Higher amplitudes were also elicited in posterior electrodes with smaller N400 amplitudes at centre and anterior sites. Similarly, low maths anxious individuals had a smaller N400 for addition over multiplication, supporting the N400's manipulation due to task difficulty (Atchley & Kwasny, 2003; Jost et al., 2004). This further indicates that low maths anxious individuals consider addition less of a threat, which would be expected due to its early teaching in maths education.

4.4.3 Summary

In summary, this research has begun to show similarities to previous behavioural research in that high maths anxious participants tend to show an increased reaction time overall for processing maths stimuli. It was thought that because high maths anxious individuals typically show an increased reaction time during processing in behavioural tasks; ERP components would also be delayed however, this was not shown to be the case. Observing the components in more depth, it could be suggested that this may have taken place before the response was given. For example, the P1 is associated with contrast perception and the N1 with recognition. Based on previous research, we would not expect intrusive thoughts to interfere with these components as at this point, as there is little to be fearful of (bar anticipation). Nevertheless, this may be experienced at components such as the P3 or N400 as they involve processing of task and can fluctuate based on difficulty, yet still there was no neurophysiological latency difference between anxiety groups. Instead, this delay may occur prior to the response being given. The answer may be processed at a similar rate to low maths anxious participants; it is contemplating whether or not the proposed answer is correct, where high maths anxious individuals are hindered by intrusive thoughts. The working memory deficit, suggested by Maloney, Risko, Ansari, & Fugelsang (2010), may occur at this point, inhibiting performance. Components did show amplitude differences between MA groups which may contribute to the poorer performance in high maths anxious individuals but this does not fully explain how these processes relate.

The research did have some flaws that will endeavour to improve on in subsequent studies. Previous research has identified problems with verification paradigms within MA tasks noting that they can sometimes be unreliable when a time pressure is added to stimuli, causing further anxiety and worry through evaluation (Kellogg, Hopko, & Ashcraft, 1999b). Research has shown examples of increasing reaction time for those with HMA, although accuracy also severely decreases substantially (Ashcraft & Faust, 1994). This has shown that high maths anxious individuals will continuously sacrifice accuracy in order to avoid processing threatening mathematical stimuli and can be exacerbated within verification paradigms as a simple ‘yes’ or ‘no’ is required to respond. It would be advantageous to provide participants with multiple answers, one correct and three randomly distanced from the true answer, to encourage calculation techniques. This is supported by research evidencing that high maths anxious individuals experience higher rates of anxiety when ‘doing maths’ (Ashcraft & Faust, 1994; Jones et al., 2012) rather than approximating. Furthermore, the current research did not investigate electro-cortical differences between correctly and incorrectly presented answers among MA groups. This was not the aim of the present study but has previously been shown in neurophysiological, MA research in simple arithmetic (Suárez-Pellicioni et al., 2013a).

The research conducted above is extremely useful for providing an insight and foundation to the electrophysiological correlates of maths anxiety, particularly when looking at temporal and amplitude differences across regions associated with maths processing. Whilst this gives an indication of maths processing in these participant groups, it does not fully give an explanation of anxiety differences between populations in these areas. Previous research has identified the gamma band's involvement in the manipulation of the amygdala during the processing of threat and anxiety. However, the current study acquired and analysed bands of activity (between .5 and 30Hz), encompassing delta, theta, alpha and beta thus, excluding gamma. This restriction was applied due to previous MA research, including lower bands of activity, for example, Suárez-Pellicioni et al. (2013) measured between 0.5-30Hz and Jones et al. (2012) filtered from 1-30Hz. Previous research tends to avoid gamma activity due to the increase likelihood of artefacts at higher frequencies (Muthukumaraswamy, 2013). However, this band of activity has been associated with anxiety and threat (Garcia-Garcia, Yordanova, Kolev, Domínguez-Borràs, & Escera, 2010; Luo, Holroyd, Jones, Hendler, & Blair, 2007a; Maratos et al., 2012), and used to look at anxious populations. There is a need for this analysis within MA populations and it could be argued that this may be the 'signature' that math anxiety has on brain activity (Ashcraft, 2002). This study has identified that the current methodological model of acquiring data below 30Hz is not sufficient for measuring the neurophysiological effects of MA and that future research should involve the measurement of gamma activity much like other anxiety research areas have.

In conclusion, this exploratory study has contributed to the foundation of research identifying the electrophysiological correlates of MA whilst aiming to relate the neurophysiological results to the behavioural effects of MA. This has contributed to the subject area by combining research across neurophysiological maths processing and behavioural MA research in order to relate them to how the MA brain behaves, causing reduced accuracy and increased reaction time. Whilst the results have shown little differences between MA groups in line with these effects, it is noted that a more challenging task may be appropriate to generate higher anxious responses. This study has also identified one of the pitfalls in neurophysiological MA research methodology noting a wider frequency range is necessary. It is of interest to identify the role of gamma activity due to its involvement in processing anxious and threatening stimuli. This will be outlined in the next chapter.

Chapter 5: Investigating the relationship between gamma-band activity and maths anxiety

5.1: Introduction

The previous study provided a foundation for exploring the electrophysiological aspects of maths anxiety but found little evidence for the neurophysiological correlates (amplitude and latency) being consistent with behavioural effects (accuracy and reaction time). It was noted that a more challenging task may be appropriate to generate higher anxious responses as well as identifying that another method alongside ERPs was necessary. It is of interest to identify the role of gamma activity due to its manipulation of the amygdala and involvement in processing anxious and threatening stimuli. This is pertinent as high maths anxious individuals are noted to perceive maths as threatening (Lyons & Beilock, 2012).

Maths processing research has identified several contributing areas of the brain, such as temporal, parietal and occipital regions (Dehaene, Dehaene-Lambertz, & Cohen, 1998; Schmithorst & Brown, 2004). This has resulted in predictions stating that as cognitive neuroscience becomes more prominent in MA research, it is likely that the neural activity will bear a resemblance to other negative phobic states, as well as affect the same regions evoked during working memory activity (Ashcraft, 2002). Whilst other methods have been applied, neurophysiological MA research has tended to steer towards ERP differences in components (amplitude and latency) and the relation to maths processing in general. (David Sheffield & Hunt, 2006; Suárez-Pellicioni, Núñez-Peña, & Colomé, 2013b). However, there is a lack of research concerning the EEG gamma band which plays a large role in response to threat and anxiety, corresponding to processing in the amygdala. This is surprising yet increasingly relevant at present based on recent research regarding the anticipation of maths in high maths anxious individuals (Lyons & Beilock's, 2012) whereby, it is theorised that anticipation of maths heightens anxiety, rather than doing maths itself.

Research has shown that there are evolutionary advantages to attending to negative stimuli over neutral stimuli (see Davis & Whalen, 2001 for a review), which is why anxious individuals tend to bias towards threat-related stimuli more than non-anxious individuals (Bar-Haim, Lamy, Pergamin, Bakermans-Kranenburg, & van IJzendoorn, 2007). A meta-analysis looking at threat-related attentional bias found this to be consistent across anxious populations and concluded that this bias is not evident in non-anxious individuals (Bar-Haim et al., 2007b).

Gamma activity has been shown to mark higher cortical arousal with high frequency oscillations elicited more in individuals with higher arousal ability for example, those with high levels of anxiety (Knyazev, Savostyanov, & Levin, 2005). Knyazev, Savostyanov, & Levin (2004) investigated EEG power measures across a range of anxious individuals, identified using the Taylor Manifest scale (Taylor, 1953) and the STAI (Spielberger et al., 1970). Whilst the primary objective was to investigate alpha oscillations as a correlate of trait anxiety, they also noted that the power of high frequency oscillations were consistently greater in high anxious individuals. Furthermore, they theorise that high anxious individuals are still vigilant when a good outcome may arise, as defeat in a situation would elicit a painful response. This research suggests that high frequency bands such as gamma, play a significant role in high anxious individuals and moreover, even when confronted with the possibility of performing well, high anxious individuals will still remain vigilant as if presented with a threat. This can be expected in those with HMA, whereby they remain aroused and expectant of a threat, even when the task is simple.

This relates to two theories from the introductory chapters. The first concerns the cognitive theory of intrusive thoughts, whereby high maths anxious individuals will occupy working memory with these thoughts (Ford et al., 2005; Hunt et al., 2014) inhibiting them from completing the task. Gamma activity could be indicative of their irrational vigilance towards a perceived threat, causing intrusive thoughts and promoting the idea of a painful defeat. A second theory, the concept of number anxiety as opposed to MA, is also relevant here. Knyazev et al. (2005) note that even when the task has a promising outcome, high anxious individuals will remain vigilant and aroused, elicited by increases in gamma power. Again, it is theorised that manipulation or even observation of number would cause similar activity in high maths anxious individuals rather than complex mathematical processing. This will be outlined further in chapter seven.

Research also notes that the gamma band range is responsible for the processing of complex cognition, such as working memory and attention (Jensen et al., 2007; Keil et al., 2001; Müller et al., 1999; Oya et al., 2002; Tallon-Baudry et al., 2005; Taylor et al., 2000). Gamma band activity could be responsible for both anxiety and processing of maths tasks however, this is likely part of an overarching process of attention encompassing aspects of working memory. It is theorised that those with HMA would also experience high levels of gamma power due to an increased levels of anxiety, threat and attention in order to increase motivation to combat negative thoughts (Eysenck et al., 2007).

Research has shown that increased activity in the amygdala plays a role in processing negative emotions in MA (Maloney & Beilock, 2012) resulting in reduced activity in regions associated with memory and numerical processing (Young et al., 2012). This maps on to the previously stated attentional control theory (Eysenck et al., 2007), whereby the lack of attentional resources needed for the primary task are consumed by threat perception and intrusive thoughts. Research has shown that the amygdala is responsible for threat perception and that gamma activity can manipulate processing of this area. Nevertheless, few studies have observed gamma oscillations in response to threat in relation to specific forms of anxiety, e.g. MA.

Other investigations have associated fluctuations in gamma activity with changes in the amygdala during, learning (Popescu, Popa, & Paré, 2009), cognitive processing (Hughes, 2008) and anxiety (Maratos et al., 2012; Oathes et al., 2008). For example, Oathes et al. (2008) presented worry inducing stimuli to participants diagnosed with general anxiety disorder (GAD) as well as a control group. They found that EEG gamma band activity (35-70Hz) was highly exhibited in GAD participants in comparison to control groups particularly at posterior electrodes. They further identified that following psychotherapy for treatment, GAD participants exhibited lower power of gamma activity. This provides evidence for the use of the EEG gamma band in monitoring anxiety and worry, further identifying it as an appropriate method for monitoring treatment.

In contrast, Maratos et al. (2012) identified a reduction of gamma band activity when participants were exposed to threat related versus neutral facial expressions using MEG. However, they note this difference due to their methodological variance of the task; for example, threatening stimuli were task irrelevant whereas, previous research uses threatening stimuli as the primary focus (for example, Luo et al., 2009). Maratos et al. (2012) note that threatening stimuli is still associated with modulation of the gamma band and amygdala activity.

Another current theory also notes that anxiety is experienced as a reoccurrence of previous memory encoding. For example, Jensen et al. (2007) note that if an item is encoded whilst experiencing a high form of anxiety (thus an increase in gamma activity), during recall the increased gamma activity experienced “may reflect reactivation of synaptically encoded representations” (Jensen et al., 2007, p.322). This is not to say that the anxiety is false and is only a representation of a previous memory, but rather individuals experience the same feelings based on how the original information was encoded. For instance, if an individual was taught maths under an anxiety provoking task (e.g. did not understand the theory behind calculation or was absent during previous lessons) the information will have been encoded into long term memory during heightened anxiety levels and therefore, potentially increased gamma activity. When asked to recall this at a later point, the originally created pathways will activate and the feelings of anxiety will reoccur. It may be possible to link this to maths avoidance, typically experienced in high maths anxious individuals, such that they would want to avoid the feelings of anxiety therefore, avoid maths and unintentionally limit future career prospects.

The aforementioned research supports the association between gamma activity and the amygdala and infers that increased gamma activity can regulate the perception of threat. Furthermore, there is a plethora of neurophysiological research stating how the amygdala is responsible for processing fear, threat and negative emotions (Cisler & Koster, 2010; Davis, 1992; Davis & Whalen, 2001; LeDoux, 2003; Ohman, 2005; Oya et al., 2002) with some recent research focusing on MA (Young et al., 2012).

It is clear that high maths anxious individuals see maths as negative and whilst it may be seen as neutral among low maths anxious participants, it can be assumed that high maths anxious individuals observe maths automatically as a difficult task or an obstacle (Ashcraft & Kirk, 2001). High anxious populations have been shown to acquire a threat-related attentional bias more sensitive than non-anxious populations (see Bar-Haim et al., 2007a, for a review). It is assumed that as maths is seen as a difficulty and can impair performance, it may also be perceived as threatening as well as evoking negative emotions. These theories outline a clear need for MA research investigating gamma activity, in relation to worry and threat. With the above information it is proposed that the processing of maths in high maths anxious populations is manipulated by gamma activity.

In summary, research has shown that highly anxious populations experience higher power of gamma activity than low anxious individuals (Oathes et al., 2008) and that high maths anxious individuals often avoid maths based situations due to anticipation of threat and pain, associated with increased amygdala activity (Lyons & Beilock, 2012). Finally, gamma activity has also been shown to be associated with the amygdala. The following studies in this thesis will aim to bring these theories together and fill the gaps left in them, for example, whether gamma activity differ across MA populations in response to threatening stimuli. Furthermore, if any differences are found between high and low MA populations, are they consistent across maths and in particular, number processing which may then identify number anxiety as a precursor to MA? As stated in previous chapters, number anxiety is a pertinent aspect to MA research being that the majority focuses on numerical manipulation or arithmetic.

The aim of this study is to further explore this whilst increasing the level of calculation required. It also aims to identify whether gamma band activity contributes to anxiety and threat perception in high maths anxious individuals. This study had two objectives; (a) to compare ERP latencies and amplitude differences across high and low MA participants, (b) to observe differences in gamma activity between high and low MA groups and conditions.

To achieve this, complex addition and multiplication tasks will be presented to participants. This differs from the previous study as rather than verifying the answer, participants will be required to choose from one of four answers including 1 correct and 3 randomly distanced from the correct answer (1 to 10 digits either above or below). Multiple choice answers will be used for three purposes: high maths anxious individuals have been shown to sacrifice accuracy in favour of avoiding maths during verification tasks (Ashcraft & Faust, 1994) and providing multiple results will likely increase consideration of the answer instead of having a 50/50 chance of guessing correctly. Secondly, low maths anxious individuals are likely to use estimation techniques for verification tasks where the answer can quickly be identified as correct or incorrect. The use of multiple choice answers prohibits this as some incorrect answers will contain the same digits as the correct answer. This was accomplished by randomising the last digit (1 column) to an increment of 1-10 above or below the correct answer (for example: 64 71 74 68). Finally, multiple choice answers were used, rather than generating an answer using keyboard presses in order to limit motor interference from multiple button presses.

It is predicted that the increase in stimuli difficulty will generate higher levels of anxiety, eliciting varied latency and amplitude ERP correlates (in relation to *a priori* established components: P1, N1, P3 and N400) with reaction time and accuracy. It is predicted that these will differ due to overloading of working memory in high maths anxious individuals. Specifically, it is hypothesised that ERP components will differ in amplitude between MA groups in relation to accuracy and that reaction time differences will appear in line with ERP component latency differences. Furthermore, it is hypothesised that there will be differences in gamma activity between high and low maths anxious individuals due to its involvement in threat and anxiety processing.

5.2 Method:

The method is not dissimilar from the study two therefore, aspects of this section will be omitted to avoid repetition throughout.

5.2.1 Design

The ERP analysis employed a 2 (high/low MA groups) × 2 (addition/multiplication stimuli) × 3 (anterior/centre/posterior electrodes) × 3 (left/midline/right electrodes) mixed design. The between subjects IV was MA group and within subjects IVs included stimulus type, horizontal and vertical electrodes. Electrical activity at electrodes acted as the DV.

MA and STAI scores were taken to observe correlations between the two measures, in order to identify whether MA existed solely or part of an overarching anxiety within this participant group. Multiple stimuli were then administered per condition in a random order to avoid complacency during tasks. As ERP methods were used, a minimum of 60 of each stimulus type were presented in each condition. In order to compare neurophysiological and behavioural data, stimuli similar to those used in previous MA research were presented to participants. This included both complex addition and multiplication problems with 1 correct and 3 incorrect answers. This was chosen due to the quantity of MA research concerning addition and multiplication over subtraction, division and algebra (Ashcraft & Kirk, 2001; Ashcraft & Krause, 2007; Faust et al., 1996).

A priori assumptions based on previous maths research were made for specific ERP components. All 70 electrodes (including a reference, ground, 2 mastoid, 2 horizontal and 2 vertical electro-oculogram electrodes) were used for data acquisition. The same nine electrodes were used for the analysis (T7, Cz, T8, P5, Pz, P6, O1, Oz, O2) and were allocated to groups based on their horizontal and vertical layout (see table 5.1).

Table 5.1.

Layout of Horizontal and vertical electrodes.

		Vertical		
		Left	Midline	Right
Horizontal	Anterior	T7	Cz	T8
	Centre	P5	Pz	P6
	Posterior	O1	Oz	O2

A pilot study was conducted prior to testing to ensure stimulus presentation, lighting and procedure was adequate and followed in an appropriate manner.

The analysis of gamma activity was also necessary for this study therefore; relevant electrodes were selected based on *a priori* assumptions. To analyse data from these previously suggested sites, different electrodes were used compared to those used in the ERP analysis (T3/T7, C3, C4, T4/T8, T5/P7, P3, P4, T6/P8). This analysis resulted in a 2 (high/low MA) x 2 (addition/multiplication stimuli) x 2 (anterior/posterior electrodes) x 4 (left/midline left/midline right/right electrodes) mixed factorial design. Again, electrodes were allocated to groups based on their horizontal and vertical layout (see table 5.2).

Table 5.2.

Layout of Horizontal and vertical electrodes for gamma analysis:

		Vertical			
		Left	Midline Left	Midline Right	Right
Horizontal	Anterior	T7	C3	C4	T8
	Posterior	P7	P3	P4	P8

5.2.2 Participant Selection

Two hundred and three participants were recruited from the University of Derby, and were asked to complete the MAS-UK (Hunt et al., 2011). Sample size was considered adequate for cluster analysis based on factor analysis properties (Comrey & Lee, 1992). Participants were asked to complete the questionnaire pack containing the consent form, scale and debrief (see appendix ii). Participants were told that they may be selected for the second part of the study which involved EEG recording but were not told how they would be selected, again to avoid demand characteristic confounds. Data was collected and input into SPSS for analysis.

5.2.3 Cluster analysis:

A hierarchical cluster analysis indicated two clusters. The first cluster had 52.2% of cases (N=106) and contained those who scored low on the MAS-UK indicating a LMA cluster. The second had 47.8% of the total sample (N=97) and contained those who scored higher on the MAS-UK indicating a HMA cluster. In order to distinctly invite those with the highest and lowest levels of MA, participants were systematically selected, with scores up to 40 and down to 65, for the EEG phase of the study.

Thirty participants were invited, via email, to participate in the EEG phase of the research. Individuals consisted of 15 HMA and 15 LMA, 14 males and 16 females (Mean age = 25.17 SD = 8.60) and were all right handed. Participants reported normal or corrected to normal vision and had not been diagnosed with dyslexia.

5.2.4 Materials: and equipment:

One-hundred and twenty maths equations; 60 complex, two-digit addition, e.g. 19+54= (answers displayed as: 73 67 79 68) and 60 complex 2x1 digit multiplication, e.g. 19x5= (answers displayed as: 86 103 95 91) were presented to participants. Again, complex addition was defined by using double digit addition and the need to implement a carry operation (Faust et al., 1996; Wu et al., 2012) and complex multiplication was defined by using a one digit by two digit equation (Tronsky, 2005). Multiplication problems with 0 and 1 as an operand were not used because they act as simple rule-based problems (e.g., LeFevre et al., 1996). Again, problems and answers were displayed on screen at the same time to prevent the need for participants to hold the question in short-term memory whilst calculating, using more working memory resources than necessary.

5.2.5 Procedure:

Participants were emailed with the required information (see appendix iii) and asked to arrive at the university at a mutually agreed time. The researcher explained the procedure and timings of the study. Participants were asked to complete a consent form and then the state-trait anxiety inventory (STAI) to ensure that they were not just anxious instead of specifically maths anxious.

Participants were seated in a dimly lit room whilst white stimuli (font size 64) were presented on a black background. This was changed from the previous paradigm as participants had noted that the white background strained their eyes. The change lowered luminosity levels and was noted as less straining by participants. Luminance levels were measured from the visual display unit (3.8 cd/m^2) distanced at 72cm at eye height with the centre of the screen. Participants were sat in a comfortable chair at eye height to the centre of the screen. Participants were asked to note the correct answer to the problems by pressing the corresponding button on a button box (1, 2, 3 or 4). Each stimulus was presented for 8000ms with a response window of 8000ms followed by a fixation with a duration of 500ms. Inter trial intervals were pseudo randomised between 500ms and 2500ms to avoid habituation. The duration of stimulus presentation was increased from the previous parameters, as the current design included more on-screen information requiring further attention and working memory load for processing the maths task. Impedances of all electrodes were kept below 15kΩ however; the majority were below 5kΩ.

5.3: Results

5.3.1 Analytical Strategy:

The results are split into four stages: The first (section 5.3.2) comprises behavioural data including MA and state and trait anxiety correlations, accuracy and reaction time. A Spearman's rho correlation was conducted to analyse whether MA significantly correlates with state and trait anxiety, to identify if MA exists solely or as a factor in an overarching anxiety in this population. Mixed factorial ANOVAs were also used to measure behavioural differences across MA groups and conditions.

The second (section 5.3.3) includes ERP latency processing and analysis: Latency of components (based on *a priori* hypotheses) were noted to be different between high and low maths anxious groups. Analyses for each component were conducted to determine the significance of the differences between MA group and stimulus condition, as significant differences will justify using different latency windows for each group and/or condition.

The third section (5.3.4) includes ERP amplitude processing and analysis: *A priori* hypotheses were used alongside GFP to distinguish appropriate components for analysis. Three components were each analysed to identify significant interactions and main effects. A *post-hoc* split was applied to the N1 component and was found to represent two components (N1 and P3). Due to the nature of GFP calculation, all peaks display in positive format therefore, the distinct positive and negative components were not initially differentiated.

Finally, section 5.3.5 includes gamma activity processing and analysis: A mixed factorial ANOVA was used to identify any significant main effects or interactions in gamma activity between condition, MA group and horizontal and vertical electrodes.

5.3.2 Correlation, accuracy and reaction time data:

Correlations

Data showed significant kurtosis therefore, a Spearman's rho correlation was used to look at the relationship between MAS-UK and STAI scores. There was a weak, positive, non-significant correlation between maths anxiety and state anxiety scores (r(28)=.284, p=.128) and maths anxiety and trait anxiety scores (r(28)=.270, p=.149). The lack of a significant relationship again demonstrates that MA is not correlated to state and trait anxiety scores (see figure 5.1).

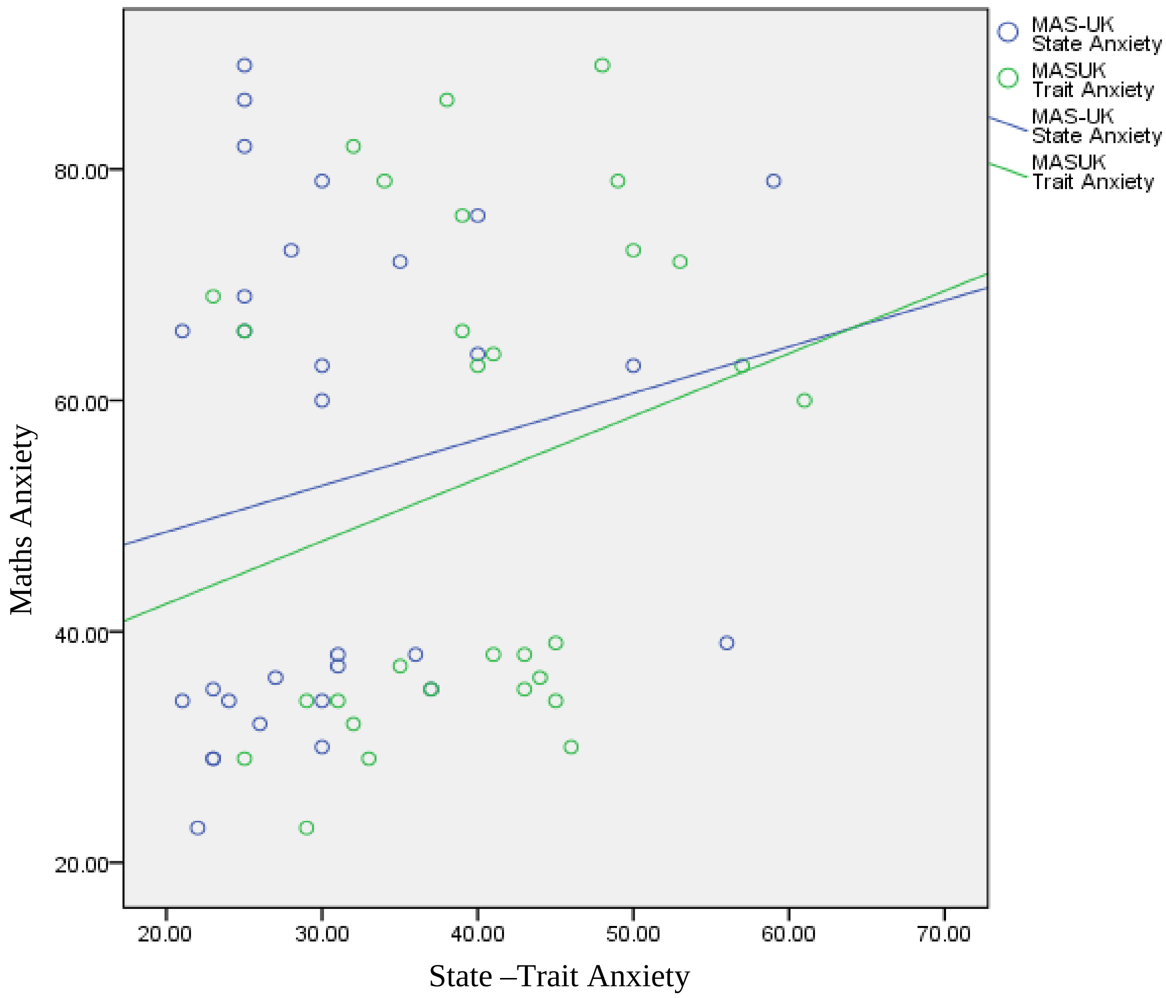

Figure 5.1: Scatterplot showing the relationship between MA and state anxiety scores, and MA and trait anxiety scores.

Accuracy and Reaction time

Data was screened prior to analysis and was found to be normally distributed. Two 2 (High/Low MA) × 2 (addition/multiplication stimuli) mixed factorial ANOVAs were run to identify any interactions between accuracy and reaction time for responses.

Accuracy

There was no significant main effect of MA ($F(1,28) = .54$, $p=.468$, $\eta^2 = .02$). However, there was a significant main effect of stimulus type ($F(1,28) = 10.31$, $p=.003$, $\eta^2 = .27$), such that accuracy was significantly higher for multiplication than for addition. There was no significant interaction between MA group and stimulus type ($F(1,28) = .43$, $p=.520$, $\eta^2 = .01$).

Reaction Time

There was a significant main effect of stimulus type ($F(1,28) = 8.94$, $p=.006$, $\eta^2 = .23$), such that reaction time was quicker overall for addition than multiplication. There was also a significant main effect of MA ($F(1,28) = 11.59$, $p=.001$, $\eta^2 = .03$), such that those with LMA had a quicker reaction time than those with HMA. There was no significant interaction between MA and stimulus type ($F(1,28) = .003$, $p=.954$, $\eta^2 = .04$).

Table 5.3:

Mean (SD) accuracy and reaction time scores between high and low MA groups during calculation.

		Maths Anxiety Group		
	Stimulus Type	**High**	**Low**	**Total**
Accuracy	Addition	25.47 (17.85)	28.93 (17.79)	27.20 (17.60)
	Multiplication	28.87 (13.90)	34.07 (16.32)	31.47 (15.13)
Reaction Time (ms)	Addition	5295 (845)	4184 (756)	4740 (969)
	Multiplication	5463 (700)	4570 (946)	5016 (935)

In summary, accuracy was higher overall for multiplication but high and low MA groups had no significant main effects or interactions with stimulus type. Reaction time was faster for addition than multiplication and low maths anxious individuals had a faster reaction time overall than high maths anxious individuals.

5.3.3: ERP latency processing and analysis

5.3.3.1 ERP latency preparation and processing

Previous research provided *a priori* assumptions of appropriate components as well as component latencies. GFP was then conducted across all electrodes (excluding M1, M2, VEOG, HEOG and the central reference) to refine the latency interval for ERP components. Four components were identified as P1, N1, P3 and N400 however; two of the predicted components were represented by one large component in the GFP figure. This will be further explained in chapter 5.3.4 after latency results and initial component amplitude analyses are presented.

After conducting averages across each condition and participant group it was determined that there was a 10-20ms difference for some components between high and low maths anxious participants (see figure 5.2) therefore, this was measured across all conditions to ensure that there was no significant differences across components. If the differences showed to be significant, separate latency windows would be used to define high and low MA components to prevent bias towards any group.

Peak latency was identified across the four components within four groups/conditions (HMA, LMA, addition and multiplication) at nine specific electrodes. These were identified *a priori* based on relevant research (T7, Cz, T8, P5, Pz, P6, O1, Oz, O2). Four 2 (High/Low MA group) × 2 (addition/multiplication stimuli) × 3 (anterior/centre/posterior electrodes) × 3 (left/midline/right electrodes) mixed factorial ANOVAs were used to identify any interactions and main effects. These were conducted separately for the P1, N1, P3 and N400 components. All ANOVAs included the Greenhouse-Geisser correction to ensure type I error rates were not inflated (Greenhouse & Geisser, 1959) being that neurophysiological data is rarely homogenous. The key effects of interest were differences in MA group and stimulus type as these would require separate latency windows if they were found to be significant. A breakdown of the overall analysis is listed below.

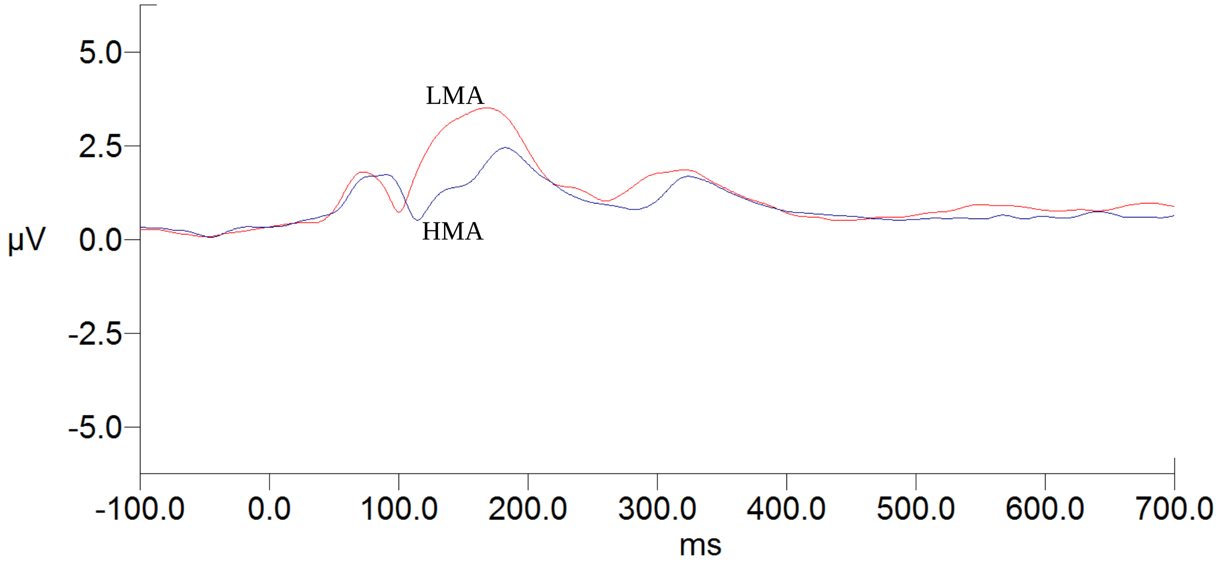

Figure 5.2: Scalp ERP latency differences in GFP calculation between high and low MA from -100ms (pre-stimulus onset) to 700ms (post-stimulus onset).

5.3.3.2 ERP latency analysis

P1 Component Latency Analysis

The results display the findings of the P1 latency, explaining the overall analysis, interactions and finally, main effects (see table 5.4).

Table 5.4:

P1 ANOVA F values, degrees of freedom, significance levels and effect size (η^2) for latency interactions (horizontal electrodes, vertical electrodes, stimulus type and MA group) and main effects.*

Interaction / Main Effect	ANOVA			
	F	***df***	***p***	**η^2**
Horizontal x Vertical x Stim x MA	.81	3.29,91.99	.504	2.25×10^{-3}
Horizontal x Vertical x Stim	.70	3.25,94.16	.569	2.16×10^{-3}
Vertical x Stim x MA	.03	1.81,50.55	.959	3.30×10^{-3}
Horizontal x Stim x MA	.05	1.74,48.62	.937	7.56×10^{-5}
Horizontal x Vertical x MA	.50	3.11,86.99	.690	5.12×10^{-5}
Vertical x Stim	.18	1.81,52.33	.817	2.80×10^{-4}
Horizontal x Stim	2.78	1.74,50.32	.079	.01
Horizontal x Vertical	2.60	3.14,90.94	.055	.044
Stim x MA	.42	1,28	.521	8.99×10^{-4}
Vertical x MA	.34	1.88,52.63	.700	1.95×10^{-3}
Horizontal x MA	4.80	1.18,32.93	.030	.044
Vertical	1.33	1.88,54.37	.273	7.45×10^{-3}
Horizontal	1.06	1.16,33.53	.321	.01
Stim	1.97	1,29	.171	4.19×10^{-3}
MA	3.34	1,28	.078	.11

*significant main effects and interactions are highlighted

The 3×3×2×2 analysis showed no significant interaction between horizontal, vertical electrodes, stimulus type and maths anxiety group. There was no significant interaction between stimulus type, horizontal and vertical electrodes or between horizontal, vertical electrodes and maths anxiety group. There was no significant interaction between maths anxiety group, stimulus type and horizontal electrodes or between maths anxiety group, stimulus type and vertical electrodes.

There was no significant interaction between maths anxiety group and vertical electrodes. There was no significant interaction between stimulus type and horizontal electrodes and stimulus type and vertical electrodes. There was no significant interaction found between maths anxiety group and stimulus type. However, there was a significant interaction between maths anxiety group and horizontal electrodes such that the P1 component reached its peak earlier for low maths anxious participants at posterior electrodes (mean = 73.00ms, SD = 19.46) than those high maths anxious individuals (mean = 85.41ms, SD = 19.17). This would indicate that those with LMA perceive contrast at faster rates than those with HMA. There was no significant main effect of horizontal electrodes, and vertical electrodes and no significant interaction of horizontal and vertical electrodes. The interaction between MA group and horizontal electrodes may have occurred due to anticipation effects in high maths anxious individuals, using more working memory resources and ultimately delaying processing.

Nevertheless, there was no significant main effect of MA groups or stimulus type identifying that, for the P1 component, there was no significant latency difference between high and low maths anxious groups as well as addition and multiplication stimuli. This begins to support the use of an average including all groups and conditions rather than separate group averages.

N1 Component Latency Analysis

The results display the findings of the N1 latency, explaining the overall analysis, interactions and finally, main effects (see table 5.5).

Table 5.5:

N1 ANOVA F values, degrees of freedom, significance levels and effect size for latency interactions and main effects.

Interaction / Main Effect	**ANOVA**			
	F	***df***	***p***	***η²***
Horizontal x Vertical x Stim x MA	.76	2.95,82.52	.520	2.77×10^{-3}
Horizontal x Vertical x Stim	1.41	3.00,87.07	.244	4.83×10^{-3}
Vertical x Stim x MA	1.21	1.80,50.43	.303	9.24×10^{-3}
Horizontal x Stim x MA	3.31	1.99,55.59	.044	6.31×10^{-3}
Horizontal x Vertical x MA	1.29	3.03,84.76	.282	2.33×10^{-5}
Vertical x Stim	2.59	1.78,51.65	.091	
Horizontal x Stim	3.55	1.97,57.06	.036	7.30×10^{-3}
Horizontal x Vertical	8.34	3.03,87.87	<.001	5.00×10^{-3}
Stim x MA	.78	1,28	.384	1.70×10^{-3}
Vertical x MA	.99	1.77,49.59	.371	5.23×10^{-3}
Horizontal x MA	.58	1.58,44.15	.525	7.86×10^{-3}
Vertical	3.24	1.76,50.92	.053	7.45×10^{-3}
Horizontal	3.38	1.59,45.98	.053	.02
Stim	.04	1,29	.841	8.87×10^{-5}
MA	3.88	1,28	.059	.12

The 3×3×2×2 analysis showed no significant interaction between horizontal, vertical electrodes, stimulus type and maths anxiety group. There was no significant interaction between stimulus type, horizontal and vertical electrodes or between horizontal, vertical electrodes and maths anxiety group. There was also no significant interaction between maths anxiety group, stimulus type and vertical electrodes.

There was a significant interaction between maths anxiety group, stimulus type and horizontal electrodes (see table 5.6), whereby low maths anxious individuals had significantly earlier latency than high maths anxious individuals at centre and posterior electrodes. This is likely to follow from the earlier P1 component latency for low maths anxious individuals. High maths anxious individuals had faster latency for addition recognition at centre and anterior electrodes than for multiplication. This is likely because maths processing occurs in parietal areas and addition is considered easier than multiplication, being that it is learnt earlier in education and a prerequisite to learning multiplication.

Table 5.6:

N1 mean latency (ms) and standard deviation depicting the interaction between MA group horizontal electrodes and stimulus type.

		MA group	
Horizontal	**Stimulus type**	**High**	**Low**
Anterior	Addition	156.51 (60.27)	160.80 (63.91)
	Multiplication	170.76 (65.61)	157.67 (64.69)
Central	Addition	146.98 (36.84)	132.64 (28.10)
	Multiplication	160.04 (55.50)	131.31 (26.69)
Posterior	Addition	159.22 (48.53)	136.40 (27.84)
	Multiplication	144.33 (33.46)	133.07 (29.21)

There was no significant interaction found between maths anxiety group and stimulus type, as well as between maths anxiety group and horizontal electrodes and maths anxiety group and vertical electrodes. There was also no significant interaction between stimulus type and vertical electrodes. However, there was a significant interaction between stimulus type and horizontal electrodes such that the N1 peaked quicker for multiplication at posterior electrodes (mean = 138.70ms, SD = 31.74) than addition (mean = 147.81ms, SD = 40.97). Again, this is likely to be because maths processing occurs in parietal regions therefore, occurring faster for recognition of shorter length equations e.g. 2x1 digit over 2x2 digit. There was also a significant interaction of horizontal and vertical electrodes (see table 5.7), showing faster processing at occipital and parietal sites. This can be expected as recognition will occur quickly after the P1 component experienced at posterior sites. Left centre and anterior sites elicited faster than right indicating quicker processing in left parietal regions. This can also be expected as this region is responsible for recognition as well as the build-up to processing the task (during the P3 component). There was no significant main effect of horizontal electrodes or vertical electrodes.

There was no significant main effect of maths anxiety groups or stimulus type identifying that, for the N1 component, there is no significant latency difference between high and low maths anxious group as well as addition and multiplication stimuli. Again this provides evidence for an average encompassing all groups and conditions for the analysis of amplitude data.

Table 5.7:

N1 mean (ms) and standard deviation depicting the interaction between horizontal and vertical electrodes.

	Vertical Electrodes		
Horizontal Electrodes	Left	Midline	Right
Anterior	135.03 (45.57)	140.85 (37.54)	149.15 (41.62)
Centre	179.42 (72.33)	144.90 (47.75)	137.67 (31.90)
Posterior	169.85 (60.60)	142.48 (33.94)	142.95 (36.05)

P3 Component Latency Analysis

The results display the findings of the P3 latency, explaining the overall analysis, interactions and finally, main effects (see table 5.8).

Table 5.8:

P3 ANOVA F values, degrees of freedom, significance levels and effect size for latency interactions and main effects.

Interaction / Main Effect	**ANOVA**			
	F	***df***	***p***	***η²***
Horizontal x Vertical x Stim x MA	.44	3.37,94.24	.747	1.23×10^{-3}
Horizontal x Vertical x Stim	.36	3.40,98.56	.809	9.79×10^{-4}
Vertical x Stim x MA	.81	1.54,43.04	.423	1.86×10^{-3}
Horizontal x Stim x MA	.78	1.93,54.15	.462	2.00×10^{-3}
Horizontal x Vertical x MA	3.09	3.60,100.77	.381	6.88×10^{-3}
Vertical x Stim	1.80	1.53,44.47	.185	4.09×10^{-3}
Horizontal x Stim	.38	1.95,56.51	.376	2.54×10^{-3}
Horizontal x Vertical	3.08	3.52,102.11	.024	.002
Stim x MA	.40	1,28	.533	9.67×10^{-3}
Vertical x MA	.72	2.00,55.95	.493	1.32×10^{-3}
Horizontal x MA	3.14	1.46,40.88	.068	.002
Vertical	.39	2.00,57.92	.628	1.33×10^{-3}
Horizontal	15.86	1.51,43.89	<.001	.12
Stim	2.03	1,29	.165	4.82×10^{-3}
MA	2.58	1,28	.119	.03

The 3×3×2×2 analysis showed no significant interaction between horizontal, vertical electrodes, stimulus type and maths anxiety group. There was no significant interaction between stimulus type, horizontal and vertical electrodes or between horizontal, vertical electrodes and maths anxiety group. There was no significant interaction between MA group, stimulus type and horizontal electrodes or between maths anxiety group, stimulus type and vertical electrodes. There was no significant interaction found between maths anxiety group and stimulus type.

There was no significant interaction between maths anxiety group and horizontal electrodes and maths anxiety group and vertical electrodes. It was also found that there was no significant interaction between stimulus type and horizontal electrodes and stimulus type and vertical electrodes. There was a significant interaction of horizontal and vertical electrodes (see table 5.9) such that left posterior, midline and left centre, and midline and right anterior were faster. There was also a significant main effect of horizontal electrodes, such that, the P3 peaked earlier at anterior electrodes (mean = 186.59ms, SD = 36.21) but later for centre (mean = 209.04ms, SD = 36.24) and posterior (mean = 216.13ms, SD = 34.15) sites. This may be due to the shift from the closely occurring N1 and P3 components. There was no significant effect of vertical electrodes.

Again, there was no significant main effect of maths anxiety groups or stimulus type identifying that, for the P3 component, there is no significant latency difference between high and low maths anxious groups as well as addition and multiplication stimuli. This further supports the use of an overall average for amplitude measurement.

Table 5.9:

P3 mean (ms) and standard deviation depicting the interaction between horizontal and vertical electrodes.

	Vertical Electrodes		
Horizontal Electrodes	Left	Midline	Right
Anterior	194.47 (33.53)	206.60 (39.25)	209.75 (40.90)
Centre	184.08 (24.97)	203.90 (33.74)	219.55 (26.15)
Posterior	181.23 (46.18)	216.63 (34.85)	219.10 (33.45)

N400 Component Latency Analysis

Finally, the results display the findings of the N400 latency, explaining the overall analysis, interactions and finally, main effects (see table 5.10).

Table 5.10:

N400 ANOVA F values, degrees of freedom, significance levels and effect size for latency interactions and main effects.

Interaction / Main Effect	**ANOVA**			
	F	***df***	***p***	***η^2***
Horizontal x Vertical x Stim x MA	1.54	3.22,90.23	.208	4.41×10^{-3}
Horizontal x Vertical x Stim	1.92	3.20,92.70	.128	5.62×10^{-3}
Vertical x Stim x MA	.23	1.98,55.31	.790	4.42×10^{-4}
Horizontal x Stim x MA	.28	1.92,53.76	.745	7.37×10^{-4}
Horizontal x Vertical x MA	2.51	2.97,83.04	.065	.02
Vertical x Stim	1.25	1.97,57.21	.295	2.30×10^{-3}
Horizontal x Stim	.39	1.92,55.70	.679	9.93×10^{-4}
Horizontal x Vertical	1.13	3.02,87.42	.343	7.53×10^{-3}
Stim x MA	.001	1,28	.978	3.91×10^{-6}
Vertical x MA	.82	1.83,51.23	.438	3.58×10^{-3}
Horizontal x MA	2.10	1.56,43.54	.141	.02
Vertical	.57	1.81,52.59	.553	2.47×10^{-3}
Horizontal	1.71	1.55,44.82	.197	.01
Stim	.87	1,29	.359	4.10×10^{-3}
MA	.54	1,28	.470	.02

The 3×3×2×2 analysis showed no significant interaction between horizontal, vertical electrodes, stimulus type and maths anxiety group. There was no significant interaction between stimulus type, horizontal and vertical electrodes or maths anxiety group, horizontal and vertical electrodes. There was no significant interaction between maths anxiety group, stimulus type and horizontal electrodes or between maths anxiety group, stimulus type and vertical electrodes. There was no significant interaction found between maths anxiety group and stimulus type. There was also no significant interaction between maths anxiety group and horizontal electrodes or maths anxiety group and vertical electrodes. There was no significant interaction between stimulus type and horizontal electrodes and stimulus type and vertical electrodes. There was also no significant interaction of horizontal and vertical electrodes or main effect of horizontal electrodes, and vertical electrodes.

There was no significant main effect of maths anxiety groups or stimulus type identifying that, for the N400 component, there is no significant latency difference between high and low maths anxious groups as well as addition and multiplication stimuli.

To summarise, the purpose of the above analyses were to identify whether there was a significant difference between the observed latency discrepancies in MA groups. The analysis revealed that whilst there were significant effects and interactions between MA groups, stimulus types and electrodes there was no main effect of MA group or stimulus type. This permitted the use of an overall average instead of splitting averages by condition or groups. The advantage of this is that one use of GFP can be applied to identify specific component latencies (based on *a priori* assumptions). This then enables the same latency windows to be applied to each component for amplitude analysis, eliminating any bias towards group or condition.

5.3.4 ERP amplitude processing and analysis

5.3.4.1: Initial amplitude processing

Preparation and processing was kept similar to the previous study. To avoid repetition, only differences in processing of data will be mentioned.

A GFP analysis was applied across all electrodes (excluding M1, M2, VEOG, HEOG and the central reference), participants, and conditions to refine the latency period of ERP components. *A priori* assumptions based on the previous study and research suggested the emergence of four components. However, the GFP average presented the emergence of 3 components identified as P1 (43-106ms), N1 (108-269ms) and N400 (272-400ms) (see figure 5.3).

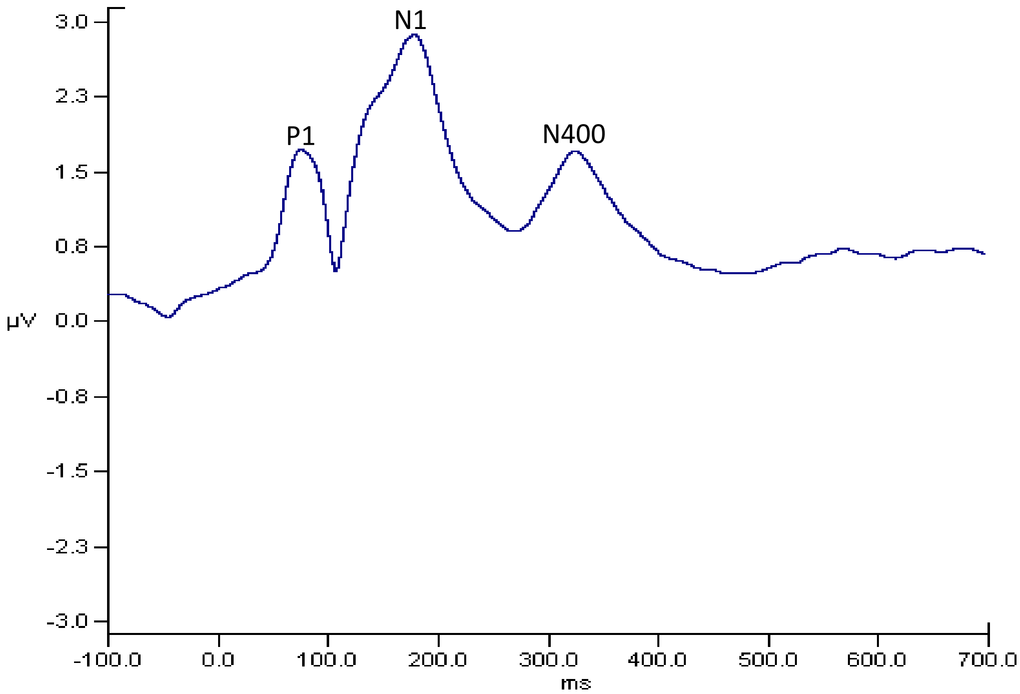

Figure 5.3: GFP electrode displaying three components for ERP analysis across the 800ms latency window.

The components were extracted from relevant electrodes (T7, Cz, T8, P5, Pz, P6, O1, Oz, O2) and four 2 (High/Low MA group) x 2 (addition/multiplication stimuli) x 3 (anterior/centre/posterior electrodes) x 3 (left/midline/right electrodes) mixed factorial ANOVAs were used to identify any interactions and main effects. These were conducted separately for the 3 components. All ANOVAs included the Greenhouse-Geisser correction to ensure type I error rates were not inflated (Greenhouse & Geisser, 1959) being that neurophysiological data is rarely homogenous.

5.3.4.2 Amplitude analysis

P1 Component Amplitude Analysis

The results display the findings of the P1 amplitude, explaining the overall analysis, interactions and finally, main effects (see table 5.11).

Table 5.11:

P1 ANOVA F values, degrees of freedom, significance levels and effect size for amplitude interactions and main effects.

Interaction / Main Effect	ANOVA			
	F	***df***	***p***	η^2
Horizontal x Vertical x Stim x MA	.46	2.74,76.73	.693	1.71×10^{-4}
Horizontal x Vertical x Stim	2.00	2.76,79.92	.126	.001
Vertical x Stim x MA	.67	1.96,54.97	.515	4.55×10^{-4}
Horizontal x Stim x MA	.20	1.20,33.72	.705	2.56×10^{-4}
Horizontal x Vertical x MA	.45	3.23,90.47	.736	1.178×10^{-3}
Vertical x Stim	.26	1.96,56.75	.765	1.77×10^{-4}
Horizontal x Stim	1.10	1.20,34.91	.314	1.38×10^{-3}
Horizontal x Vertical	13.62	3.25,94.15	<.001	.04
Stim x MA	.00	1,28	.986	4.74×10^{-7}
Vertical x MA	.79	1.96,54.76	.458	3.24×10^{-3}
Horizontal x MA	.10	1.19,33.25	.797	1.37×10^{-3}
Vertical	39.65	1.94,56.34	<.001	.16
Horizontal	6.79	1.19,34.50	.010	.09
Stim	.36	1,29	.552	2.13×10^{-3}
MA	.77	1,28	.387	.03

The 3×3×2×2 analysis showed no significant interaction between horizontal, vertical electrodes, stimulus type and maths anxiety group. There was no significant interaction between stimulus type, horizontal and vertical electrodes or between horizontal, vertical electrodes and maths anxiety group. There was no significant interaction between maths anxiety group, stimulus type and horizontal electrodes or between maths anxiety group, stimulus type and vertical electrodes.

There was no significant interaction found between maths anxiety group and stimulus type. There was no significant interaction between maths anxiety group and horizontal electrodes and maths anxiety group and vertical electrodes. There was also no significant interaction between stimulus type and horizontal electrodes and stimulus type and vertical electrodes. However, there was a significant interaction between horizontal and vertical electrodes (see table 5.12) such that left and right electrodes displayed higher P1 amplitude than midline electrodes, this can be expected due to the P1 component eliciting in the occipital region with less prominence at midline sites.

There was no significant main effect of maths anxiety groups or stimulus type. There was a significant main effect of horizontal electrodes, such that there was a higher P1 amplitude at posterior electrodes (mean = .13mv, SD = 2.13) than at centre (mean = -.34mv, SD = 2.42) and anterior sites (mean = -1.30mv, SD = 2.08). This expected due to contrast perception being exhibited in the occipital region. There was also a significant main effect of vertical electrodes such that there was a higher P1 amplitude at right (mean = .16mv, SD = 2.15) and left (mean = -.05mv, SD = 1.88) electrodes than at midline sites (mean = -1.62mv, SD = 2.07).

Table 5.12:

P1 mean (mv) and standard deviation depicting the interaction between horizontal and vertical electrodes.

	Vertical Electrodes		
Horizontal Electrodes	Left	Midline	Right
Anterior	-1.10 (1.48)	.11 (1.73)	.85 (1.88)
Centre	-2.16 (2.71)	-2.02 (2.38)	-.70 (2.01)
Posterior	-.65 (1.74)	.88 (2.13)	.23 (2.08)

N1 Component Amplitude Analysis

The results display the findings of the N1 amplitude, explaining the overall analysis, interactions and finally, main effects (see table 5.13).

Table 5.13:

N1 ANOVA F values, degrees of freedom, significance levels and effect size for amplitude interactions and main effects.

Interaction / Main Effect	**ANOVA**			
	F	***df***	***p***	**η^2**
Horizontal x Vertical x Stim x MA	.20	2.05,57.35	.823	.01
Horizontal x Vertical x Stim	.64	2.06,59.80	.538	2.74×10^{-4}
Vertical x Stim x MA	.18	1.98,55.54	.835	9.63×10^{-5}
Horizontal x Stim x MA	.03	1.44,40.32	.946	1.31×10^{-5}
Horizontal x Vertical x MA	2.56	2.96,82.83	.062	4.62×10^{-3}
Vertical x Stim	.39	1.98,57.47	.681	2.01×10^{-4}
Horizontal x Stim	1.12	1.44,41.80	.318	5.20×10^{-4}
Horizontal x Vertical	30.31	3.09,89.71	<.001	.06
Stim x MA	.17	1,28	.680	5.66×10^{-4}
Vertical x MA	3.06	1.95,54.49	.056	.01
Horizontal x MA	2.09	1.21,33.97	.155	.03
Vertical	20.98	1.93,56.04	<.001	.08
Horizontal	5.61	1.20,34.80	.019	.08
Stim	.50	1,29	.486	1.58×10^{-3}
MA	.14	1,28	.709	5.05×10^{-3}

The 3×3×2×2 analysis showed no significant interaction between horizontal, vertical electrodes, stimulus type and maths anxiety group. There was no significant interaction between stimulus type, horizontal and vertical electrodes or between horizontal, vertical electrodes and maths anxiety group. There was no significant interaction between maths anxiety group, stimulus type and horizontal electrodes or between maths anxiety group, stimulus type and vertical electrodes.

There was no significant interaction found between maths anxiety group and stimulus type. There was no significant interaction between maths anxiety group and horizontal electrodes and maths anxiety group and vertical electrodes. There was also no significant interaction between stimulus type and horizontal electrodes and stimulus type and vertical electrodes. There was a significant interaction between horizontal and vertical electrodes (see table 5.14), such that higher N1 amplitudes were observed in right anterior and left posterior sites and a high positive amplitude across midline electrodes.

There was no significant main effect of maths anxiety groups or stimulus type. However, there was a significant main effect of horizontal electrodes, such that a higher N1 amplitude was elicited at posterior electrodes (mean = 1.06mv, SD = 1.06) than at centre (mean = 1.78mv, SD = 1.78) and anterior electrodes (mean = 2.49mv, SD = 2.52). There was also a significant main effect of vertical electrodes such that there was a higher N1 amplitude towards right electrodes (mean = 1.06mv, SD = 2.50) than at left (mean = 1.80mv, SD = 2.30) and midline sites (mean = 2.47mv, SD = 2.81).

Table 5.14:

N1 mean (mv) and standard deviation depicting the interaction between horizontal and vertical electrodes.

	Vertical Electrodes		
Horizontal Electrodes	Left	Midline	Right
Anterior	2.71 (1.76)	1.80 (1.98)	.88 (2.70)
Centre	3.86 (2.75)	2.33 (2.41)	1.23 (2.69)
Posterior	.90 (2.04)	1.21 (2.64)	1.07 (2.78)

N400 Component Amplitude Analysis

The results display the findings of the N400 amplitude, explaining the overall analysis, interactions and finally, main effects (see table 5.15).

Table 5.15:

N400 ANOVA F values, degrees of freedom and significance levels for amplitude interactions and main effects.

Interaction / Main Effect	**ANOVA**			
	F	***df***	***p***	***η^2***
Horizontal x Vertical x Stim x MA	1.19	2.64,73.97	.317	6.76×10^{-4}
Horizontal x Vertical x Stim	8.65	2.67,77.34	<.001	4.94×10^{-3}
Vertical x Stim x MA	.45	1.94,54.29	.635	3.32×10^{-4}
Horizontal x Stim x MA	.04	1.52,42.43	.918	2.99×10^{-5}
Horizontal x Vertical x MA	.58	2.52,70.49	.600	1.06×10^{-3}
Vertical x Stim	21.87	1.95,56.48	<.001	.01
Horizontal x Stim	.26	1.52,43.93	.710	1.69×10^{-4}
Horizontal x Vertical	25.57	2.54,73.62	<.001	.05
Stim x MA	.16	1,28	.689	7.20×10^{-4}
Vertical x MA	1.55	1.92,53.61	.223	4.79×10^{-3}
Horizontal x MA	.89	1.29,36.06	.378	7.25×10^{-3}
Vertical	26.52	1.89,54.81	<.001	.08
Horizontal	33.30	1.31,38.10	<.001	.27
Stim	.64	1,29	.432	2.71×10^{-3}
MA	3.40	1,28	.076	.11

The 3×3×2×2 analysis showed no significant interaction between horizontal, vertical electrodes, stimulus type and maths anxiety group. There was a significant interaction between stimulus type, horizontal and vertical electrodes (see table 5.16), such that higher N400 amplitude were seen in posterior electrodes across right and midline sites for addition. Addition may have been considered more difficult, hence the higher N400 amplitude and accuracy scores. There was no significant interaction between horizontal, vertical electrodes and maths anxiety group. There was no significant interaction between maths anxiety group, stimulus type and horizontal electrodes or between maths anxiety group, stimulus type and vertical electrodes.

Table 5.16:

N400 mean (mv) and standard deviation depicting the interaction between horizontal electrodes, vertical electrodes and stimulus type.

		Stimulus Type	
Horizontal Electrodes	**Vertical Electrodes**	**Addition**	**Multiplication**
Anterior	Left	3.18 (1.75)	2.30 (1.70)
	Midline	2.64 (2.39)	2.89 (2.35)
	Right	-.17 (1.95)	1.04 (1.50)
Centre	Left	2.79 (1.79)	2.42 (1.63)
	Midline	2.17 (2.28)	2.46 (2.08)
	Right	1.41 (2.06)	1.92 (1.66)
Posterior	Left	.44 (1.99)	.42 (1.64)
	Midline	-.41 (2.20)	-.13 (1.61)
	Right	-.54 (2.23)	.01 (1.77)

There was no significant interaction found between maths anxiety group and stimulus type. There was no significant interaction between maths anxiety group and horizontal electrodes and maths anxiety group and vertical electrodes. There was also no significant interaction between stimulus type and horizontal electrodes. However, there was a significant interaction between stimulus type and vertical electrodes, such that higher N400 amplitudes were elicited in left electrodes for multiplication (mean = 1.71mv, SD = 1.88) but also at midline (mean = 1.47mv, SD = 2.42) and right sites (mean = .24mv, SD = 1.81) for addition. There was also a significant interaction between horizontal and vertical electrodes (see table 5.17), such that higher N400 amplitude were elicited at midline and right electrodes in posterior regions. The N400 component amplitude remained higher for right electrodes at anterior and centre sites compared to left and midline electrodes.

There was no significant main effect of maths anxiety groups or stimulus type. However, there was a significant main effect of horizontal electrodes, such that higher N400 amplitudes were identified at posterior electrodes (mean = -.04mv, SD = 1.93) than anterior (mean = 1.98mv, SD = 2.27) and centre sites (mean = 2.20mv, SD = 1.95). There was also a significant main effect of vertical electrodes such, that there was a higher N400 amplitude at right electrodes (mean = .61mv, SD = 2.06) than midline (mean = 1.60mv, SD = 2.52) and left sites (mean = 1.92mv, SD = 2.05).

Table 5.17:

N400 mean and standard deviation depicting the interaction between horizontal and vertical electrodes.

	Vertical Electrodes		
Horizontal Electrodes	Left	Midline	Right
Anterior	2.74 (1.77)	2.60 (1.71)	.43 (1.81)
Centre	2.76 (2.36)	2.31 (2.17)	-.27 (1.91)
Posterior	.44 (1.83)	1.67 (1.87)	-.27 (2.02)

5.3.4.3: Post-hoc component analysis

Whilst the above analysis shows the N1 component spanning 161ms, it was noted that this could be a combination of two components overlapping in the average ERP due to a positive deflection on a typically negative N1 component. This was later confirmed after observing the topography within the joint component (see figure 5.3). *A post-hoc* split was applied to the large component (108-269ms) into two smaller components, thought to represent the N1 (108-158ms) and P3 (159-269ms) components. This was also identified due to posterior electrodes eliciting a negative peak (N1), followed closely by a positive peak (P3) in left central parietal regions, identifying an overlap in components (see figure 5.5). A further two 2×2×3×3 Factorial mixed ANOVAs were conducted to identify any interactions and main effects. Again, these were conducted separately for the two components and included the Greenhouse-Geisser correction. A breakdown of the overall analysis for the N1 and then the P3 is listed below. Alongside summaries of components, topographical maps are used illustrating positive inflections highlighted in red and negative in blue. Translucent shapes highlight the dipoles averaged over component latencies.

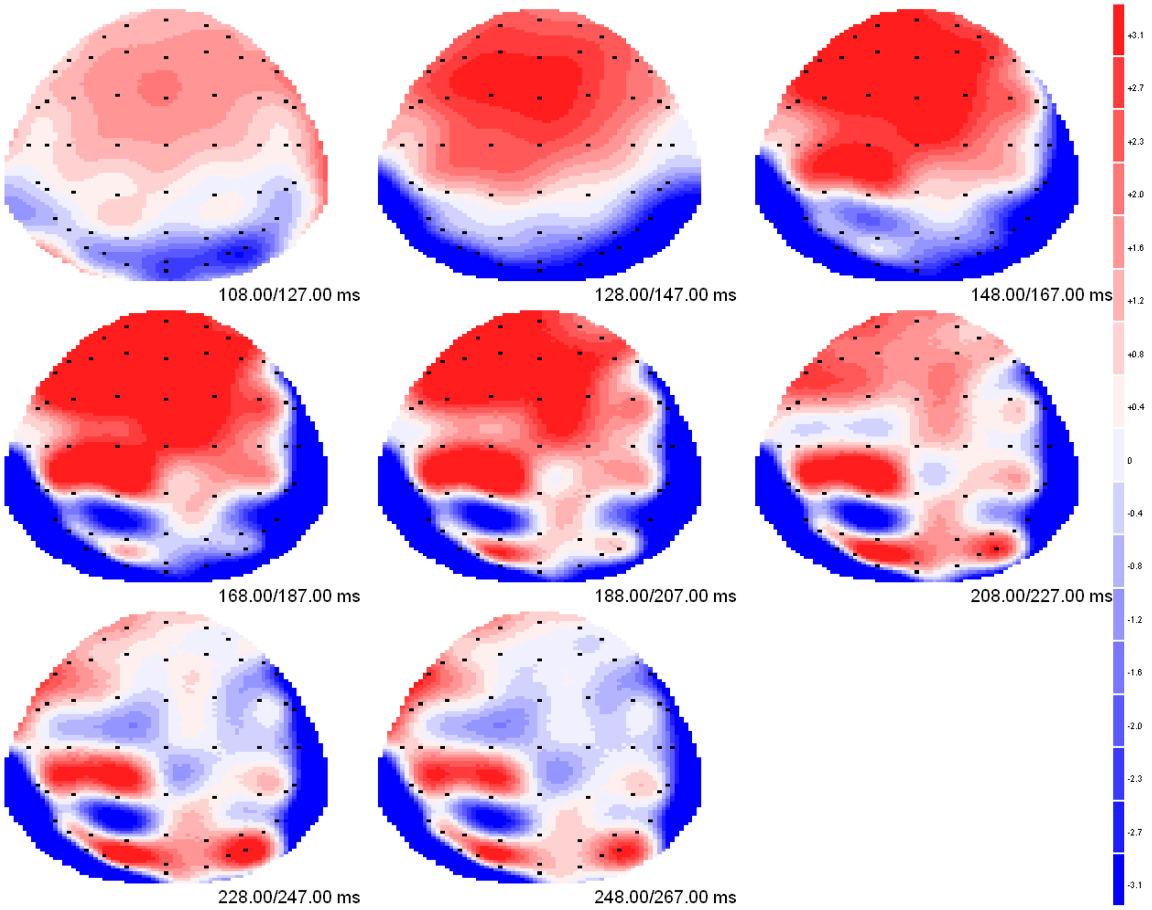

Figure 5.5: Topography of two dipoles (N1 followed by P3) at component crossover over initial N1 latency window from top left (108-127ms) to bottom right (248-269ms). The colour key (right) shows positive (red) and negative (blue) inflections.

N1 Component *Post-hoc* Amplitude Analysis

The results display the findings of the N1 amplitude, explaining the overall analysis, interactions and finally, main effects (see table 5.18).

Table 5.18:

N1 ANOVA F values, degrees of freedom, significance levels and effect size for amplitude interactions and main effects.

Interaction / Main Effect	**ANOVA**			
	F	***df***	***p***	η^2
Horizontal x Vertical x Stim x MA	.50	2.56,71.69	.653	1.08 x 10^{-3}
Horizontal x Vertical x Stim	.74	2.59,75.05	.511	6.15 x 10^{-3}
Vertical x Stim x MA	.14	1.96,54.94	.140	3.47 x 10^{-5}
Horizontal x Stim x MA	.31	1.47,41.20	.666	1.43 x 10^{-4}
Horizontal x Vertical x MA	1.80	2.66,74.56	.161	2.52 x 10^{-3}
Vertical x Stim	4.47	1.94,56.85	.016	1.07 x 10^{-3}
Horizontal x Stim	2.33	1.47,42.63	.123	1.04 x 10^{-3}
Horizontal x Vertical	10.29	2.86,82.92	<.001	.01
Stim x MA	.01	1,28	.905	4.97 x 10^{-4}
Vertical x MA	4.03	1.68,46.90	.031	.01
Horizontal x MA	2.96	1.18,32.98	.089	.05
Vertical	7.98	1.74,50.54	.002	.03
Horizontal	12.51	1.18,34.21	.001	.21
Stim	.32	1,29	.575	4.97 x 10^{-4}
MA	1.23	1,28	.276	.04

The 3×3×2×2 analysis showed no significant interaction between horizontal, vertical electrodes, stimulus type and maths anxiety group. There was no significant interaction between stimulus type, horizontal and vertical electrodes or between horizontal, vertical electrodes and maths anxiety group. There was no significant interaction between maths anxiety group, stimulus type and horizontal electrodes or between maths anxiety group, stimulus type and vertical electrodes. There was no significant interaction found between maths anxiety group and stimulus type or between MA group and horizontal electrodes.

There was a significant interaction between maths anxiety group and vertical electrodes, such that higher N1 amplitudes were identified at right electrodes for low maths anxious individuals (mean = -2.31mv, SD = 3.59) than for high maths anxious individuals (mean = -.63mv, SD = 3.35). There was no significant interaction between stimulus type and horizontal electrodes. There was a significant interaction between stimulus type and vertical electrodes, such that higher N1 amplitudes were identified for addition across left (mean = -.85mv, SD = 2.75) and midline (mean -.39mv, SD = 3.60) sites than for multiplication (mean = -.559mv, SD = 3.70, mean = -.10mv, SD = 3.66, respectively). There was also a significant interaction between horizontal and vertical electrodes (see table 5.19), such that higher N2 amplitudes were shown to elicit at posterior sites and at centre right electrodes. This is likely due to the N1 tendency to elicit in posterior electrodes (see figure 5.6).

There was no significant main effect of maths anxiety groups or stimulus type. However, there was a significant main effect of horizontal electrodes, such that higher N1 amplitudes were identified at posterior sites (mean = -2.39mv, SD = 3.73) than at anterior (mean = -1.15mv, SD = 2.94) and centre sites (mean = -1.12, SD = 3.11). There was also a significant main effect of vertical electrodes such that there was a higher N1 amplitude at right electrodes (mean = -1.47mv, SD = 3.57) than at left (mean = -.70mv, SD = 2.95) and centre (mean = -.25mv, SD = 3.98).

Table 5.19:

N1 mean (mv) and standard deviation depicting the interaction between horizontal and vertical electrodes.

	Vertical Electrodes		
Horizontal Electrodes	Left	Midline	Right
Anterior	.81 (2.22)	-.76 (2.33)	-2.16 (3.39)
Centre	2.23 (3.75)	-.53 (2.98)	-2.44 (3.72)
Posterior	.31 (2.30)	-2.16 (3.42)	-2.57 (4.09)

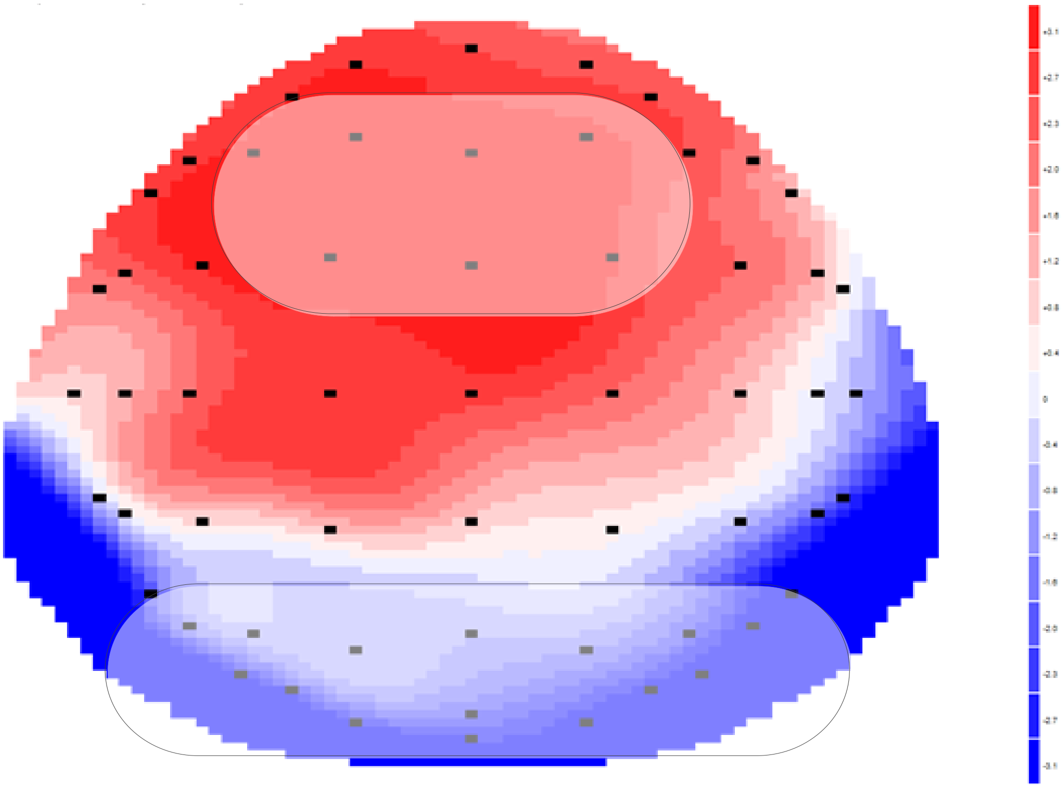

Figure 5.6: Topography showing horizontal and vertical differences at dipoles during N1 component averaged over 108-158ms.

P3 Component *Post-hoc* Amplitude Analysis

The results display the findings of the N1 amplitude, explaining the overall analysis, interactions and finally, main effects (see table 5.20).

Table 5.20:

P3 ANOVA F values, degrees of freedom and significance levels for amplitude interactions and main effects.

Interaction / Main Effect	**ANOVA**			
	F	***df***	***p***	***η²***
Horizontal x Vertical x Stim x MA	.20	2.12,59.39	.829	1.21×10^{-3}
Horizontal x Vertical x Stim	1.46	2.13,61.88	.241	8.44×10^{-4}
Vertical x Stim x MA	.21	1.99,55.59	.812	1.51×10^{-4}
Horizontal x Stim x MA	.19	1.65,46.09	.789	9.47×10^{-5}
Horizontal x Vertical x MA	1.70	3.37,94.41	.168	4.76×10^{-3}
Vertical x Stim	2.14	1.98,57.52	.128	1.52×10^{-3}
Horizontal x Stim	1.20	1.64,47.64	.304	5.93×10^{-4}
Horizontal x Vertical	37.35	3.36,97.46	<.001	.11
Stim x MA	.13	1,28	.719	5.51×10^{-4}
Vertical x MA	1.65	1.98,55.48	.202	8.54×10^{-3}
Horizontal x MA	.69	1.41,39.41	.462	8.18×10^{-3}
Vertical	19.58	1.99,57.66	<.001	.10
Horizontal	.98	1.40,40.54	.357	.01
Stim	.19	1,29	.669	7.56×10^{-4}
MA	.004	1,28	.947	1.59×10^{-4}

The 3×3×2×2 analysis showed no significant interaction between horizontal, vertical electrodes, stimulus type and maths anxiety group. There was no significant interaction between stimulus type, horizontal and vertical electrodes or between horizontal, vertical electrodes and maths anxiety group. There was no significant interaction between maths anxiety group, stimulus type and horizontal electrodes or between maths anxiety group, stimulus type and vertical electrodes.

There was no significant interaction found between maths anxiety group and stimulus type. There was no significant interaction between maths anxiety group and horizontal electrodes and maths anxiety group and vertical electrodes. There was also no significant interaction between stimulus type and horizontal electrodes and stimulus type and vertical electrodes. However, there was a significant interaction between horizontal and vertical electrodes (see table 5.21) such that anterior midline and left sites showed higher P3 amplitudes. This can be seen in figure 5.7 showing the positive component at midline and left electrodes.

There was no significant main effect of maths anxiety groups, stimulus type or horizontal electrodes. However, there was a significant main effect of vertical electrodes, such that there was a higher P3 amplitude at midline electrodes (mean = 3.75mv, SD = 2.76) than left (mean = 2.99mv, SD = 2.45) and right (mean = 2.25mv, SD = 2.64).

Table 5.21:

P3 mean (mv) and standard deviation depicting the interaction between horizontal and vertical electrodes.

	Vertical Electrodes		
Horizontal Electrodes	Left	Midline	Right
Anterior	3.59 (1.88)	3.02 (2.40)	2.36 (2.86)
Centre	4.59 (2.80)	3.67 (2.72)	2.98 (2.58)
Posterior	1.16 (2.22)	2.80 (2.84)	2.80 (2.54)

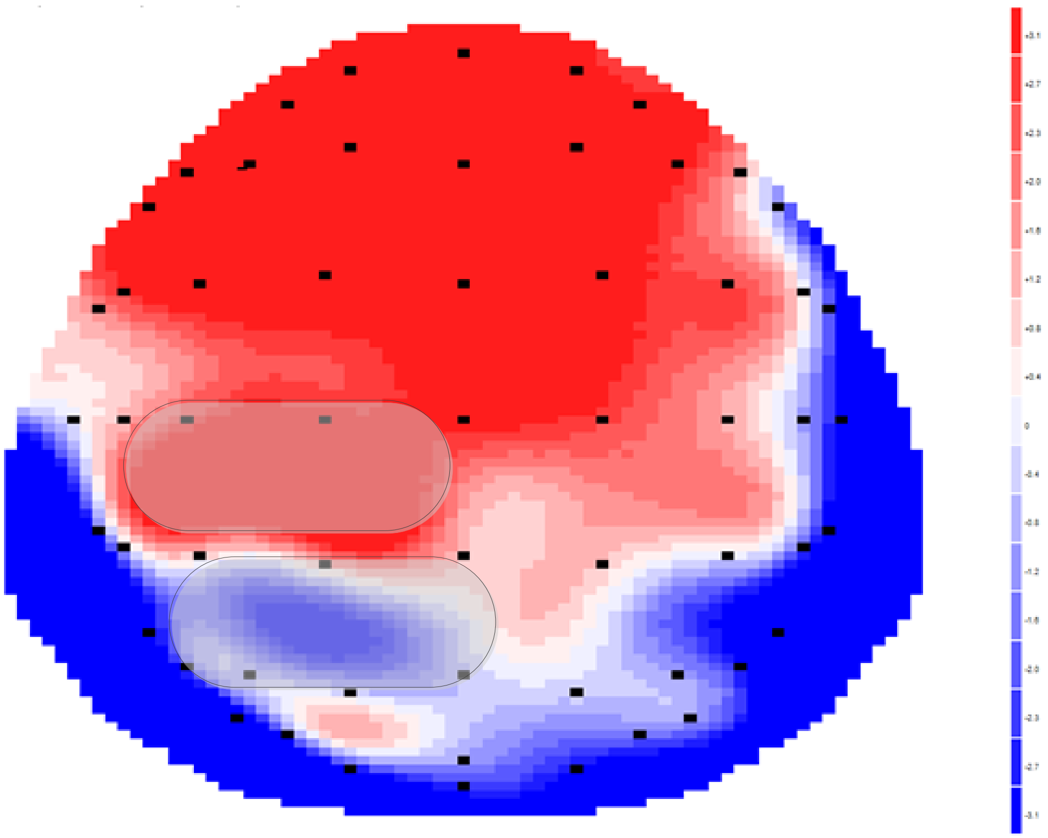

Figure 5.7: Topography showing horizontal and vertical differences at P3 component, highlighting the P3 dipole averaged over 159-269ms.

Whilst the initial amplitude analysis highlighted a large component, not indicative of an N1 or P3 component, the *post-hoc* split and ANOVAs of components above are more representative of N1 and P3 components with the N1 eliciting negative inflections and the P3 eliciting positive inflections in appropriate regions.

5.3.5: Gamma activity

5.3.5.1: Gamma activity processing

To analyse gamma band activity, data was corrected for ocular artefacts and then fast Fourier transformed (cosine 10% taper). Amplitude was squared to power (μV^2) to observe frequency contribution over time. To rule out movement artefacts in the gamma band, the earliest response time across the study was taken. This was found to be at 2400ms so data were splined to 2048 points to fit with the frequency analysis parameters (see chapter 2). Data was then extracted from the gamma frequency band (35-70 Hz).This segment was chosen based on previous research observing gamma activity and threat (30-50Hz; Luo et al., 2009, 2007), anxiety (35-70; Oathes et al., 2008), decision making (~40Hz) and visual processing (~60Hz; (Castelhano, Duarte, Wibral, Rodriguez, & Castelo-Branco, 2014). Using electrodes across temporal and parietal regions, based on *a priori* assumptions (T3/T7, C3, C4, T4/T8, T5/P7, P3, P4, T6/P8), a 2 (high/low MA group) × 2 (addition/multiplication stimuli) × 2 (anterior/posterior electrodes) × 4 (left/midline left/midline right/right electrodes) mixed measures ANOVA was conducted to identify any interactions and main effects (see figure 5.8 for electrodes used in frequency analysis). All ANOVAs included the Greenhouse-Geisser correction. A breakdown of the overall analysis is listed below (see table 5.22).

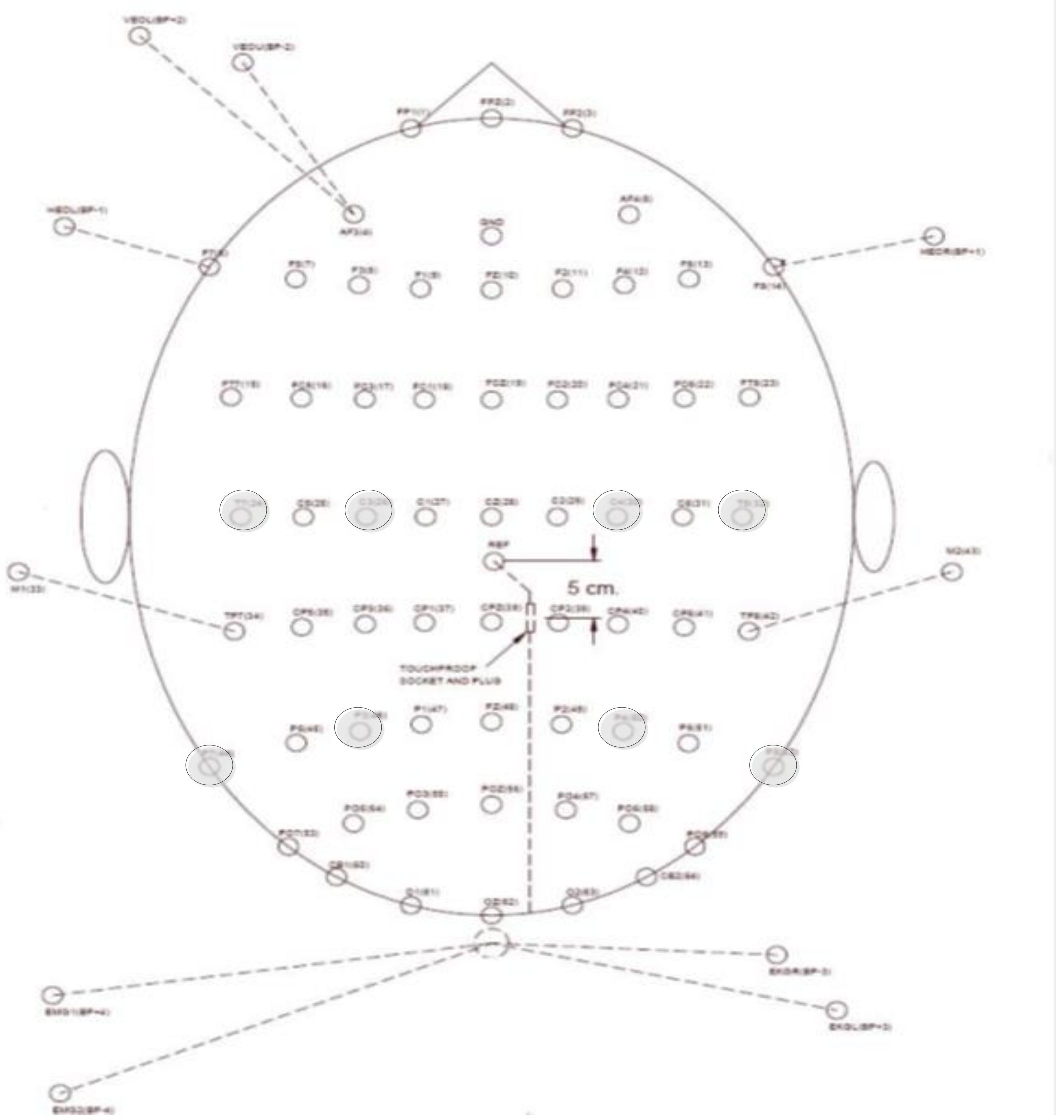

Figure 5.8: Neuroscan Synamps 64 channel Quik-Caps electrode layout with sites used for gamma analysis highlighted.

5.3.5.2: Gamma activity analysis

Table 5.22:

Gamma activity ANOVA F values, degrees of freedom, significance levels and effect size for interactions and main effects.

Interaction / Main Effect	ANOVA			
	F	***df***	***p***	***η²***
Horizontal x Vertical x Stim x MA	1.10	1.84,51.51	.336	.01
Horizontal x Vertical x Stim	1.24	1.81,53.12	.294	7.85×10^{-4}
Vertical x Stim x MA	.85	1.88,52.70	.429	3.88×10^{-4}
Horizontal x Stim x MA	.19	1,28	.671	7.40×10^{-4}
Horizontal x Vertical x MA	1.01	1.50,42.03	.376	5.50×10^{-3}
Vertical x Stim	1.08	1.87,54.35	.344	
Horizontal x Stim	.17	1,29	.683	6.64×10^{-5}
Horizontal x Vertical	1.01	1.56,43.32	.355	5.50×10^{-3}
Stim x MA	.58	1,28	.454	7.85×10^{-4}
Vertical x MA	.86	1.47,41.03	.400.	7.85×10^{-3}
Horizontal x MA	5.09	1,28	.032	.05
Vertical	1.38	1.45,42.16	.258	.001
Horizontal	6.35	1,29	.018	.08
Stim	.44	1,29	.514	7.85×10^{-4}
MA	4.78	1,28	.037	.15

There were no significant four-or three-way interactions (see table 5.22). There was a significant two-way interaction between MA group and horizontal electrodes (see table 5.23) such that higher gamma power was elicited at anterior regions but was higher for high maths anxious individuals. There were no other two-way interactions. There was a significant main effect of horizontal electrodes, such that there was higher gamma power in temporal and central regions (mean = .05μV², SD = .082) than parietal (mean = .02μV², SD = .022).

Table 5.23:

Mean power (μV²) and standard deviation depicting the interaction between horizontal and MA group.

	Maths Anxiety	
Horizontal Electrodes	**Low**	**High**
Anterior	.02 (.03)	.08 (.13)
Posterior	.01 (.01)	.03 (.03)

Finally, there was a significant main effect of maths anxiety groups such that those with HMA showed higher gamma power (mean = .05μV², SD = .07) than those with LMA (mean = .01μV², SD = .01). This shows high maths anxious individuals experience higher gamma power than low maths anxious individuals throughout the study. There were no other main effects.

5.3.6 Analysis Summary

To conclude, this section will highlight and summarise the significant ERP findings for each component and the gamma activity analysis. Significant latency differences will be omitted as it was previously established that the latency window was adequate for amplitude analyses (section 5.3.3.2). The summary will include significant main effects and interactions of ERP amplitude analyses (P1, N400, *post-hoc* N1 and P3) and gamma frequency analysis, not inlcuding main effects of horizontal and vertical electrodes and interactions between horizontal and vertical electrodes. This will be ommitted due to their clear findings on where components spatially appear, which is inline with previous research (see section 5.4).

The P1 and P3 showed no significant main effects or interactions, except those concerning only horizontal and vertical electrodes. The N1 showed a significant interaction between vertical electrodes and stimulus type, such that higher amplitudes were identified for addition across left and midline sites than for multiplication at the same electrodes. There was also a significant interaction between MA group and vertical electrodes, such that higher N1 amplitudes were identified at right electrodes for those with LMA than for those with HMA.

The N400 showed a significant interaction between stimulus type, horizontal and vertical electrodes such that, higher amplitudes were seen in posterior electrodes across right and midline sites, for addition. There was also a significant interaction between stimulus type and vertical electrodes, such that higher N400 amplitudes were elicited in left electrodes for multiplication but also at midline and right sites for addition.

The frequency analysis showed a significant main effect of MA group whereby, those with HMA showed higher gamma power than those with LMA overall. This analysis also showed a significant interaction between horizontal electrodes and MA group, such that that higher gamma power was elicited at anterior regions but was higher for high maths anxious individuals. In the discussion (see section 5.4), the results outlined above will be explained in relation to psychological and behavioural effects, theorising why these results were gained.

5.4: Discussion

This study set out to ERP differences between MA groups using stimuli with increased difficulty levels. It was hypothesised that electrophysiological correlates would show differences consistent with behavioural results typically experienced by those with HMA (e.g. delayed reaction time and decreased in accuracy). It also aimed to observe differences in gamma activity between high and low maths anxious groups and conditions. The above section identified some promising results, particularly concerning gamma band activity and further builds on the foundation of the previous study. It was predicted that would be differences in gamma power between high and low maths anxious individuals due to its involvement in threat and anxiety processing. The neurophysiological data will be explained subsequent to the behavioural aspects discussed below:

5.4.1 Behavioural Measures

Correlation results were consistent with findings from study one, whereby there was a weak positive correlation between MAS-UK and STAI scores. This data supports that MA exists separately, as noted by Richardson & Suinn (1972).

There was no significant difference in MA groups for accuracy however, the significant main effect of stimulus type shows there were more correct answers given for multiplication than addition. This could be due to an artefact whereby participants may have developed a technique to calculate multiplication quicker. Multiplication complexity tends to be increased in research when a larger amount of digits are used (Zago et al., 2001) for example, 35×15= would be more difficult than 18×9=. Participants may have applied a technique multiplying only the last digits to choose the correct answer more easily. Addition is made more difficult by increasing digits as well as ensuring that the correct answer requires a carry-over (Geary, Hoard, Byrd-Craven, & Catherine DeSoto, 2004) for example, 25+37= would be considered more difficult than 13+24=, which places a larger demand on attentional resources as calculating the last digit becomes more challenging. This may explain why higher accuracy scores were present for multiplication.

In contrast, reaction time was shown to be quicker for addition overall. If addition was seen to be more difficult, a slower reaction time would have been expected. Previous research has shown that when faced with a difficult maths problems individuals will often guess to avoid threat or anxiety (Ashcraft & Faust, 1994) which may explain the quicker reaction time and poorer accuracy for addition. Overall, low maths anxious individuals had quicker reaction time than high maths anxious individuals. This result provides support for many previous behavioural studies showing that high maths anxious individuals struggle more with math based tasks and will, on average, take longer to problem solve in these situations (Ashcraft & Kirk, 2001).

5.4.2 ERP Latency Analysis

A small latency difference was observed between high and low MA groups (between 10-20ms). The analysis showed latency differences between high and low maths anxious groups as well as differences between addition and multiplication to be non-significant, which permitted a GFP analysis to be conducted on all groups and conditions. It could be expected that a latency shift was caused by differences in MA groups, as previous behavioural studies have shown (Faust et al., 1996; Maloney et al., 2011), however it is more likely that this was a population distinction created by individual differences within the two MA groups. Due to the lack of significant results the following amplitude analysis proceeded.

5.4.3 ERP Amplitude Analysis

Originally, the inspection of the GFP calculation showed 3 peaks but the large, second peak was noted to represent two individual components. This then made it difficult to differentiate between the two components to get an average for the N1 and a separate one for the P3. The N1 and P3 *post-hoc* split will be discussed following a discussion of the P1 and N400 components.

5.4.3.1 P1 Component Analysis

Significant main effects for the P1 were identified for both horizontal and vertical electrodes as well as a significant interaction between horizontal and vertical electrodes. The main effect of horizontal electrodes showed a higher P1 amplitude at posterior regions whilst the main effect of vertical electrodes showed a higher P1 amplitude over the right hemisphere. Overall, the significant interaction between horizontal and vertical electrodes showed higher P1 amplitude at posterior left and right electrodes. This is to be expected as the P1 has been shown to represent contrast perception in occipital regions (Odom et al., 2004). The P1 is generally elicited during checkerboard or similar light flashing tasks and due to the stimuli being presented in black and white, this component is in accordance. The high amplitude of the P1 shown here can also be expected due to the demand of a quick response required from participants (Vogel & Luck, 2000).

5.4.3.2 N400 Component Analysis

Similar main effects and interactions were experienced for the N400 component with higher amplitudes at posterior right electrodes overall. The significant interaction between stimulus type, horizontal and vertical electrodes supports the role of the N400 theorised to be manipulated by task difficulty with harder tasks eliciting a higher N400 amplitude (Jost et al., 2004). This can be seen in table 5.16 with higher amplitudes being exhibited for addition in right and midline electrodes and for multiplication in right electrodes. This supports previous research showing a higher N400 amplitude for difficult maths processing (Atchley & Kwasny, 2003; Jost et al., 2004). Higher amplitudes were also elicited in posterior electrodes with smaller N400s at centre and anterior electrodes. This component has been shown to be smaller when correct solutions are presented (Niedeggen & Rösler, 1999), which implies that the calculation process (especially during difficult processing) relies heavily on working memory and fact retrieval. However, as there were no main effects or interactions involving MA, it is likely that those with HMA do not have a working memory deficit, suggested by Maloney et al. (2011), being that they are still able to apply working memory resources to the primary task.

5.4.3.3 N1 Component Analysis

The initial large N1 component showed similar characteristics to the P1 in that there were significant main effects and interactions across horizontal and vertical electrodes. It would be expected that this would show a higher N1 amplitude at posterior electrodes. However, this component was rarely below 1mv, whereas the typical N1 elicits a negative component. For example; the previous study exhibited a large N1 (-1.57mv) at electrode O1 (posterior left) in comparison to the current study (.88mv) at the same site. This again gave rise to the thought that this component may contain two components rather than a large, single component. After the components were separated the N1 showed similar main effects and interactions across horizontal and vertical electrodes. However, this was now indicative of a typical N1 component where higher amplitudes were elicited in posterior electrodes across the occipital region (Hopf, Vogel, Woodman, Heinze, & Luck, 2002) and inferior temporal regions (Bokura et al., 2001). This supports previous research in regard to the location, latency and function of the N1, which is theorised to represent object recognition (Wang & Suemitsu, 2007).

Higher N1 amplitudes were also elicited in the right hemisphere overall, supporting previous findings that the right hemisphere has a large involvement in maths processing (Szűcs & Csépe, 2005b). The significant interaction between stimulus type and vertical electrodes also supports previous research where complex multiplication elicits higher activation in the right hemisphere (Kiefer & Dehaene, 1997). The significant interaction between MA and vertical electrodes identified that low maths anxious participants showed a higher N1 amplitude than high maths anxious individuals at right electrodes, indicating higher activity during recognition. An explanation for this can be provided by research noting that the N1's amplitude increases for attended-location stimuli than neutral or distributed attention conditions (Vogel & Luck, 2000). Those with LMA may attend to the problem more readily than those with HMA who show a decreased N1. A further explanation for a reduced N1 amplitude has been shown where an increased level of arousal (due to time pressure or threat perception) can lead to a smaller N1 (Hopf et al., 2002). Attentional control theory (Eysenck et al., 2007) explains part of this in that a smaller N1 is produced because feeling of anxiety consume resources needed for recognition. However, the results do not show that this had any behavioural repercussions as there were no significant differences between MA groups for accuracy.

5.4.3.4 P3 Component Analysis

The P3 component showed a significant interaction between horizontal and vertical electrodes and a significant main effect of vertical electrodes, whereby higher P3 amplitudes were elicited at anterior left sites. Figure 5.7 clearly identifies the dipole showing the positive component occurring between electrodes T7 and Cz, extending into parietal regions, where the P3 is typically represented (Coull, 1998), supporting the representation of the P3 for processing maths stimuli (Ullsperger, Freude, & Erdmann, 2001).

Overall, there was no significant main effect or interaction involving MA group. These results infer that complex addition and multiplication provides no significant neurophysiological effects between high and low maths anxious individuals however, this is not consistent with previous behavioural MA research (Ashcraft & Moore, 2009). Whilst this and previous behavioural research have identified differences between MA groups, it may be that ERP analyses in regions associated with maths processing cannot clearly identify a link to behavioural differences in MA groups.

5.4.4 Gamma Activity Results

Being confronted with maths based tasks is considered anxiety inducing (affecting attentional resources) for those with HMA (Ashcraft & Krause, 2007). The gamma band has been associated with attention (Fell, Fernández, Klaver, Elger, & Fries, 2003; Jensen et al., 2007; Müller, Gruber, & Keil, 2000), threat and anxiety (Luo et al., 2007a; Maratos et al., 2012; Oathes et al., 2008) therefore, it was fitting that this study explored gamma activity in order to understand whether those with HMA experienced similar gamma differences in response to perceived negative stimuli.

The significant main effect of MA showed higher gamma activity in individuals with HMA. It can be assumed that those with HMA would experience more threat towards maths stimuli and therefore, have higher gamma activity. The significant interaction between horizontal electrodes and MA also identified increased gamma activity for high maths anxious individuals, at anterior temporal sites. This higher gamma activity in temporal regions has been previously shown when individuals are presented with threat-related faces (Luo et al., 2007a). It can be theorised that a similar process occurs here where those with HMA experience significantly higher gamma activity due to perceived threat of maths stimuli and calculation.

This relates to attentional control research, for example, (Young et al., 2012) state that increased activity of this nature subsequently reduces activity in regions associated with memory and numerical processing. Support also comes from Eysenck et al.'s (2007) attentional control theory, whereby the lack of attentional resources needed for numerical processing are consumed by threat perception which in turn may have contributed to the significantly increased reaction time for high maths anxious individuals. This may to bridge the gap between behavioural and neurophysiological effects of MA.

5.4.4 Summary

The above gamma activity results have contributed to understanding the neurophysiological effects of MA however; there were flaws in this research. Gamma activity (being in higher bands of activity) has a lower power than typical EEG bands, which can result in a higher contamination of muscle artefacts (Nunez & Srinivasan, 2006), meaning that the main effect and interaction of MA was caused by higher muscle activity. However, this could further identify increased tension towards maths problems in high maths anxious individuals. Previous research has found that those with high anxiety have increased muscular tonus during stressful tasks (Hazlett, McLeod, & Hoehn-Saric, 1994) suggesting that those with HMA could have experienced this form of artefact when stress inducing stimuli were presented.

The above results indicate that those with HMA consume attentional resources due to a perceived threat, typically causing poorer accuracy and slower reaction time than low maths anxious individuals. However, this study only implemented numerical tasks indicating that high maths anxious individuals may perceive other non-numerical stimuli as threatening and could be just anxious in evaluation situations. To identify whether high maths anxious individuals show attentional bias and threat perception to numerical stimuli the following study will include both numerical and non-numerical tasks to act as a control.

In conclusion, ERP results identified few differences between MA groups but these were not in line with behavioural results. Gamma activity analyses provide a strong foundation for identifying the role of this band in numerical processing for those with HMA. However, as the stimuli were solely comprised of maths based tasks, it is noted that this study only highlights differences between populations and may not represent attention, threat and anxiety towards maths. Further research implementing word tasks would be beneficial in providing a control to compare against maths processing. The following study will aim to achieve this and shed more light on gamma band activity and its role within MA.

Chapter 6: Maths anxious gamma-band activity in response to numerical and non-numerical tasks

6.1: Introduction

The previous study identified few ERP differences between MA groups indicating that it may not be an effective way of identifying differences in maths processing between maths anxious individuals. The study also showed significant differences in gamma activity between MA groups supporting the theory that gamma activity may be involved in maths processing in high maths anxious individuals. The research suggested that high maths anxious individuals experience higher power of gamma activity in response to threatening stimuli. However, a flaw in this was that no control or valid non-numerical tasks were used to compare this against. The current study will implement changes in stimuli sets which will be necessary to identify the role of gamma's involvement in the MA brain.

As stated in chapter 5.1, previous research has identified the role of gamma band activity in highly anxious individuals and threat perception (Luo et al., 2007a; Maratos et al., 2012; Oathes et al., 2008) and that this can manipulate amygdala activity (Popescu et al., 2009; Sato et al., 2011). Together these are associated with anxious processes in the brain but this has only been observed in GAD individuals, rather than specific forms of anxiety e.g. MA. The research in this area may also fit with current understandings of MA. For example, gamma activity has been shown to mark high cortical arousal (Knyazev et al., 2005) in response to anxiety provoking stimuli. In turn these stimuli are considered threatening to the point that high anxious individuals will bias towards them (Bar-Haim et al., 2007a). This links with Lyons & Beilock's (2012) research noting that threat related stimuli causes activation in pain networks, leading to avoidance of such tasks. It is important for these research areas to be brought together to understand how gamma activity may be responsible for manipulating these processes, limiting high maths anxious individuals' future prospects.

Current theories dictate that high maths anxious individuals are overloaded with negative, intrusive thoughts (Ford et al., 2005; Hunt et al., 2014) leaving little resources for working memory to complete the primary task (Eysenck et al., 2007). However, there have also been arguments stating that high maths anxious individuals may have a working memory deficit that is responsible for poorer accuracy and reaction time. Maloney et al., (2011) outline this with an enumeration task, whereby a number of squares (between 1-9) were presented to high and low maths anxious individuals. When 1-4 squares were presented they found that both groups enumerated equally as quick. However, when 5-9 squares were presented high maths anxious individuals took significantly longer, supporting that those with HMA may struggle with numerical processing. Maloney et al. (2011) further examined why the processing of number would have an effect on high maths anxious individuals and whether it is through MA impacting on working memory or a numerical deficit. Participants were asked to state whether a number (1-4 or 6-9) was higher or lower than 5. This study manipulated the numerical distance effect (NDE) task, stating that the further away the number is from 5 (e.g. 1 or 9 being the furthest), the easier it becomes to distinguish differences between it and the target number. Overall they identified a slower reaction time for high maths anxious individuals showing the NDE was more prominent than low maths anxious individuals. This can be expected due to anxiety affecting working memory whilst it's in use keeping the target number (5) active during the task.

In order to rule out working memory's role in the study Maloney et al. (2010) conducted a follow up using a modified version of the low/high 5 task. Participants were instead presented with two stimuli on screen and were asked to press either the left or right end on the keyboard to correspond to which number they identified as being the largest. This showed a replication of the previous NDE results, without the need for a target number active in working memory. Their findings raise some issues concerning the current theories of MA. It is assumed that working memory is impaired due to the amount of resources consumed by anxious responses, which creates delay and performance issues when solving a mathematically based task. However, Maloney et al. (2010) note there is no research currently stating that numerical comparison is demanding of working memory resources. Therefore, they theorise that those with HMA may have a low level deficit during numerical processing. This contradicts previous research noting that low working memory capacity is not a consequence or precursor to MA. This infers that cognitive performance in other areas would also be affected (Ashcraft and Kirk, 2001) and anxiety reduction would likely show no performance improvements for MA intervention, which is not the case (see Park, Ramirez, & Beilock, 2014).

Nevertheless, Maloney et al.'s (2011) deficit theory is understandable considering that high maths anxious individuals still performed worse during their simple task. They argue that a task like this is unlikely to consume working memory resources and it wouldn't matter if these resources were consumed by anxiety, therefore poor performance must be caused by a deficit.

However, there was no non-numerical task to compare these findings against. Whilst their findings are plausible, it is not known how the high maths anxious group would react to a non-numerical task.

More recent research compared both maths and word task performance between MA groups and identified that it may be the anticipation of doing something numerical that triggers an anxious response which in turn would cause individuals to focus on the threatening stimuli (Lyons & Beilock, 2012). This then causes poorer accuracy as individuals may not want to attempt the task and can leave a fluctuated reaction time i.e. longer if they try to focus on the task and shorter if they quickly respond to avoid confronting the threatening stimuli (Ashcraft & Krause, 2007). This identifies that it is solely maths processing that affects high maths anxious individuals, being that discrepancies in brain activity and behavioural results reflect poorer performance in math tasks only (Lyons & Beilock, 2012). However, Lyons & Beilock (2012) state that they ensured that no significant differences occurred in word task. This may have been conducted to ensure that brain activity discrepancies reflected only maths processing. The present study will use a control stimuli set alongside numerically based stimuli to identify whether this anxious behavioural responses, elicited by greater gamma activity power, is present in only numerically-based stimuli or across all conditions, rather than ruling out non-numerical tasks.

The aim of study three was to replicate the previous design but differed by using control stimuli as well as maths tasks. This study had two objectives; (a) to compare ERP latencies and amplitude differences between high and low maths anxious participants across maths and word tasks, and (b) to observe gamma power differences between word and maths tasks and MA groups.

Whilst the previous study found little evidence for the use of ERPs in regions associated with maths processing, the current study still used this analysis method in order to comply with current research in this area. Research has identified a manipulation of the N400 during compound word presentation when task difficulty is manipulated (Vergara-Martínez, Duñabeitia, Laka, & Carreiras, 2009). Vergara-Martínez et al. (2009) noted that when the second constituent is easily recognised or more frequently used in language, smaller N400s were produced, whereas low-frequency second constituents elicited higher N400 amplitudes. These components occurred at central parietal regions with a right hemispheric dominance. It is hypothesised that word tasks in the present study (see section 6.2.3) are likely to elicit components in the same regions due to the nature of the non-numerical stimulus type (being compound words).

ERP components, such as the P1, N1 and P3 are also hypothesised to be relevant based on the previous studies, as well as ERP maths research (Azizian & Polich, 2007; Curran & Cleary, 2003; Guo et al., 2006; Hillyard et al., 1998; Johannes et al., 1995; Kramer et al., 1985; Vogel & Luck, 2000) as they are elicited either for the parameters of stimuli (P1 and N1) or a representative of task processing (P3 and N400). It is predicted that there will be differences in accuracy and reaction time for simple addition, compound numbers and compound words, when compared to complex addition. However, it should be noted that there is a possibility of all stimuli types being disrupted by the anticipation of maths tasks (Lyons & Beilock, 2012) in high maths anxious individuals.

For ERPs, it is hypothesised that typical horizontal and vertical interactions and main effects will be present dependent on the component amplitude and latency. Again, it is proposed that the processing of maths in high maths anxious populations will be evidenced with differences in gamma power. Furthermore, it is predicted that gamma power will fluctuate in high maths anxious participants as predicted task difficulty decreases (see figure 6.1).

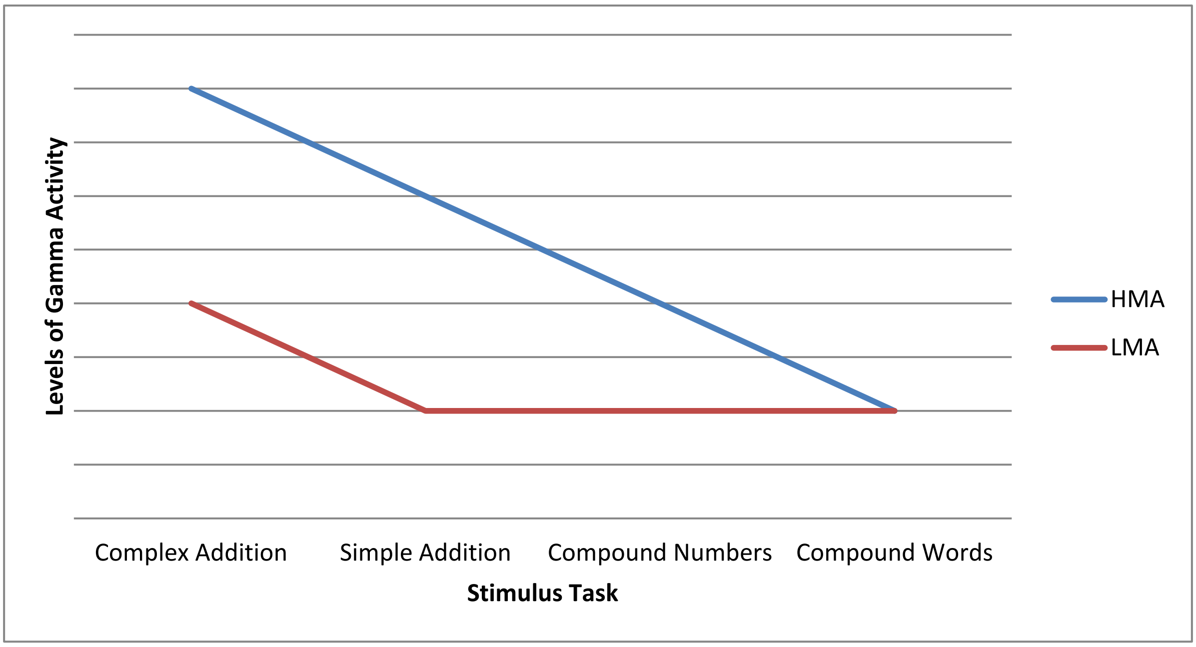

Figure 6.1: Predicted power of gamma activity experienced across tasks between high and low MA groups.

6.2 Method:

Again, as the method is not dissimilar from the previous study, aspects of this section will be omitted to avoid repetition throughout.

6.2.1 Design

The ERP analysis employed a 2 (high/low MA group) x 4 (complex addition/simple addition/compound numbers/compound words) x 3 (anterior/centre/posterior) x 3 (left/midline/right) mixed factorial design. The between subjects IV was MA group and within subjects IVs included stimulus set, horizontal and vertical electrode layout. Electrical activity at electrodes acted as the DV.

MA and STAI scores were taken to observe correlations between the two measures, in order to identify whether MA existed solely or part of an overarching anxiety within this participant group. *A priori* assumptions based on previous maths research were made for specific ERP components. All 70 electrodes (including a reference, ground, 2 mastoid, 2 horizontal and 2 vertical electro-oculogram electrodes) were used for data acquisition. The same nine electrodes from the previous ERP analyses were used for this analysis (T7, Cz, T8, P5, Pz, P6, O1, Oz, O2) and electrodes were allocated to groups based on their horizontal and vertical layout (see table 6.1).

Table 6.1:

Layout of horizontal and vertical electrodes.

		Vertical		
		Left	Midline	Right
Horizontal	Anterior	T7	Cz	T8
	Centre	P5	Pz	P6
	Posterior	O1	Oz	O2

A pilot study was conducted prior to testing to ensure stimulus presentation, lighting and procedure was adequate and followed in an appropriate manner.

The analysis of gamma activity was also necessary for this study therefore; relevant electrodes were selected based on *a priori* assumptions. To analyse data from these previously suggested sites, different electrodes were used compared to those used in the ERP analysis (T3/T7, C3, C4, T4/T8, T5/P7, P3, P4, T6/P8). This analysis resulted in a 2 (high/low MA group) x 4 (complex addition/simple addition/compound numbers/compound words) x 2 (anterior/posterior electrodes) x 4 (left/midline left/midline right/right electrodes) mixed factorial design. Again, electrodes were allocated to groups based on their horizontal and vertical layout (see table 6.2).

Table 6.2:

Layout of horizontal and vertical electrodes for gamma analysis.

		Vertical			
		Left	Midline Left	Midline Right	Right
Horizontal	Anterior	T7	C3	C4	T8
	Posterior	P7	P3	P4	P8

6.2.2 Participants

One hundred and eighty seven participants were recruited from the University of Derby, post-lecture, and asked to complete the MAS-UK (Hunt et al., 2011).

Cluster analysis:

Nine participants were removed due to missing data. A hierarchical cluster analysis indicated two clusters. The first cluster had 42.7% of cases (N=76) and contained those who scored low on the MAS-UK indicating a LMA cluster. The second had 57.3% of the total sample (N=102) and contained those who scored higher on the MAS-UK indicating a HMA cluster. In order to distinctly invite those with the highest and lowest levels of MA, participants were systematically selected, with scores up to 40 and down to 65, for the EEG phase of the study.

Thirty participants were invited, via email, to participate in the EEG phase of the research. Individuals consisted of 15 HMA and 15 LMA, 13 males and 17 females (mean age = 26.27, SD = 7.60) and were all right handed. Participants reported normal or corrected to normal vision and had not been diagnosed with dyslexia.

6.2.3 Materials and Equipment

Two hundred and forty maths and word tasks were used, including 60 complex two-digit addition (e.g. 19+54=), 60 simple one digit addition (e.g. 7+3=), 60 compound numbers (e.g. 90+3=) and 60 compound words (e.g. THUNDER+STORM=) and presented to participants. Originally, a higher number of stimuli aimed to be used however; comfort of the participant took precedence as the study length (not including capping) would have amounted to an hour. Using the MRC Psycholinguistic Database (n.d.) compound words were selected and the amount of letters (6-14), phonemes (4-13), syllables (2-4) and Thorndike-Lorge written frequency (0-3679) were recorded.

Complex addition was defined by using 2 by 2 digit addition and the need to implement a carry operation (Faust et al., 1996; Wu et al., 2012). As this study aimed to compare varying difficulty levels of maths tasks to simple word tasks, complex addition and simple addition were used as a comparison to the previous study. The researcher acknowledged that there is unlikely to be an adequate word task comparison to maths tasks. With this in mind, a task was created to provide a similar challenge that would be expected from a maths sum: using compound words provided a problem solving condition in a non-numerical format. In a similar procedure to the previous study, a question would be visually presented (THUNDER+STORM= or STORM+THUNDER=) and four answers would follow, one being a correct true word (THUNDERSTORM) and three incorrect (CLOUDTHUNDER, STORMTHUNDER, THUNDERCLOUD). Whilst compound words have been used in previous neurophysiological research (Chee, Tan, & Thiel, 1999; Vergara-Martínez et al., 2009), it has predominantly been employed for reading rather than as a task. This was assumed as the closest non-numerical visual task (useable in an ERP paradigm) to provide a control against maths related stimuli. In addition, a compound numbers condition was included to ensure the complexity of the compound words condition was matched within a numerical task.

Like compound words, it contained a (maths based) question (90+3= or 3+90=) with four answers, one correct (93) and three incorrect (89, 93, 98). Just as THUNDER+STORM=THUNDERSTORM, so would 90+3=93.

The majority of research involving visual word tasks in ERP formats typically consist of reading words or sentences (for example, Barber, Otten, Kousta, & Vigliocco, 2013; Nie et al., 2014; Sereno & Rayner, 2003) or involves an emotional stroop task (Thomas, Johnstone, & Gonsalvez, 2007) however, these are either unchallenging or provide unnecessary semantic context. Previous research has also noted that emotionally negative words are associated with sustained amygdala activity (Maloney & Beilock, 2012) therefore, to ensure that semantic responses to certain words were minimised, stimuli with emotional context were removed from the sample. Those who were diagnosed with dyslexia were not included in the EEG study, due to possible anxiety effects experienced during word task presentation (Carroll & Iles, 2006).

Table 6.3:

Predicted levels of difficulty for each task with example stimuli and correct answers.

	Condition			
	Complex Addition	**Simple Addition**	**Compound Numbers**	**Compound Words**
Difficulty	High	Medium	Low	Low
Question Example	25+37= 62	9+6= 15	90+3= 93	THUNDER+STORM= THUNDERSTORM

6.2.4 Procedure

Participants were emailed with the required information (see appendix iii) and asked to arrive at the university at a mutually agreed time. The researcher informed participants of the procedure and timings of the study. Participants were then asked to complete a consent form and then the STAI (Spielberger, 1983) to identify any possible correlations between state and trait anxiety and MA.

Similar to the procedure of the previous study, participants were seated in a dimly lit room whilst white stimuli (font size 64) were presented on a black background. Luminance levels were measured from the visual display unit (4.0 cd/m^2) distanced at 72cm at eye height with the centre of the screen. Participants were sat in a comfortable chair at eye height to the centre of the screen. Participants were asked to note the correct answer to the equations by pressing the corresponding button on a button box e.g. 1 (top left), 2 (top right), 3 (bottom left) or 4 (bottom right). A practice test, including two of each stimuli set, was conducted with each participant before the main task which gave participants a chance to practice the mechanisms of the task, including button press locations (see figure 6.2). Each stimulus was presented for 8000ms with a response window of 8000ms followed by a fixation point with a duration of 500ms. Inter trial intervals were pseudo randomised between 500ms and 2500ms to avoid complacency. Impedances of all electrodes were kept below 15kΩ however; the majority were below 5kΩ. Processing procedure was kept similar to the previous study (see chapter 5.2.2).

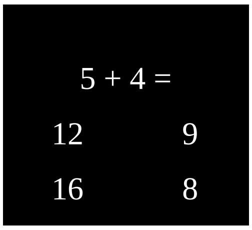

Figure 6.2: An example illustrating the arrangement of stimuli presentation to participant.

6.3: Results

6.3.1: Analytical Strategy

The results are split into three stages: The first (section 6.3.2) comprises behavioural data, concerning correlations, accuracy and reaction time. A Spearman's rho correlation was conducted to analyse whether MA significantly correlates with state and trait anxiety, to identify if MA exists solely or as a factor in an overarching anxiety in this population. Mixed factorial ANOVAs were also used to measure differences across MA groups and conditions for accuracy and reaction time.

The second section (6.3.3) comprises ERP amplitude processing and analysis: *A priori* hypotheses were used alongside GFP to distinguish appropriate components for analysis. Three components were each analysed to identify significant interactions and main effects. A *post-hoc* split was applied to the N1 component and was found to represent two components (N1 and P3). Due to the nature of GFP calculation, all peaks display in positive format therefore, the distinct positive and negative components were not originally differentiated.

Finally, section 6.3.4 comprises gamma activity processing and analysis: A mixed factorial ANOVA was used to identify any significant main effects or interactions in gamma activity between condition, MA group and horizontal and vertical electrodes.

6.3.2: Correlation, accuracy and reaction time data

Correlations

Data showed significant kurtosis therefore, a Spearman's rho correlation was used to look at the relationship between MAS-UK and STAI scores. There was a weak, positive, non-significant correlation between MA and state anxiety scores (r(28)=.28, p=.133) and MA and trait anxiety scores (r(28)=.12, p=.540). The lack of a significant relationship demonstrates that MA is not correlated to state and trait anxiety scores (see figure 6.3).

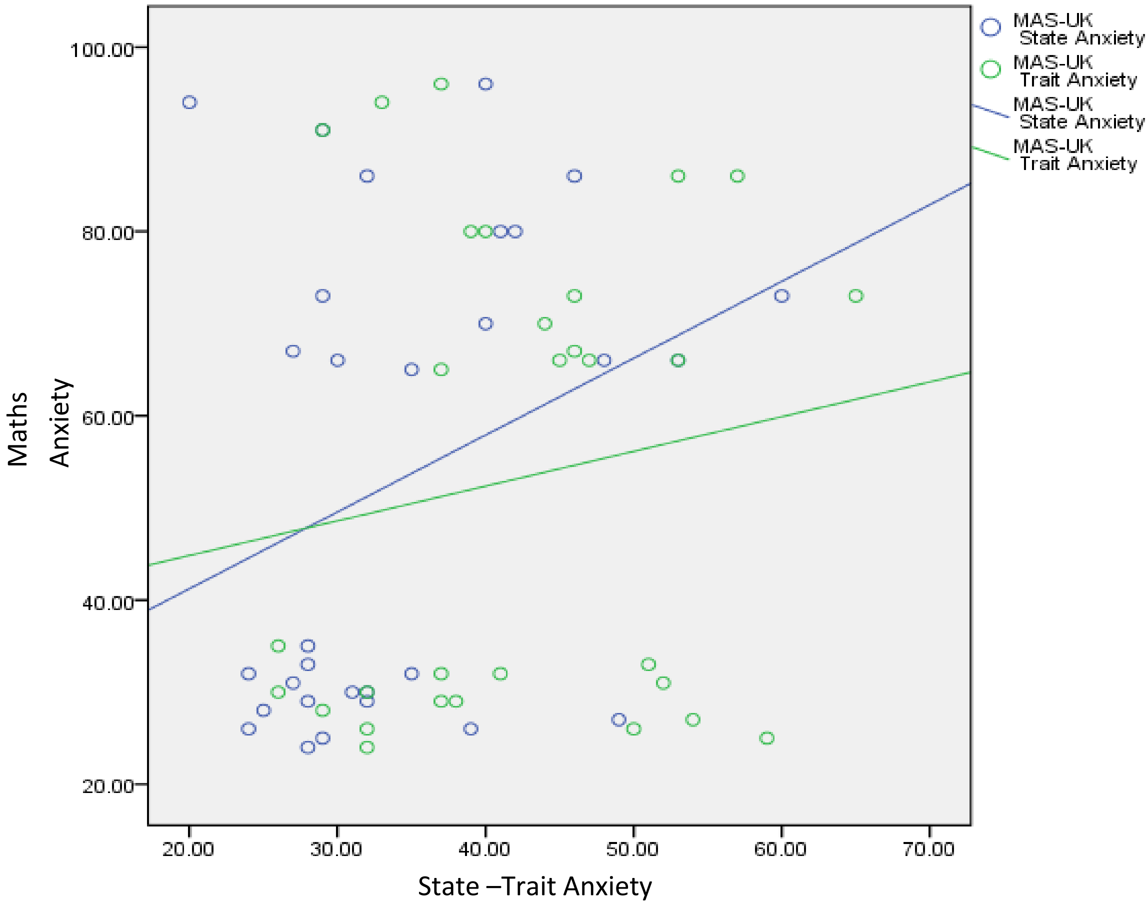

Figure 6.3: A scatterplot showing the relationship between MA and state anxiety scores, and MA and trait anxiety scores.

Accuracy and Reaction time

Two 2 (High/Low MA) x 4 (complex addition/simple addition/compound numbers/compound words) mixed factorial ANOVAs were run to identify any interactions between accuracy and reaction time for behavioural responses to stimuli.

Accuracy

Mauchly's test of sphericity was found to be significant therefore, the Greenhouse-Geisser was applied to reduce type I error rate. There was a significant main effect of stimulus type ($F(1.25,35.12) = 59.90$, $p<.001$, $\eta^2 = .63$), such that lower accuracy was identified during complex addition. However, there was no significant main effect of MA ($F(1,28) = 3.49$, $p=.072$, $\eta^2 = .11$), showing that whilst high maths anxious individuals performed worse than low maths anxious individuals overall, the difference was minimal. There was a significant interaction between MA group and stimulus type ($F(3,35.12) = 6.18$, $p=.013$, $\eta^2 = .07$), such that accuracy was higher in low maths anxious individuals, particularly during complex addition (see table 6.4).

Reaction Time

Again, Mauchly's test of sphericity was found to be significant therefore, the Greenhouse-Geisser was applied to reduce type I error rate. There was a significant main effect of stimulus type ($F(1.84,51.45) = 278.21$, $p<.001$, $\eta^2 = .86$), such that reaction time was significantly longer for complex addition than other conditions. There was a significant main effect of MA ($F(1,28) = 13.96$, $p=.001$, $\eta^2 = .33$), such that low maths anxious individuals had a quicker reaction time than those with HMA. There was also a significant interaction between MA and condition on reaction time ($F(1.837,51.448) = .15.450$, $p<.001$, $\eta^2 = .05$), such that high maths anxious individuals took significantly longer to respond to stimuli particularly during complex addition (see table 6.4).

Table 6.4:

Mean (SD) accuracy and reaction time scores between high and low MA during conditions.

		Maths Anxiety Group		
	Stimulus Type	**High**	**Low**	**Total**
Accuracy	Complex Addition	45.73 (7.67)	51.93 (6.03)	48.83 (7.47)
	Simple Addition	54.00 (2.67)	55.33 (1.76)	54.67 (2.32)
	Compound Numbers	58.53 (3.39)	59.40 (2.20)	58.97 (2.37)
	Compound Words	54.67 (3.83)	55.13 (2.36)	54.90 (3.13)
Reaction Time (ms)	Complex Addition	4947.80 (514.62)	3711.18 (567.28)	4329.49 (823.83)
	Simple Addition	2513.61 (622.30)	1993.65 (414.58)	2253.63 (582.97)
	Compound Numbers	2345.88 (556.00)	2047.60 (277.11)	2196.74 (457.52)
	Compound Words	3037.31 (589.76)	2835.50 (354.82)	2936.41 (489.11)

In summary, accuracy was lower overall for complex addition as expected and this effect was also present between MA groups, with high maths anxious individuals showing reduced accuracy within this condition. There was no significant difference in accuracy between MA groups. Reaction time was slower for complex addition and more so for high maths anxious individuals. Overall low maths anxious individuals had significantly faster reaction time than high maths anxious individuals.

6.3.3: ERP processing and analysis

After conducting averages across each condition and participant group it was determined that there were no latency differences and amplitude analysis proceeded. This enabled the use of the average GFP's component identification (below) applied across all groups and conditions.

6.3.3.1: ERP amplitude processing

An average GFP was observed across all electrodes (excluding M1, M2, VEOG, HEOG and the central reference), participants, and conditions to refine ERP component windows. *A priori* assumptions based on the previous study and research suggested the emergence of four components. However, the GFP presented 3 components identified as P1 (50-95ms), N1 (99-255ms) and N400 (275-363ms) (see figure 6.4).

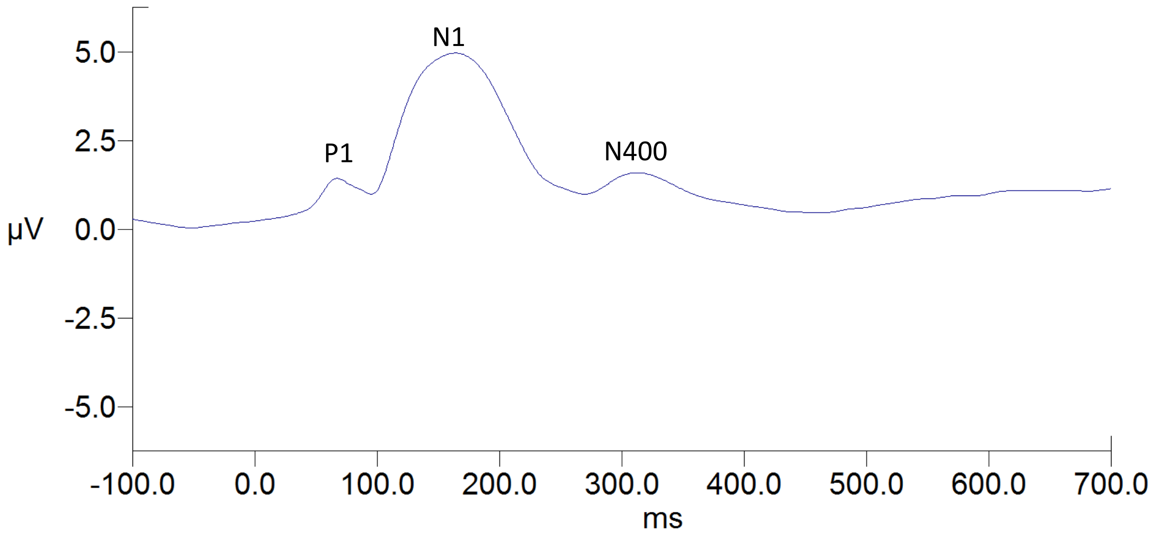

Figure 6.4: GFP electrode displaying 3 components for analysis.

The component were extracted from relevant electrodes (T7, Cz, T8, P5, Pz, P6, O1, Oz, O2) and four 2 (High/Low MA group) x 4 (complex addition/simple addition/compound numbers/compound words) x 3 (anterior/centre/posterior) x 3 (left/midline/right) mixed factorial ANOVAs were run to identify any interactions and main effects. These were conducted separately for the 3 components. All ANOVAs included the Greenhouse-Geisser correction to ensure type I error rates were not inflated (Greenhouse & Geisser, 1959) being that neurophysiological data is rarely homogenous.

6.3.3.2: ERP amplitude analysis

P1 Component Amplitude Analysis

The results display the findings of the P1 amplitude, explaining the overall interactions and main effects (see table 6.5).

Table 6.5:

*P1 ANOVA F values, degrees of freedom, significance levels and effect size (Ƞ²) for amplitude interactions and main effects.**

Interaction / Main Effect	ANOVA			
	F	***df***	***p***	***Ƞ²***
Horizontal x Vertical x Stim x MA	.38	4.30,120.49	.836	2.33×10^{-4}
Horizontal x Vertical x Stim	4.63	4.35,126.21	.001	.002
Vertical x Stim x MA	.29	3.77,105.43	.941	3.31×10^{-4}
Horizontal x Stim x MA	.34	1.70,47.63	.676	.001
Horizontal x Vertical x MA	1.09	3.31,92.57	.360	.002
Vertical x Stim	11.23	3.80,110.17	<.001	.01
Horizontal x Stim	.93	1.72,50.00	.390	.002
Horizontal x Vertical	18.38	3.77,97.72	<.001	.03
Stim x MA	.47	2.63,73.50	.677	.002
Vertical x MA	.33	1.96,54.86	.719	.001
Horizontal x MA	.53	1.20,33.53	.504	.007
Vertical	41.39	1.95,56.66	<.001	.13
Horizontal	3.08	1.22,35.23	.081	.04
Stim	2.79	2.63,76.18	.053	.01
MA	1.56	1,28	.222	.05

The 3×3×2×2 analysis showed no significant interaction between horizontal, vertical electrodes, stimulus type and MA group. There was a significant interaction between stimulus type, horizontal and vertical electrodes such that higher P1 amplitudes were elicited at right parieto-occipital regions with the largest during the compound words condition (mean = .93mv, SD = 3.44) in comparison to complex addition (mean = .54mv, SD = 2.50), simple addition (mean = .40mv, SD = 2.21) and compound numbers (mean = 64mv, SD = 2.49) at similar sites. This is likely to be elicited higher for compound words as the stimuli occupied a wider area of the visual field on screen than math based stimuli. There was no significant interaction between horizontal, vertical electrodes and MA group or between MA group, stimulus type and horizontal electrodes. There was also no significant interaction between MA group, stimulus type and vertical electrodes.

There was no significant interaction found between MA group and stimulus type. There was no significant interaction between MA group and horizontal electrodes and MA group and vertical electrodes. There was also no significant interaction between stimulus type and horizontal electrodes. There was a significant interaction between stimulus type and vertical electrodes, such that compound words stimuli (larger digit span) elicited a higher P1 amplitude at right sites (mean = .03mv, SD = 3.68) than compound numbers (mean = -.14mv, SD = 2.48), simple addition (mean = -.22mv, SD = 2.21) and complex addition (mean = -.24mv, SD = 2.57). There was also a significant interaction between horizontal and vertical electrodes (see table 6.6), such that left and right electrodes displayed higher P1 amplitude than midline electrodes, as well as higher component amplitudes at posterior than anterior electrodes. This can be expected due to the P1 component eliciting in the occipital region with less prominence at midline sites.

There was no significant main effect of MA group or stimulus type. There was no significant main effect of horizontal electrodes. However, there was a significant main effect of vertical electrodes such that there was a higher P1 amplitude at right (mean = -.15mv, SD = 2.78) than at left (mean = -.60mv, SD = 2.84) sites with a smaller P1 elicited at midline electrodes (mean = -1.92mv, SD = 2.37). Again, this is consistent with previous interactions, showing a lower P1, exhibited at midline sites.

Table 6.6:

P1 mean and standard deviation depicting the interaction between horizontal and vertical electrodes.

	Horizontal Electrodes		
Vertical Electrodes	Anterior	Centre	Posterior
Left	-1.58 (.04)	-.52 (.31)	.30 (.34)
Midline	-2.01 (.33	-2.05 (.72)	-1.73 (.62)
Right	-.88 (.32)	.62 (.23)	-.18 (.24)

N1 Component Amplitude Analysis

The results display the findings of the N1 amplitude, explaining the overall interactions and main effects (see table 6.7).

Table 6.7:

N1 ANOVA F values, degrees of freedom, significance levels and effect size for amplitude interactions and main effects.

Interaction / Main Effect	**ANOVA**			
	F	***df***	***p***	η^2
Horizontal x Vertical x Stim x MA	.65	4.54,127.03	.650	2.20×10^{-4}
Horizontal x Vertical x Stim	6.80	4.64,134.48	<.001	.002
Vertical x Stim x MA	1.05	3.73,104.48	.383	5.04×10^{-4}
Horizontal x Stim x MA	1.46	3.22,90.17	.229	8.45×10^{-4}
Horizontal x Vertical x MA	.42	2.87,80.29	.731	5.50×10^{-4}
Vertical x Stim	1.34	3.71,107.61	.260	6.47×10^{-4}
Horizontal x Stim	3.98	3.24,93.85	.009	.002
Horizontal x Vertical	30.31	3.09,89.71	<.001	.06
Stim x MA	.95	2.65,74.32	.491	.001
Vertical x MA	.15	1.58,44.20	.809	5.84×10^{-4}
Horizontal x MA	3.71	1.34,37.62	.050	.02
Vertical	31.38	1.58,45.95	<.001	.12
Horizontal	83.80	1.31,37.87	<.001	.41
Stim	.97	2.68,77.78	.405	.003
MA	1.87	1,28	.183	.06

The 3×3×2×2 analysis showed no significant interaction between horizontal, vertical electrodes, stimulus type and MA group. Again, there was a significant interaction between stimulus type, horizontal and vertical electrodes, such that higher N1 amplitudes were elicited at parieto-occipital regions at midline and right sites. Conditions that were considered easier than those that involved calculation, i.e. compound numbers and words, had higher N1 amplitude in these areas than simple and complex addition. There was no significant interaction between horizontal, vertical electrodes and MA group. There was no significant interaction between MA group, stimulus type and horizontal electrodes. There was also no significant interaction between MA group, stimulus type and vertical electrodes.

There was no significant interaction found between MA group and stimulus type and between MA group and vertical electrodes. However, there was a significant interaction between MA group and horizontal electrodes, such that those with LMA displayed higher N1 amplitudes, particularly at occipital electrodes (mean = -2.10mv, SD = 2.62) than those with HMA (mean = -.60mv, SD = 2.14). This can be expected as high maths anxious individuals are theorised to have less attentional resources for the primary task as a portion are used to combat anxious intrusive thoughts and threat perception. There was no significant interaction between stimulus type and horizontal electrodes and stimulus type and vertical electrodes. As expected, there was a significant interaction between horizontal and vertical electrodes (see table 6.8) such that higher N1 amplitudes were observed in posterior sites particularly at left and right electrodes. This is indicative of N1 components, typically exhibited in left and right parieto-occipital sites (Bokura et al., 2001; Wang & Suemitsu, 2007).

There was no significant main effect of MA groups or stimulus type. However, there was a significant main effect of horizontal electrodes, such that a higher N1 amplitude occurred at posterior electrodes (mean = -1.35mv, SD = 2.50) than at centre (mean = .37mv, SD = 2.74) and anterior sites (mean = 2.86mv, SD = 2.58). Similarly there was also a significant main effect of vertical electrodes such that there was a higher N1 amplitude towards right electrodes (mean = -.47mv, SD = 2.84) than at left (mean = .57mv, SD = 3.40) and midline sites (mean = 1.78mv, SD = 2.69).

Table 6.8:

N1 mean and standard deviation depicting the interaction between horizontal and vertical electrodes.

	Horizontal Electrodes		
Vertical Electrodes	Anterior	Centre	Posterior
Left	3.05 (.22)	.28 (.22)	-1.60 (.16)
Midline	4.82 (.22)	1.56 (.27)	-1.04 (.18)
Right	.72 (.55)	-.72 (.24)	-1.41 (.23)

N400 Component Amplitude Analysis

The results display the findings of the N400 amplitude, explaining the overall interactions and main effects (see table 6.9).

Table 6.9:

N400 ANOVA F values, degrees of freedom and significance levels for amplitude interactions and main effects.

Interaction / Main Effect	**ANOVA**			
	F	***df***	***p***	***η²***
Horizontal x Vertical x Stim x MA	1.89	3.48,97.51	.128	.001
Horizontal x Vertical x Stim	29.68	3.60,104.44	<.001	.02
Vertical x Stim x MA	1.02	2.96,82.90	.388	.001
Horizontal x Stim x MA	.30	2.73,76.44	.808	4.95×10^{-4}
Horizontal x Vertical x MA	.58	2.89,80.85	.626	8.93×10^{-4}
Vertical x Stim	24.03	3.08,89.40	<.001	.03
Horizontal x Stim	10.93	2.77,80.43	<.001	.02
Horizontal x Vertical	37.01	2.95,85.39	<.001	.06
Stim x MA	2.21	2.56,71.76	.104	.01
Vertical x MA	.09	1.83,51.18	.912	3.99×10^{-4}
Horizontal x MA	.05	1.22,34.10	.870	3.65×10^{-4}
Vertical	7.93	1.83,53.14	.001	.03
Horizontal	28.34	1.22,35.39	<.001	.20
Stim	3.62	2.50,72.38	.023	.02
MA	.07	1,28	.795	.002

The 3×3×2×2 analysis showed no significant interaction between horizontal, vertical electrodes, stimulus type and MA group. There was a significant interaction between stimulus type, horizontal and vertical electrodes such that higher N400 amplitudes were seen in posterior midline and right electrodes particularly within complex addition (mean = -.50, SD = 2.72, mean = -.05, SD = 2.91, respectively) and compound word conditions (mean = -.57, SD = 3.20, mean = -.11, SD = 3.24, respectively). As the N400 is manipulated by task difficulty with complex tasks displaying higher N400 amplitudes, it is logical that complex addition would display this. Processing of words can also elicit higher N400 amplitudes as words are more semantically processed than numbers (considering semantic processing is language based (Steedman & Stone, 2006)), which is likely why the N400 amplitude was higher in the compound words condition. There was no significant interaction between horizontal, vertical electrodes and MA group. There was no significant interaction between MA group, stimulus type and horizontal electrodes. There was also no significant interaction between MA group, stimulus type and vertical electrodes.

There was no significant interaction found between MA group and stimulus type. There was no significant interaction between MA group and horizontal electrodes and MA group and vertical electrodes. However, there was a significant interaction between stimulus type and horizontal electrodes such that higher N400 amplitudes were experienced at posterior electrodes for complex addition (mean = -.10mv, SD = 2.67) and compound words (mean = .01mv, SD = 3.08) in comparison to compound numbers (mean = .60mv, SD = 2.46) and simple addition (mean = 1.17mv, SD = 2.32). There was also a significant interaction between stimulus type and vertical electrodes such that higher N400 amplitudes were elicited in right electrodes for compound words and complex addition. There was also a significant interaction between horizontal and vertical electrodes (see table 6.10) such that higher N400 amplitudes elicited at posterior sites, particularly at midline electrodes. The N400 component amplitude remained higher for right electrodes at anterior and sites compared to left and midline electrodes.

There was no significant main effect of MA groups or stimulus type. However, there was a significant main effect of horizontal electrodes, such that higher N400 amplitudes were identified at posterior electrodes (mean = .45mv, SD = 2.68) than at anterior (mean = 2.30mv, SD = 2.71) and centre sites (mean = 2.87mv, SD = 2.47). Similarly there was also a significant main effect of vertical electrodes such that there was a higher N400 amplitude at right electrodes (mean = 1.27mv, SD = 2.70) than at left (mean = 2.07mv, SD = 3.27) and midline sites (mean = 2.25mv, SD = 2.33).

Table 6.10:

N400 mean and standard deviation depicting the interaction between horizontal and vertical electrodes.

	Horizontal Electrodes		
Vertical Electrodes	Anterior	Centre	Posterior
Left	2.72 (1.34)	2.74 (.55)	.74 (.39)
Midline	3.44 (1.08)	3.27 (.46)	.05 (.72)
Right	.74 (.96)	2.61 (.54)	.47 (.68)

It should be noted that this although the N400 was identified as a negative component, there are some electrodes that show positive results. This will be discussed later (see end of chapter 6.3.3.3).

6.3.3.3: *Post-hoc* component analysis

Whilst the above analysis shows the N1 component spanning 156ms, it was noted that this large window could be a combination of two components overlapping in the average ERP. This was later confirmed after observing the topography within the joint component (see figure 6.6). With this in mind a *post-hoc* split was applied to the large component (99-255ms) into two smaller components, thought to represent the N1 (99-177ms) and P3 (178- 255ms) components. This was also supported by activity in posterior electrodes as a negative peak (N1), followed closely by a positive peak (P3) in left central parietal regions, identifying an overlap in components (see figure 6.6). A further two 2×4×3×3 mixed factorial ANOVAs were conducted to identify any interactions and main effects at the N1 and P3 components. Again, these were conducted separately for the two components and included the Greenhouse-Geisser correction. A breakdown of the overall analysis for the N1 and then the P3 is listed below. Alongside summaries of components, topographical maps are used illustrating positive inflections highlighted in red and negative in blue. Translucent shapes highlight the dipoles averaged over component latencies.

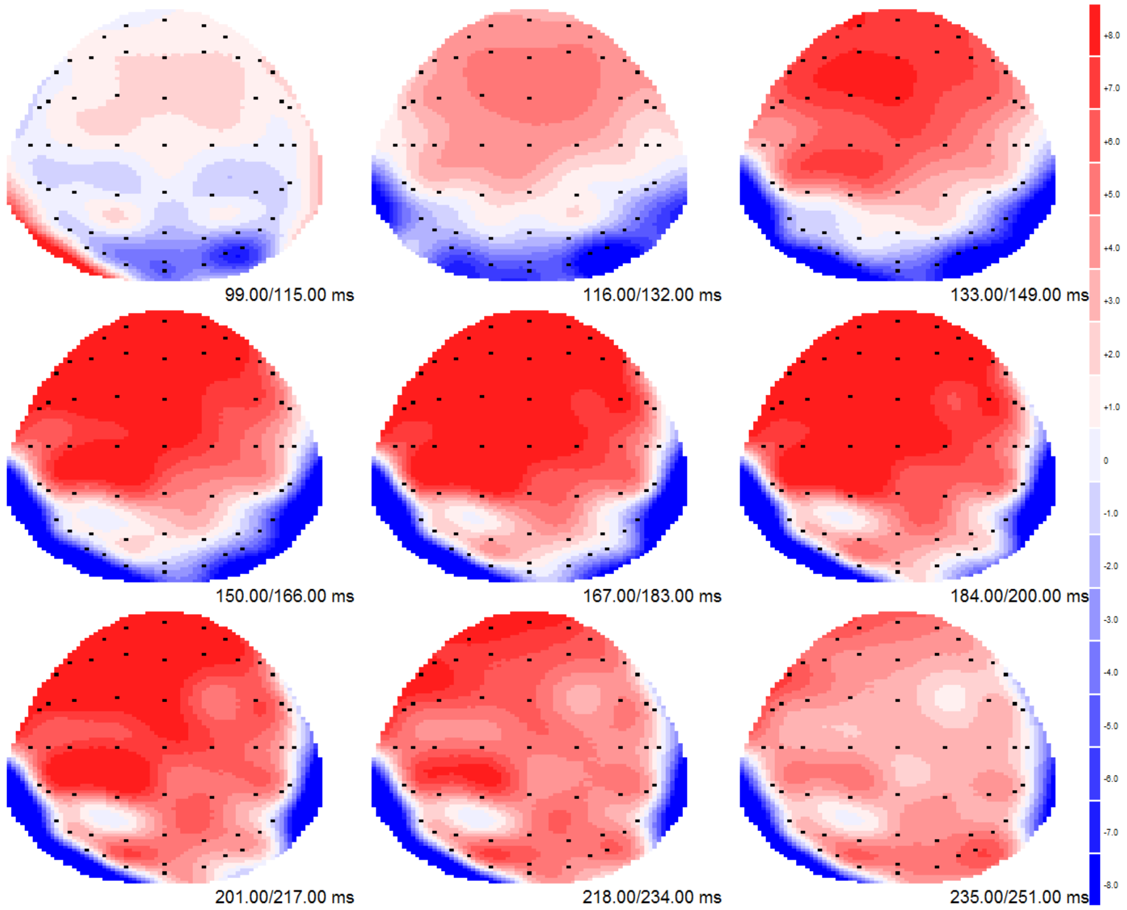

Figure 6.6: Topographical map of two dipoles (N1 followed by P3) at component crossover over time from top left (99-115ms) to bottom right (235-251ms). The colour key (right) shows positive (red) and negative (blue) inflections.

Post-hoc N1 Component Amplitude Analysis

The results display the findings of the N1 amplitude, explaining the overall interactions and main effects (see table 6.11).

Table 6.11:

N1 ANOVA F values, degrees of freedom, significance levels and effect size for amplitude interactions and main effects.

Interaction / Main Effect	**ANOVA**			
	F	***df***	***p***	***η²***
Horizontal x Vertical x Stim x MA	.30	2.10,58.72	.751	1.69×10^{-4}
Horizontal x Vertical x Stim	2.91	2.13,61.87	.059	.002
Vertical x Stim x MA	1.17	3.14,87.78	.327	4.85×10^{-4}
Horizontal x Stim x MA	.87	3.05,85.51	.459	5.39×10^{-4}
Horizontal x Vertical x MA	.36	3.01,84.13	.780	4.13×10^{-4}
Vertical x Stim	6.34	3.23,93.67	<.001	.002
Horizontal x Stim	3.71	3.03,87.89	.014	.002
Horizontal x Vertical	20.74	3.00,86.88	<.001	.02
Stim x MA	.25	2.31,64.72	.813	6.89×10^{-4}
Vertical x MA	.06	1.71,47.85	.921	.07
Horizontal x MA	3.45	1.39,38.89	.058	.02
Vertical	24.52	1.71,49.53	<.001	.07
Horizontal	100.18	1.34,38.97	<.001	.51
Stim	1.63	2.33,67.42	.200	.004
MA	1.68	1,28	.206	.06

The 3×3×2×2 analysis showed no significant interaction between horizontal, vertical electrodes, stimulus type and MA group. There was no significant interaction between stimulus type, horizontal and vertical electrodes. There was no significant interaction between horizontal, vertical electrodes and MA group and between MA group, stimulus type and horizontal electrodes. There was also no significant interaction between MA group, stimulus type and vertical electrodes.

There was no significant interaction found between MA group and stimulus type. There was no significant interaction between MA group and horizontal electrodes and MA group and vertical electrodes. However, it was found that there was a significant interaction between stimulus type and horizontal electrodes such that higher N1 amplitudes were identified at posterior electrodes but a higher N1 amplitude was identified for compound words at centre electrodes (mean = -2.00mv, SD = 3.33) than complex addition (mean = -1.43mv, SD = 3.55), simple addition (mean = -1.35mv, SD = 3.37) and compound numbers (mean = -1.30mv, SD = 3.72). There was also a significant interaction between stimulus type and vertical electrodes, such that higher N1 amplitudes were identified for across all right electrodes but were higher at left sites for compound words (mean = -2.46mv, SD = 3.52) than complex addition (mean = -.95mv, SD = 3.76), simple addition (mean = -.39mv, SD = 4.10) and compound numbers (mean = -.70mv, SD = 3.42). This is likely due to language processing predominantly localised in the left hemisphere. There was also a significant interaction between horizontal and vertical electrodes (see table 6.12), such that higher N1 amplitudes were shown to elicit, predominantly, at posterior sites with lower N1 amplitudes at right and left centre, and right anterior sites. This is due to the N1 tendency to elicit in posterior electrodes (see figure 6.7).

There was no significant main effect of MA groups or stimulus type. However, there was a significant main effect of horizontal electrodes, such that higher N1 amplitudes were identified at posterior sites (mean = -4.32mv, SD = 3.25) than at centre (mean = -1.52mv, SD = 3.49) and anterior sites (mean = 2.54mv, SD = 3.07). There was also a significant main effect of vertical electrodes such that there was a higher N1 amplitude identified at right electrodes (mean = -2.45mv, SD = 4.03) than at left (mean = -.93mv, SD = 3.73) and centre (mean = .08mv, SD = 4.76). As number comparison (used when multiple answers are presented) elicits higher amplitude in right posterior sites (Pinel, Dehaene, Rivière, & LeBihan, 2001b) and based on the number of maths based conditions compared to non-numerical conditions, this localisation is consistent with expectations.

Table 6.12:

N1 mean and standard deviation depicting the interaction between horizontal and vertical electrodes.

	Horizontal Electrodes		
Vertical Electrodes	Anterior	Centre	Posterior
Left	2.37 (.66)	-1.05 (.49)	-4.14 (.60)
Midline	4.57 (.38)	-.22 (.51)	-4.10 (.62)
Right	.66 (.24)	-3.30 (.04)	-4.72 (.39)

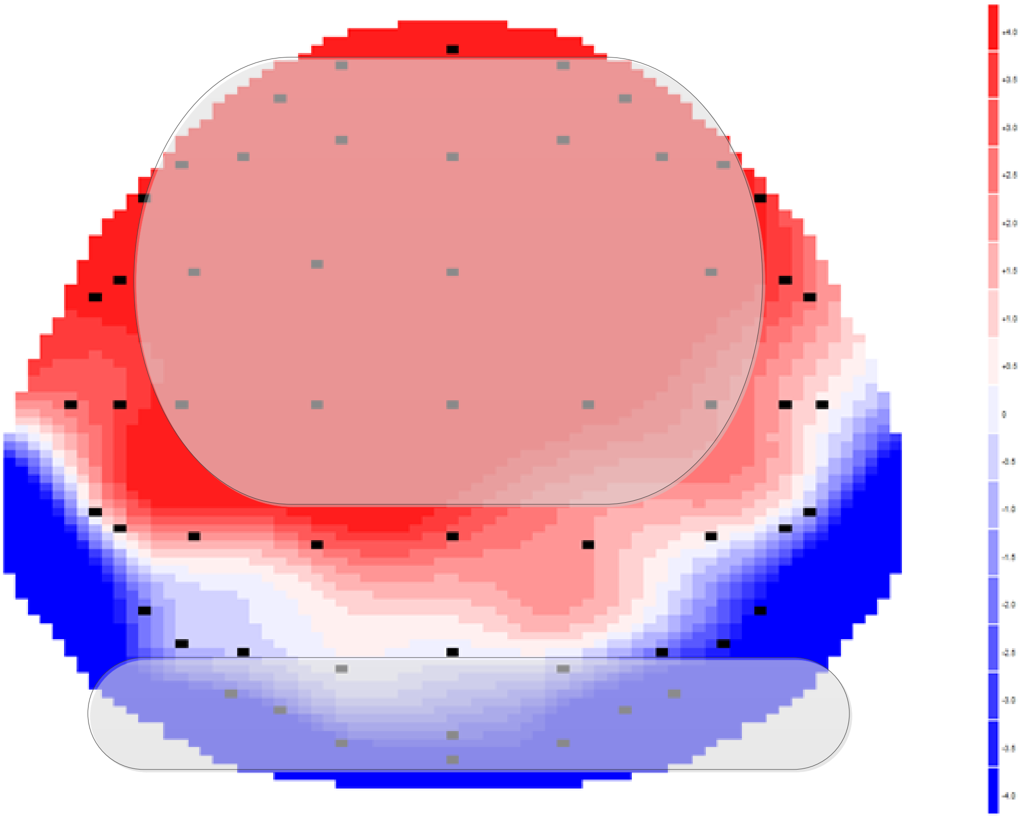

Figure 6.7: Topographical map showing horizontal and vertical differences at dipoles during N1 component, averaged over 99-177ms.

Post-hoc P3 Component Amplitude Analysis

The results display the findings of the P3 amplitude, explaining the overall interactions and main effects (see table 6.13).

Table 6.13:

P3 ANOVA F values, degrees of freedom and significance levels for amplitude interactions and main effects.

Interaction / Main Effect	**ANOVA**			
	F	***df***	***p***	***η²***
Horizontal x Vertical x Stim x MA	.61	3.87,108.32	.653	4.33×10^{-4}
Horizontal x Vertical x Stim	22.50	3.94,114.39	<.001	.02
Vertical x Stim x MA	.54	3.35,97.76	.676	5.84×10^{-4}
Horizontal x Stim x MA	1.23	3.47,97.10	.303	.001
Horizontal x Vertical x MA	.72	2.62,73.42	.528	.002
Vertical x Stim	18.07	3.41,98.91	<.001	.02
Horizontal x Stim	19.87	3.54,102.58	<.001	.02
Horizontal x Vertical	53.24	2.66,77.09	<.001	.15
Stim x MA	.88	2.46,68.77	.458	.005
Vertical x MA	1.71	1.71,47.96	.726	.001
Horizontal x MA	1.43	1.39,38.99	.247	.007
Vertical	26.51	1.73,50.07	<.001	.13
Horizontal	14.86	1.39,40.28	<.001	.07
Stim	.72	2.47,71.62	.520	.004
MA	1.73	1,28	.199	.06

The 3×3×2×2 analysis showed no significant interaction between horizontal, vertical electrodes, stimulus type and MA group. There was a significant interaction between stimulus types, horizontal and vertical electrodes such that higher P3 amplitudes were elicited at anterior midline sites for complex addition (mean = 5.03mv, SD = 2.70), simple addition (mean = 5.50mv, SD = 2.90) and compound numbers (mean = 5.14mv, SD = 2.48) but lower for compound words (mean = 4.43mv, SD = 2.62). The P3 amplitude was also higher for compound words at anterior left electrodes (mean = 4.92mv, SD = 2.10) than complex addition (mean = 3.97mv, SD = 1.65), simple addition (mean = 3.34mv, SD = 2.90) and compound numbers (mean = 3.73mv, SD = 2.62). This provides further support for left hemispheric dominance of word processing.

There was no significant interaction between horizontal, vertical electrodes and MA group. There was no significant interaction between MA group, stimulus type and horizontal electrodes or between MA group, stimulus type and vertical electrodes. There was no significant interaction found between MA group and stimulus type. There was also no significant interaction between MA group and horizontal electrodes and MA group and vertical electrodes.

There was a significant interaction between stimulus type and horizontal electrodes, such that higher P3 amplitudes were elicited across anterior sites for complex addition (mean = 3.35mv, SD = 2.77), simple addition (mean = 3.52mv, SD = 2.78) and compound numbers (mean = 3.43mv, SD = 2.71) than compound words (mean = 2.78mv, SD = 3.63) showing the large demand for working memory resources during maths based tasks. Similarly, a significant interaction was found between stimulus type and vertical electrodes, such that higher P3 amplitudes were elicited at left sites for complex addition (mean = 2.41mv, SD = 2.63), compound numbers (mean = 2.13mv, SD = 2.37) and compound words (mean = 2.86mv, SD = 3.54) than for simple addition (mean = 1.66mv, SD = 2.33). There was also significant interaction between horizontal and vertical electrodes (see table 6.14) such that midline sites elicited a higher P3 amplitude than left and right electrodes with higher P3 amplitudes at anterior sites. This can be seen in figure 6.8 showing the positive component at midline and left electrodes.

There was no significant main effect of MA groups or stimulus type. However, there was a significant main effect of horizontal electrodes, such that higher P3 amplitudes were elicited at anterior sites (mean = 3.27mv, SD = 3.00) than at centre (mean = 2.38mv, SD = 2.66) and posterior (mean = 1.83mv, SD = 2.47) sites. There was also a significant main effect of vertical electrodes, such that there was a higher P3 amplitude at midline electrodes (mean = 3.56mv, SD = 2.45) than left (mean = 2.27mv, SD = 2.81) and right (mean = 1.65mv, SD = 2.73).

Table 6.14:

P3 mean and standard deviation depicting the interaction between horizontal and vertical electrodes.

	Horizontal Electrodes		
Vertical Electrodes	Anterior	Centre	Posterior
Left	3.09 (.67)	1.68 (.30)	1.13 (.59)
Midline	5.02 (.44)	3.42 (.12)	2.23 (.69)
Right	.80 (1.24)	2.02 (.49)	2.14 (.50)

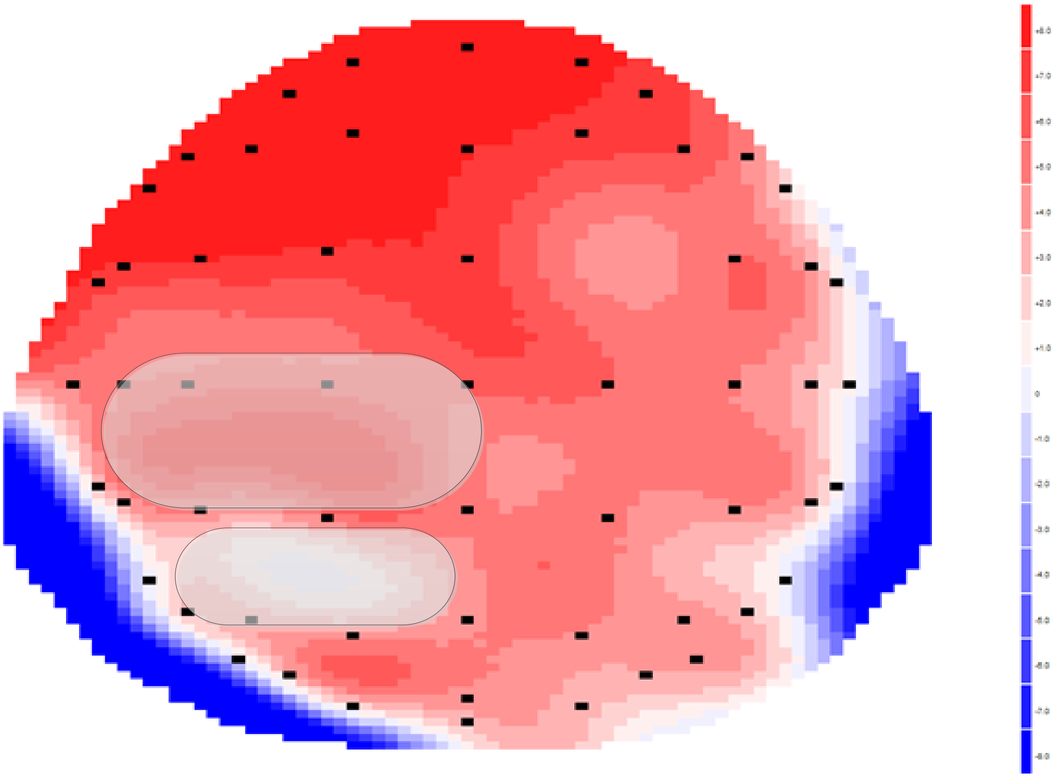

Figure 6.8: Topographical map showing horizontal and vertical differences at P3 component averaged over 178-255ms.

It can be seen that the N400 component appeared more positive than usual due to the short time between the P3 and N400 components (20ms), which can be seen in figure 6.9. [1]

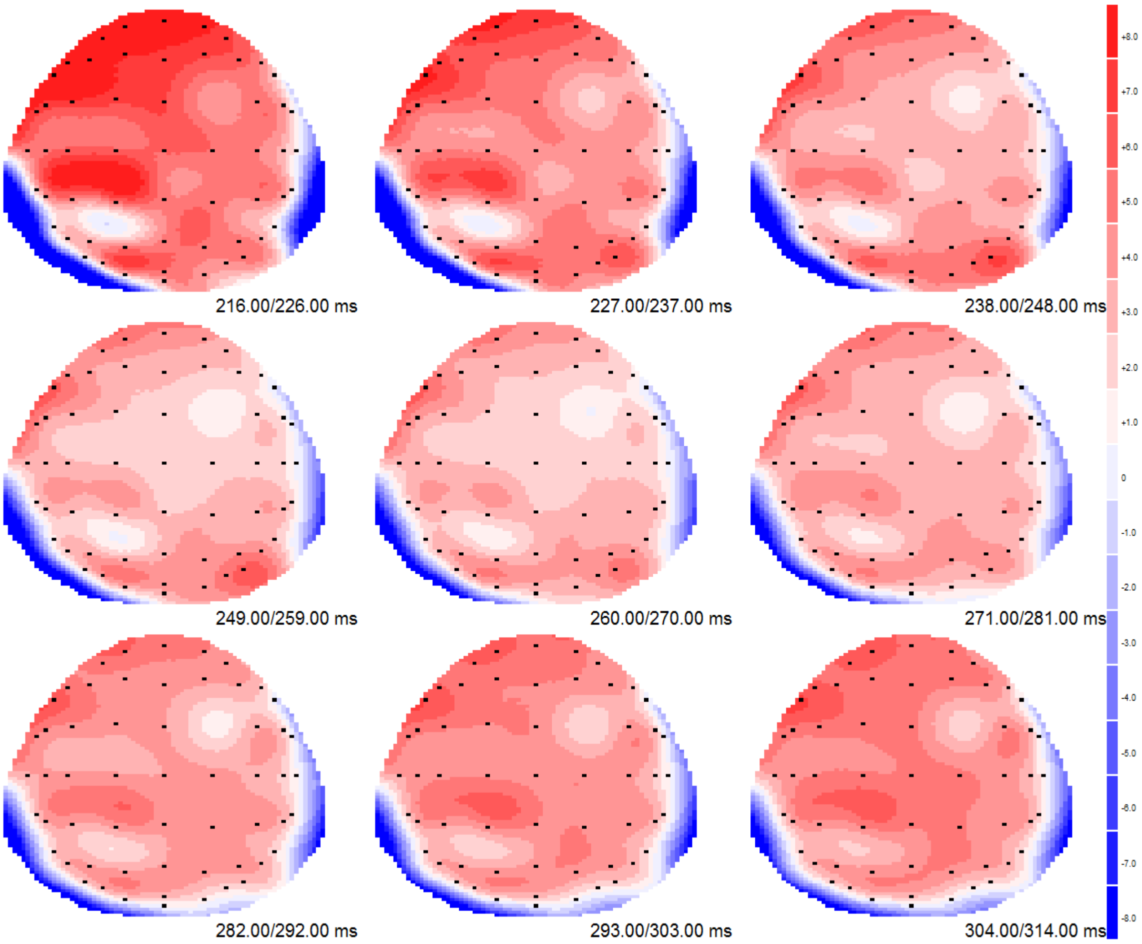

Figure 6.9: Topographical map showing transition from P3 to N400 overlap over time from top left (216-226ms) to bottom right (304-314ms). The colour key (right) shows positive (red) and negative (blue) inflections.

[1] It should be noted that whilst the N400 is described as a negative component occurring around 400ms, this potential is not always negative but generally has a more negative inflection than other components (Kutas & Federmeier, 2009).

6.3.4: Gamma activity

To analyse Gamma band activity, data was corrected for ocular artefacts and then fast Fourier transformed to measure frequency over time (cosine 10% taper). This amplitude was squared to power (μV^2) to observe frequency contribution over time. To rule out movement artefacts in the gamma band, the earliest response time across the study was taken. This was identified at 741ms so data were splined to 512 points to fit with the frequency analysis parameters. Data was then extracted from the gamma frequency band (35-70 Hz). Using electrodes across temporal and parietal regions, based on *a priori* assumptions, (T3/T7, C3, C4, T4/T8, T5/P7, P3, P4, T6/P8) a 2 (MA group) × 4 (complex addition/simple addition/compound numbers/compound words) × 2 (anterior/posterior electrodes) × 4 (left/midline left/midline right/right electrodes) mixed measures ANOVA was conducted to identify any interactions and main effects. All ANOVAs included the Greenhouse-Geisser correction. A breakdown of the overall analysis is listed below (see table 6.15).

Table 6.15:

Gamma activity ANOVA F values, degrees of freedom, significance levels and effect size for interactions and main effects.

Interaction / Main Effect	**ANOVA**			
	F	***df***	***p***	η^2
Horizontal x Vertical x Stim x MA	.35	2.20,61.61	.726	6.51×10^{-4}
Horizontal x Vertical x Stim	.51	2.25,65.12	.622	9.36×10^{-4}
Vertical x Stim x MA	.25	2.19,61.24	.802	1.47×10^{-5}
Horizontal x Stim x MA	.31	1.88,52.70	.719	5.82×10^{-4}
Horizontal x Vertical x MA	2.49	1.89,52.89	.095	.01
Vertical x Stim	.54	2.22,64.31	.602	.001
Horizontal x Stim	.76	1.91,55.47	.467	.001
Horizontal x Vertical	2.09	1.83,53.17	.138	.01
Stim x MA	.89	2.16,60.34	.422	.005
Vertical x MA	1.25	1.83,51.27	.294	.01
Horizontal x MA	2.29	1,28	.141	.01
Vertical	.31	1.92,55.61	.467	.003
Horizontal	12.32	1,29	.001	.05
Stim	.72	2.21,64.09	.505	.004
MA	4.92	1,28	.035	.15

There were no significant four, three or two-way interactions (see table 6.16). There was a significant main effect of horizontal electrodes, such that there was higher gamma power in temporal and central regions (Mean = .23, SD =.44) than parietal (Mean = .09, SD = .25).

There was a significant main effect of MA groups such that those with HMA showed higher gamma power (mean = .24, SD = .48) than those with LMA (mean =.08, SD = .15). This shows high maths anxious individuals elicited higher gamma power than low maths anxious individuals throughout the study, suggesting that those with HMA experienced higher attention bias and threat levels overall. There were no other significant main effects.

Post–hoc MA and Condition Analysis

It was identified that there was no significant interaction between stimulus type and MA however; this may have not shown due to the larger amount of numerical over non-numerical conditions. Therefore, it was of value to ascertain whether and how MA groups were affected by each individual condition. *Post-hoc* analyses were conducted to identify MA differences at each individual condition. Table 6.16 outlines the individual 2 (high/low MA) × 2 (anterior/posterior electrodes) × 4 (left/midline left/midline right/right electrodes) mixed factorial ANOVA results for each condition.

Table 6.16:

Post-hoc gamma power ANOVA F values, degrees of freedom, significance levels and effect size for interactions and main effects.

Condition	**ANOVA**			
	F	***df***	***p***	η^2
Complex Addition	4.49	1,28	.043	.14
Simple Addition	5.64	1,28	.025	.17
Compound Numbers	4.33	1,28	.047	.13
Compound Words	1.26	1,28	.272	.04

The analysis identified that all maths based condition elicited significant gamma power differences between high and low MA individuals except compound words, which showed a non-significant difference. These results will be explained further in the discussion section.

Post-hoc analyses were conducted on individual MA groups across conditions to determine whether conditions were significantly different for high maths anxious individuals and separately for low maths anxious individuals.

There was no significant main effect of condition on high maths anxious participants ($F(1.73,24.25) = .65$, $p=.511$, $\eta^2=.01$) or on low maths anxious participants ($F(1.86,26.02) = 3.40$, $p=.052$, $\eta^2=.03$). This determined that for each MA group conditions did not significantly differ (see table 6.17). The results of the above analyses show interesting findings that will now be explained and discussed in conjunction with relevant research.

Table 6.17:

Mean (SD) gamma power between high and low MA during conditions.

	MA Group	
Stimulus Type	**High**	**Low**
Complex Addition	.27 (.16)	.06 (.10)
Simple Addition	.21 (.12)	.06 (.09)
Compound Numbers	.28 (.15)	.09 (.19)
Compound Words	.21 (.11)	.11 (.20)

6.3.5 Analysis Summary

To conclude, this section will highlight and summarise the significant ERP amplitude findings for each component and gamma frequency analysis results. The summary will include significant main effects and interactions of relevant ERP components and gamma power, not inlcuding main effects of horizontal and vertical electrodes and interactions between horizontal and vertical electrodes. This will be ommitted due to their clear findings on where components spatially appear, which is inline with previous research.

The P1 component showed a significant interaction between stimulus type, horizontal and vertical electrodes such that higher P1 amplitudes were elicited at right parieto-occipital regions with higher amplitudes found during the compound words condition in comparison to complex addition, simple addition and compound number. It also showed a significant interaction between stimulus type and vertical electrodes, such that compound words stimuli (larger digit span) elicited a higher P1 amplitude at occipital sites than compound numbers, simple addition and complex addition.

The N1 showed a significant interaction between stimulus type and horizontal electrodes, such that higher N1 amplitudes were identified at posterior electrodes but higher for compound words at centre electrodes than complex addition, simple addition and compound numbers. It also identified a significant interaction between stimulus type and vertical electrodes, such that there were higher N1 amplitudes at left sites for compound words than complex addition, simple addition and compound numbers.

The P3 component showed a significant interaction between stimulus types, horizontal and vertical electrodes such that higher P3 amplitudes were elicited at anterior, midline sites for complex addition, simple addition and compound numbers, but lower for compound words. This was also higher for compound words at anterior left electrodes than math based conditions. The P3 results identified a significant interaction between stimulus type and horizontal electrodes, such that higher P3 amplitudes were elicited across anterior sites for complex addition, simple addition and compound numbers and smaller for compound words. Finally, the P3 showed a significant interaction between stimulus type and vertical electrodes, such that higher P3 amplitudes were elicited at left sites for complex addition, compound numbers and compound words but smaller for simple addition.

The N400 showed a significant interaction between stimulus type, horizontal and vertical electrodes, such that higher N400 amplitudes were seen in posterior midline and right electrodes, particularly within complex addition and compound word conditions. There was also a significant interaction between stimulus type and horizontal electrodes such that higher N400 amplitudes were experienced at posterior electrodes for complex addition and compound words in comparison to compound numbers and simple addition. Finally, the N400 identified a significant interaction between stimulus type and vertical electrodes, such that higher N400 amplitudes were elicited in right electrodes for compound words and complex addition.

The gamma activity results showed a significant main effect of MA groups such that those with HMA showed higher gamma activity than those with LMA. A *post-hoc* analysis of MA group and condition identified that all maths based conditions produced significant gamma differences between high and low maths anxious individuals however, compound words showed a non-significant difference.

6.4: Discussion

The study set out to compare ERP differences between high and low MA participants across maths and word tasks. It also aimed to identify any gamma power activity differences between MA groups between maths and word tasks. It was hypothesised that there would be a decrease in accuracy and an increase in reaction time for complex addition compared to the three numerical conditions. Horizontal and vertical differences in ERPs were also hypothesised to differ across components. Finally, it was predicted that the processing of maths (compared to the control condition) would produce differences in gamma activity with this decreasing as maths task difficulty decreased. This section will begin by explaining the behavioural results followed by ERP and gamma band activity analyses.

6.4.1 Behavioural Measures

From the correlation analysis it can be reasoned that MA is distinct from other forms of anxiety as data showed no significant correlation between MA and state or trait anxiety within this sample.

Accuracy scores showed complex addition to be the poorest which is expected based on its complexity over other tasks. This was also seen in the interaction between MA group and condition, whereby high maths anxious individuals had particularly poorer accuracy in this condition than in others, compared to low maths anxious individuals. This was previously identified as the condition that high maths anxious individuals would struggle with most. This was also reflected in the reaction time analysis whereby, reaction time was higher for complex addition overall and was higher in high maths anxious individuals than low maths anxious individuals. Again, with this being the most complex condition, this can be expected. Overall it was found that those with HMA took significantly longer than those with LMA supporting previous behavioural research (Ashcraft & Kirk, 2001; Faust et al., 1996).

6.4.2 ERP Amplitude Analysis

Originally, the inspection of the GFP calculation showed 3 peaks but the large, second peak was later noted to represent two individual components. This then made it difficult to differentiate between the two components to get an average for the N1 and a separate one for the P3. The N1 and P3 split will be discussed following a discussion of the P1 and N400 component analyses.

6.4.2.1 P1 Component Analysis

As predicted, there was a significant interaction between horizontal and vertical electrodes such that higher P1 amplitudes were found at posterior left and right sites. Again this is indicative of a P1 component, typically associated with contrast perception; the initial process needed to identify a visual stimulus. This interaction was further supported by a significant main effect of vertical electrodes which identified a higher P1 amplitude at left and right sites than at midline electrodes, supporting previous research (Odom et al., 2004).

There was also a significant interaction between vertical electrodes and condition whereby a higher P1 amplitude was elicited in the compound words condition at right electrodes. Whilst there is evidence that associates right hemispheric activity to word and language processing (Lindell, 2006), at this early stage, differences across conditions are more likely to be low level visual differences (Halgren, Raij, Marinkovic, Jousmäki, & Hari, 2000). This supports the function of the P1 and its role in contrast perception, i.e. identifying contrast differences. Compound words stimuli contained a larger amount of characters (e.g. THUNDER+STORM=) and occupied a wider field of view on screen than other maths based conditions (e.g. 54+22=), generating a higher P1 amplitude. Other interactions at this early stage, for example, between stimulus type, horizontal and vertical electrodes are also likely to be due to differences in condition stimulus size and fluctuations in the P1 as a result of this.

6.4.2.2 N400 Component Analysis

There was a significant interaction between horizontal and vertical electrodes such that higher N400 amplitudes were experienced at posterior midline, and right anterior electrodes. This was further supported by a significant main effect of horizontal electrodes, showing a higher N400 amplitude at posterior sites as well as a significant main effect of vertical electrodes, showing a higher N400 amplitude across right sites. The N400 activity at right anterior sites can be explained by previous research stating that visually presented stimuli elicit an N400 at central and posterior sites over the right hemisphere (Kutas & Hillyard, 1982). A significant interaction between stimulus type and horizontal electrodes was identified, showing higher N400 amplitudes elicited in posterior electrodes for complex addition and compound words. Being that these were physically the largest stimuli sets and could be initially seen as the most complex it is likely that these produced a higher N400 amplitude based on perceived task difficulty and attention resources required (Eysenck et al., 2007)

A significant interaction was also identified between stimulus type and vertical electrodes, showing higher N400 amplitude across right sites, particularly for compound words and complex addition. This is likely explained by language based processing for complex words and the reliance on this type of processing for complex addition (Tang et al., 2006a). Finally, the N400 also showed an overall significant interaction between stimulus type, horizontal and vertical electrodes, such that large N400 components were elicited for compound words at posterior midline and right, and anterior, right electrodes. This was closely followed by complex addition and is likely explained by the aforementioned research.

The next two sections will continue to explain the main ERP components, excluding the original joint N1 and P3 components identified before the *post-hoc* split was applied (see chapter 6.3.3.3). These will be omitted due to the irrelevance and lack of contribution the main effects and interactions provide to the discussion.

6.4.2.3 N1 Component Analysis

Again, there was a significant interaction between horizontal and vertical electrodes such that a higher N1 amplitude was elicited in posterior electrodes (parieto-occipital sites) and was higher at right sites. This was confirmed by a significant main effect of horizontal electrodes, showing a large N1 at posterior sites, and a significant main effect of vertical electrodes showing a higher N1 amplitude at right electrodes. This can be explained using two theories; firstly, research has identified that the right hemisphere, particularly within posterior regions, can be considered more responsible for visual perception (Corballis, 2003) and secondly, the P3 component's (section 6.4.2.4) latency window encroaches on the N1 due to the *post-hoc* split (see chapter 6.3.3.3). This later P3 was also elicited at left parietal and central sites therefore, negating the N1's negative inflection.

There was also a significant interaction between stimulus type and vertical electrodes such that higher N1 amplitudes were experienced at left sites for compound words. This supports previous research outlining the role of the left hemisphere, including temporal and parietal lobes, in language processing (see Vigneau et al., 2006, for a review). There was also a significant interaction between stimulus type and horizontal electrodes. Higher N1 amplitudes were identified for compound words at parietal sites, which supports the above review noting parietal involvement in language processing. It can also be seen that a greater amount of digits produced a higher N1 amplitude in posterior regions with compound words producing a large

N1 and complex addition, compound numbers and simple addition producing consecutively lower N1 amplitudes as the amount of digits in each stimulus type decreased. This highlights the N1 component's role in visual perception and recognition.

To this point, no significant interaction or main effects have been identified between MA groups. It was thought that this might occur during the P3 component, associated with processing of stimuli.

6.4.2.4 P3 Component Analysis

There was a significant interaction between horizontal and vertical electrodes signifying higher P3 amplitudes at anterior midline and left sites. This can also be identified by observing the topography outlining the dipole in figure 6.8 (see chapter 6.3.3.3). The P3 here is also supported by the significant main effect of horizontal electrodes identifying a higher P3 amplitude at anterior (temporal and central) regions. This is further supported by the significant main effect of vertical electrodes showing a higher P3 amplitude at midline and left sites with lower P3 amplitudes across right electrodes. These results are consistent with findings explaining that Western populations employ a language process which is based in the left perisylvian cortex (Tang et al., 2006a) and supports previous research attributing language type processing to the left hemisphere (Vigneau et al., 2006).

A significant interaction was also identified between stimulus type and vertical electrodes, whereby higher P3 amplitudes were elicited for compound words in left electrodes. This can again be supported by language research attributing the distribution of processing to the left hemisphere (Vigneau et al., 2006). The significant interaction between stimulus type and horizontal electrodes identified a higher P3 amplitude at posterior electrodes for compound words than numerical conditions. Again, this could be explained by the larger amount of digits within the stimuli as those with consecutively less digits, i.e. complex addition (2x2 digits), compound numbers (2x1 digits) and simple addition (1x1 digit) elicited a smaller P3 overall.

These results are supported by the overarching interaction between stimulus type, horizontal and vertical electrodes whereby higher P3 amplitude were experienced in left and midline, anterior electrodes, particularly for compound words. All posterior positive components decreased as stimulus digit size also decreased. Nevertheless, to this point there is no explanation for the differences in accuracy and reaction time experienced between MA groups.

Whilst the ERP analyses show support for previous research, including lateralisation and differences in conditions and the processing associated with these, they do not provide any explanation or basis for identifying the accuracy and reaction time differences experienced between MA groups.

6.4.3 Gamma Activity Results

It was found that there was a significant main effect of horizontal electrodes such that higher power of gamma activity was identified in anterior electrodes than at posterior sites. This is consistent with previous research noting higher power of gamma activity at temporal than at parietal sites during worry (Oathes et al., 2008). This is further supported by the close link between temporal lobes and the amygdala (Swanson & Petrovich, 1998), linked to gamma activity (Popescu et al., 2009; Sato et al., 2011).

One of the main findings of the gamma analysis was the significant main effect of MA groups. Overall, high maths anxious individuals experienced significantly higher power of gamma activity than low maths anxious individuals. This is to be expected during the presentation of maths stimuli, based on the previous studies results. It was hypothesised that the compound words condition would produce a lower power of gamma activity for high maths anxious individuals or at least more equal power to low maths anxious individuals. However, the lack of an interaction between stimulus type and MA group indicated that this was not the case. This was explored further to assess how and if both MA groups were affected by each condition.

The *post-hoc* analyses identified that those with HMA had significantly higher power of gamma activity across all maths based conditions (complex addition, simple addition and compound numbers) but a non-significant effect was found for compound words. It can be seen that complex maths and compound numbers produced a similar power of gamma activity in high maths anxious participants however; slightly decreased power was found in high maths anxious participants for simple addition, similar to the compound words condition. High maths anxious individuals may display a higher power of gamma activity in response to increased attentional bias and therefore, perceived threat. For example, 90+3= (compound numbers) would typically be considered simple over a sum that requires more manipulation of number such as 9+7= (simple addition). Yet, at first, the perception of larger sums (containing at least one 2-digit addend) can be seen to produce higher power of gamma activity. This suggests that it may be the initial observation of maths stimuli that generates this increase in gamma activity and therefore, heightened threat perception.

This could represent just attention instead of threat, as individuals assign more attentional resources to physically larger stimuli (Eriksen & Yeh, 1985). However, the non-significant main effect of MA groups in the compound words condition identifies that the largest stimuli is not the most attended to, which does not fit this argument. This adds further support to the theory that HMA exists independently of general anxiety and that individuals within the high maths anxious group of this study are anxious towards maths. The results identify that the least threatening stimulus conditions (simple addition and compound words) show a decrease power of gamma activity experienced by high maths anxious individuals.

Still, high maths anxious individuals experienced higher power of gamma activity overall, albeit with a non-significant difference to low maths anxious individuals during the compound words condition. This was not due to high maths anxious gamma activity being decreased enough to match the low maths anxious group's low power of gamma. Rather, low maths anxious individuals experienced an increase in gamma activity for compound words even though this increase was found to be non-significant when comparing conditions.

Nevertheless, higher power of gamma activity experienced in compound numbers and word conditions for low maths anxious individuals still needs to be explained (see table 6.18). As gamma activity changes are also represented by attention to stimuli (Jensen et al., 2007; Müller et al., 2000; Tallon-Baudry et al., 2005) these tasks may involve less problem solving techniques and more auditory and semantic representations to answer successfully. For example, 90+3= and THUNDER+STORM= requires less manipulation of the numbers or words than 45+64= and 9+7=. This explains the increase in gamma activity in low maths anxious individuals. This effect would likely be seen in those with HMA if the gamma power wasn't triggered by attentional bias and threat. To further explore this theory, it would be of use to measure pre and post-stimulus gamma power in high maths anxious individuals, which could highlight anticipatory effects towards maths stimuli (pre-stimulus) and attention effects towards physically larger stimuli (post-stimulus). This would enable the identification of precisely when the perceived threat may occur in high maths anxious individuals.

Observing the results, it could be argued that it is the initial perception, or even anticipation, of maths stimuli that generates higher power of gamma activity in high maths anxious individuals. The analysis of gamma power over ERP latency could identify support for previous anticipation research (Lyons & Beilock, 2011). This would support research linking gamma band activity to the manipulation of the amygdala, involved in processing negative information (including threat) (Davis, 1992; Davis & Whalen, 2001; Luo, Holroyd, Jones, Hendler, & Blair, 2007b; Oya et al., 2002; Sato et al., 2011; Siegle, Steinhauer, Thase, Stenger, & Carter, 2002) which in turn produces fear responses (Ohman, 2005). This would account for the delay in accuracy and reaction time experienced in high maths anxious individuals as they try to combat threatening thoughts as well as the primary task, which may not display in ERP findings.

6.4.4 Summary

The aim of this study was to identify whether high maths anxious individuals, that experienced higher power of gamma activity associated with attention and threat, would still elicit a higher power when a control condition was implemented. Whilst high maths anxious individuals did experience higher power of gamma activity overall, this was lowered during the control condition (compound words) and simple addition. This is theorised to be because simple addition sums (1 digit + 1 digit) and answers are perceived as less threatening than stimuli with one or more two-digit addends.

The higher power of gamma activity in high maths anxious individuals are theorised to occur due to the anticipation of (threatening) maths stimuli and until recognition of the stimulus occurs, high maths anxious individuals are in a perpetual state of anxiety unless the stimulus is perceived as less threatening, providing a slight relief. It can be seen from accuracy and reaction time data that the power of gamma activity, for each condition, are not reflected in the score or time taken which again points more towards an anticipatory effect. It may be that the anticipation of the task explains a portion of the poorer accuracy and delay but does not explain all of the behavioural response, perhaps because participants are constantly fearful of the appearance of maths stimuli, so become more vigilant. Again, it would be of use to look at early stages of the ERP and a breakdown of the more prominent contributing frequency bands.

Whilst the control condition was useful it cannot be considered a legitimate equivalent to a maths based problem. Nevertheless, it is extremely difficult to achieve this without using a form of number in an EEG paradigm. The amount of digits displayed within the compound words condition will have also impacted on attention processes, such as contrast perception, recognition and processing (P1, N1 and P3), whereas numerically based stimuli had considerably less digits in the question and answer. Furthermore, the use of three maths-based and one word-based condition may have influenced gamma band activity power. If this is theorised to represent anticipatory effects then it is possible that this could have increased levels by 25% in high maths anxious participants than if there was an equal amount of word and maths conditions. However, to bridge results from the previous study and introduce an equivalent non-numerical condition, the use of all conditions were necessary.

The results still have large implications for MA research. It could be that those with HMA do have a deficit in working memory when maths processing is involved (Maloney et al., 2011), which is why poorer accuracy and increased reaction time is continuously identified. Alternatively, it may just be that higher power of gamma activity begins the process which inevitably reduces accuracy and increases reaction time through consuming working memory resources for intrusive, anxious thoughts (Ashcraft & Moore, 2009). Considering MA is hypothesised to begin in early years (Petronzi, 2012) and that number anxiety is theorised to begin the journey to MA (Kazelskis, 1998), it would be of use to identify whether the threatening response in high maths anxious individuals is visible through the observation of number. This would hopefully support or refute the working memory deficit suggested by Maloney et al. (2011), as little working memory resources are needed when purely observing number, as well as shedding light on the effect of observing number within a high maths anxious population. Furthermore, the use of single digit numbers or letters will reduce the amount of conditions necessary enabling a more straightforward comparison of conditions.

As stated in previous chapters, the concept of MA being exhibited towards numerical or arithmetical tasks within scale and behavioural measures, is shown more often than complex mathematical stimuli. For example, research noting MA behavioural differences (e.g. Faust et al., 1996; Maloney et al., 2010; Wu et al., 2012) typically use simple and complex arithmetic and numerical processing rather than algebra and fractions, which are arguably less arithmetical and more mathematical. Again, this provides further argument for a nomenclature shift of MA definitions to include aspects of numerical processing and arithmetic. This could include the theory that number anxiety is a potential precursor or *sine qua non* to MA (Kazelskis, 1998). The following study looks to support this theory as well as measuring the extent that high maths anxious adults show signs of attentional bias and threat perception towards simple numerical processing.

In summary, this study has shown gamma band activity results, which subscribe to previous theories concerning feelings of anticipation and threat perception. Identifying whether this theory applies to numbers within MA populations, where MA is theorised to begin (Geist, 2015; Kazelskis, 1998; Krinzinger, Kaufmann, & Willmes, 2009; Petronzi, 2012) will provide an extensive contribution to the current body of knowledge concerning MA.

Chapter 7: Maths anxious gamma activity during letter and number observation

7.1: Introduction

The previous study outlined increases in gamma power in high maths anxious individuals during maths processing but only in numerically based tasks; there were no differences in the non-numerical task. However, there were more numerically based tasks than non-numerical tasks which may have reduced the power to detect interaction effects. So, there was no significant interaction between stimulus type and MA group even though a *post-hoc* ANOVA identified significant gamma differences between high and low maths anxious individuals in each numerical task condition but not the non-numerical compound words condition.

The observed increased gamma power in high maths anxious individuals performing numerical tasks may be due to higher levels of required attention (Fell et al., 2003; Jensen et al., 2007; Müller et al., 2000), or increases in threat and anxiety (Garcia-Garcia et al., 2010; Luo et al., 2007a; Maratos et al., 2012; Oathes et al., 2008). The higher gamma power may indicate that those with HMA show attentional bias towards the more threatening stimuli, rather than anxiety and threat, as high anxious populations show attentional bias to threatening stimuli (Bar-Haim et al., 2007a). To eliminate this attention-based explanation the study presented in this chapter used one numerical and non-numerical stimulus type involving observation to minimise the attention resources needed.

The study also aimed to identify any ERP differences during number and letter observation. In the previous study ERP analyses identified differences in interactions between stimuli type and electrodes sites; stimuli with larger digit spans typically elicited higher amplitude at relevant sites associated with their typical function. Although there were no significant interaction or main effects with MA the current study still used this analytic strategy in order to remain consistent and allow comparisons with current research in this area (Suárez-Pellicioni et al., 2013b; Suárez-Pellicioni, Nuñez-Peña & Colomé, 2014).

Based on previous research, stating that MA typically develops at early stages of maths education (Geist, 2015; Krinzinger et al., 2009; Petronzi, 2012; Ramirez, Gunderson, Levine, & Beilock, 2013), it is possible that basic numerical skills may also heighten anxiety and may be illustrated by higher gamma power. (Maloney, Risko, Ansari, et al., 2010) note that high maths anxious individuals still show typical negative behavioural effects even when the need for working memory resources are reduced. They modified a high/low 5 task in order to rule out working memory involvement in storing a number or task as a target. Participants were required to identify which of two numbers was the highest by pressing a button. They found that high maths anxious individuals had poorer performance with more errors made than those with low maths anxious. Whilst participants will have not required a large amount of working memory resources, attentional resources will have still been needed to attend to stimuli. However, these resources would likely be consumed by anxiety (Derakshan & Eysenck, 2009) and intrusive thoughts in high maths anxious individuals (Ford et al., 2005; Hunt et al., 2014; Park et al., 2014).

This study will explore the consumption of attentional resources further using neurophysiological measures in high and low maths anxious individuals. Numerical observation will be used as the task to remove any demand to respond and reliance on holding problems in working memory. If increases in gamma power are displayed in the current study towards number, then it will likely be a representation of attentional bias towards a threat. As stated above, high anxious individuals have been shown to elicit increased levels of attention towards a perceived threat (Bar-Haim et al., 2007a; Cisler & Koster, 2010; Mogg et al., 1994) therefore, this could still identify the role of threat perception in high maths anxious individuals.

However, there has been little research concerning the observation of number from a neurophysiological perspective. This may be due to the absence of behavioural measures, i.e. observation of stimuli requires no participant response, which may why more simple tasks involving the manipulation of number have been used within MA research (e.g. Maloney et al., 2010). However, with more recent investigations focusing on the neurophysiological effects of MA, it makes more sense to study what could be the "*sine qau non"* of MA (Kazelskis, 1998, p.631) to identify whether number anxiety continues into adulthood. It is important to understand how this occurs, particularly because it is possible to measure neurophysiological effects rather than self-report measures post-task.

The previous studies have outlined that processing of maths stimuli in high maths anxious populations generates higher power of gamma band activity. It is hypothesised that differences in gamma power will be shown in response to number and letter observation between MA groups. This is further supported by the lower power of gamma activity during the compound words task in high maths anxious individuals (see chapter 6.3.4), which identified a non-significant difference between MA groups.

This study had 2 objectives; (a) to compare ERP differences across high and low maths anxious participants during the observation of number and letter and (b) to observe gamma activity differences between the two groups during the observation of number and letters. It is hypothesised that high maths anxious individuals will elicit greater power of gamma activity for numerical than letter-based stimuli, whereas low maths anxious individuals will show no differences between stimulus types.

7.2 Method:

As the method is similar to the previous study, aspects of this section will be omitted to avoid repetition.

7.2.1 Design

The analysis conducted resulted in a 2 (high/low MA) x 2 (letter/number) x 3 (anterior/centre/posterior electrodes) x 3 (left/midline/right electrodes) mixed factorial design. The between subjects IV was MA group and within subjects IVs included stimulus set, horizontal and vertical electrode layout. Electrical activity at electrodes acted as the DV.

Multiple stimuli were administered per condition in a random order to avoid habituation during tasks. Those who diagnosed with dyslexia were not included in the EEG study due to possible anxiety confounds (Carroll & Iles, 2006) and to remain consistent with the previous three studies. *A priori* assumptions based on previous maths research were made for specific ERP components (P1, N1 and P2). The P2 component was thought to elicit due to its association with allocation of attentional resources to simple visual stimuli (Luck & Hillyard, 1994), i.e. single digits. All 70 electrodes (including a reference, ground, 2 mastoid, 2 horizontal and 2 vertical electro-oculogram electrodes) were used for data acquisition. The same nine electrodes from previous ERP analyses were used for current the ERP analysis (T7, Cz, T8, P5, Pz, P6, O1, Oz, O2). Electrodes were allocated to groups based on their horizontal and vertical layout (see table 7.1).

Table 7.1:

Layout of Horizontal and vertical electrodes.

		Vertical		
		Left	Midline	Right
Horizontal	Anterior	T7	Cz	T8
	Centre	P5	Pz	P6
	Posterior	O1	Oz	O2

A pilot study was conducted prior to testing to ensure stimulus presentation, lighting and procedure was adequate and followed in an appropriate manner.

The analysis of gamma activity was also necessary for this study therefore; relevant electrodes were selected based on *a priori* assumptions. Previous research has outlined temporal and parietal activity for attention and visual information associated with gamma oscillations (Keil et al., 2001; Müller et al., 2000; Oathes et al., 2008; Tallon-Baudry & Bertrand, 1999) identifying these regions for analysis. To analyse data from these previously suggested sites, different electrodes were used compared to those used in the ERP analysis (T3/T7, C3, C4, T4/T8, T5/P7, P3, P4, T6/P8). This analysis resulted in a 2 (high/low MA) x 2 (letter/number) x 2 (anterior/posterior electrodes) x 4 (left/midline left/midline right/right electrodes) mixed factorial design. Again, electrodes were allocated to groups based on their horizontal and vertical layout (see table 7.2).

Table 7.2:

Layout of Horizontal and vertical electrodes for gamma analysis.

		Vertical			
		Left	Midline Left	Midline Right	Right
Horizontal	Anterior	T7	C3	C4	T8
	Posterior	P7	P3	P4	P8

7.2.2 Participants

The same participants were used from the previous study (see chapter 6.2.2). Participants were split into two groups based on MAS-UK scores which contained 15 high and 15 low maths anxious individuals.

7.2.3 Materials and Equipment

One hundred and sixty numbers and letters were used. This included 80 letters from A-Z (e.g. K) and 80 single digit numbers from 0-9 (e.g. 4). Each letter was repeated at least three times and each number eight times.

7.2.4 Procedure

Similar to the procedure of the last study, participants were seated in a dimly lit room whilst white stimuli (font size 64) were presented on a black background. Luminance levels were measured from the visual display unit (2.2 cd/m^2) distanced at 72cm at eye height with the centre of the screen. Participants were sat in a comfortable chair at eye height to the centre of the screen. Participants were asked to concentrate on the stimuli presented. Each stimulus was presented for 2000ms followed by a fixation of 500ms. Inter-trial intervals were pseudo-randomised between 500ms and 2500ms to avoid habituation. Impedances of all electrodes were kept below 15kΩ however; the majority were below 5kΩ. Processing procedure was kept similar to the previous studies (see chapter 5.2.5).

7.3: Results

7.3.1: Analytical Strategy

The previous studies and literature was used alongside GFP to refine appropriate component windows for analysis, which identified the emergence of three components. The three components were individually analysed to identify significant interactions and main effects to remain consistent with the previous studies and literature. A gamma frequency analysis was separately conducted to identify any significant interactions or main effects across groups and conditions to identify whether this band could be used to identify attentional bias, threat and/or anxiety (see chapter 7.3.3).

7.3.2: ERP processing and analysis

After conducting averages across each condition and participant group it was determined that there were no latency differences and amplitude analysis proceeded. This enabled the use of the average GFP's component identification (below) applied across all groups and conditions.

7.3.2.1: ERP amplitude processing

An average GFP calculation was conducted across all electrodes (excluding M1, M2, VEOG, HEOG and the central reference), participants, and conditions to identify to refine the latency interval for components. *A priori* assumptions based on the previous study and research suggested the emergence of three components. However, the GFP presented the emergence of 2 components identified as P1 (62-107ms) and N1 (108-248ms) (see figure 7.1). The component split will be discussed later in this section (see figure 7.2).

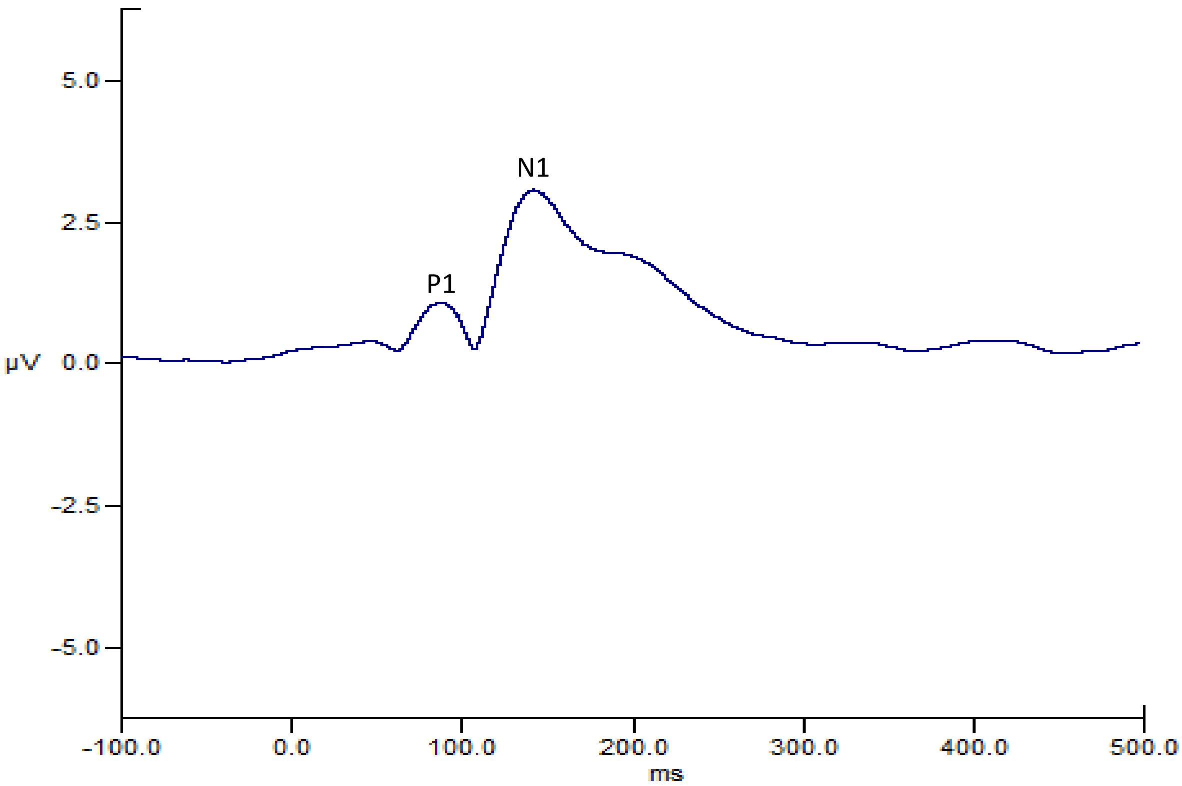

Figure 7.1: GFP diagram displaying two components for analysis.

The components were extracted from relevant electrodes (T7, Cz, T8, P5, Pz, P6, O1, Oz, O2) and 2 (High/Low MA group) × 2 (number/letter) × 3 (left/midline/right electrodes) × 3 (anterior/centre/posterior electrodes) mixed factorial ANOVAs were used to identify any interactions and main effects for each component. All ANOVAs included the Greenhouse-Geisser correction to ensure type I error rates were not inflated (Greenhouse & Geisser, 1959) as neurophysiological data is rarely homogenous.

7.3.2.2: ERP amplitude analysis

<u>P1 Component Amplitude Analysis</u>

The results display the findings of the P1 amplitude, explaining the overall analysis, interactions and main effects (see table 7.3).

Table 7.3:

P1 ANOVA F values, degrees of freedom, significance levels and effect size (η^2) for amplitude interactions and main effects.

Interaction / Main Effect	**ANOVA**			
	F	***df***	***p***	**η^2**
Horizontal x Vertical x Stim x MA	2.96	2.91,81.40	.212	.002
Horizontal x Vertical x Stim	1.16	2.86,82.85	.331	6.67×10^{-4}
Vertical x Stim x MA	.50	1.89,52.89	.432	4.39×10^{-5}
Horizontal x Stim x MA	1.17	1.51,42.19	.656	.001
Horizontal x Vertical x MA	2.05	2.95,82.47	.114	.003
Vertical x Stim	.03	1.90,55.14	.970	2.64×10^{-5}
Horizontal x Stim	4.35	1.59,46.06	.026	.004
Horizontal x Vertical	4.76	3.07,89.12	.004	.008
Stim x MA	2.79	1,28	.106	.008
Vertical x MA	.58	1.66,48.39	.534	.002
Horizontal x MA	.95	1.23,34.40	.354	.01
Vertical	18.83	1.68,48.57	<.001	.06
Horizontal	14.43	1.28,37.02	<.001	.21
Stim	3.94	1,29	.057	.01
MA	3.94	1,28	.057	.12

The 3×3×2×2 analysis showed no significant four-way interaction between horizontal, vertical electrodes, stimulus type and maths anxiety group. There was no significant interaction between stimulus type, horizontal and vertical electrodes. There was no significant interaction between horizontal, vertical electrodes and maths anxiety group or between maths anxiety group, stimulus type and horizontal electrodes. There was also no significant interaction between maths anxiety group, stimulus type and vertical electrodes.

There was no significant interaction between maths anxiety group and stimulus type, maths anxiety group and horizontal electrodes, or maths anxiety group and vertical electrodes. However, there was a significant interaction between stimulus type and horizontal electrodes across both groups, such that higher P1 amplitudes were elicited at posterior electrodes particularly for letters (mean = 1.10mv, SD = 1.77) than numbers (mean = .61mv, SD = 2.31).

There was no significant interaction between stimulus type and vertical electrodes. There was a significant interaction between horizontal and vertical electrodes across all conditions and groups (see table 7.4), such that left and right posterior electrodes displayed higher P1 amplitudes than midline and anterior electrodes.

There was no significant main effect of MA group or stimulus type. There was a significant main effect of horizontal electrodes across all conditions and groups, such that higher P1 amplitudes were elicited in posterior electrodes (mean = .86mv, SD = 2.07), than at centre (mean = -.19mv, SD = 1.71) or anterior (mean = -.73mv, SD = 1.20) sites. There was also a significant main effect of vertical electrodes across all conditions and groups, such that there was a higher P1 amplitude at right sites (mean = .31mv, SD = 2.01), than at left (mean = .13mv, SD = 1.60) and midline electrodes (mean = -.50mv, SD = 1.73).

Table 7.4:

P1 mean amplitude (mv) and standard deviation depicting the interaction between horizontal and vertical electrodes for both conditions.

	Vertical Electrodes		
Horizontal Electrodes	Left	Midline	Right
Anterior	-.56 (.03)	-1.08 (.14)	-.55 (.05)
Centre	-.13 (.29)	.39 (.24)	.39 (.33)
Posterior	1.07 (.40)	.40 (.29)	1.10 (.35)

Examining the GFP diagram (see figure 7.1) it can be seen that the second peak has an abnormally long latency, and considering the previous two studies, this portion of the waveform is likely a representation of two distinct components. Based on this knowledge and the topographical maps below (see figure 7.2), two separate GFP calculations were conducted on separate relevant electrodes. This was conducted in order to highlight the onset and offset of both components in appropriate regions. The first GFP calculation was conducted on occipital and parieto-occipital electrodes and represented the N1 component (108-194ms). The second GFP was conducted on central midline and left electrodes (as informed by the topography, see figure 7.2) and represented the P2 component (171-248ms).[2] Two 2×2×3×3 mixed factorial ANOVAs were then separately conducted for each component.

[2] It should be noted that the use of specific electrodes for the component split was purely to outline the latency windows and not for analysis below.

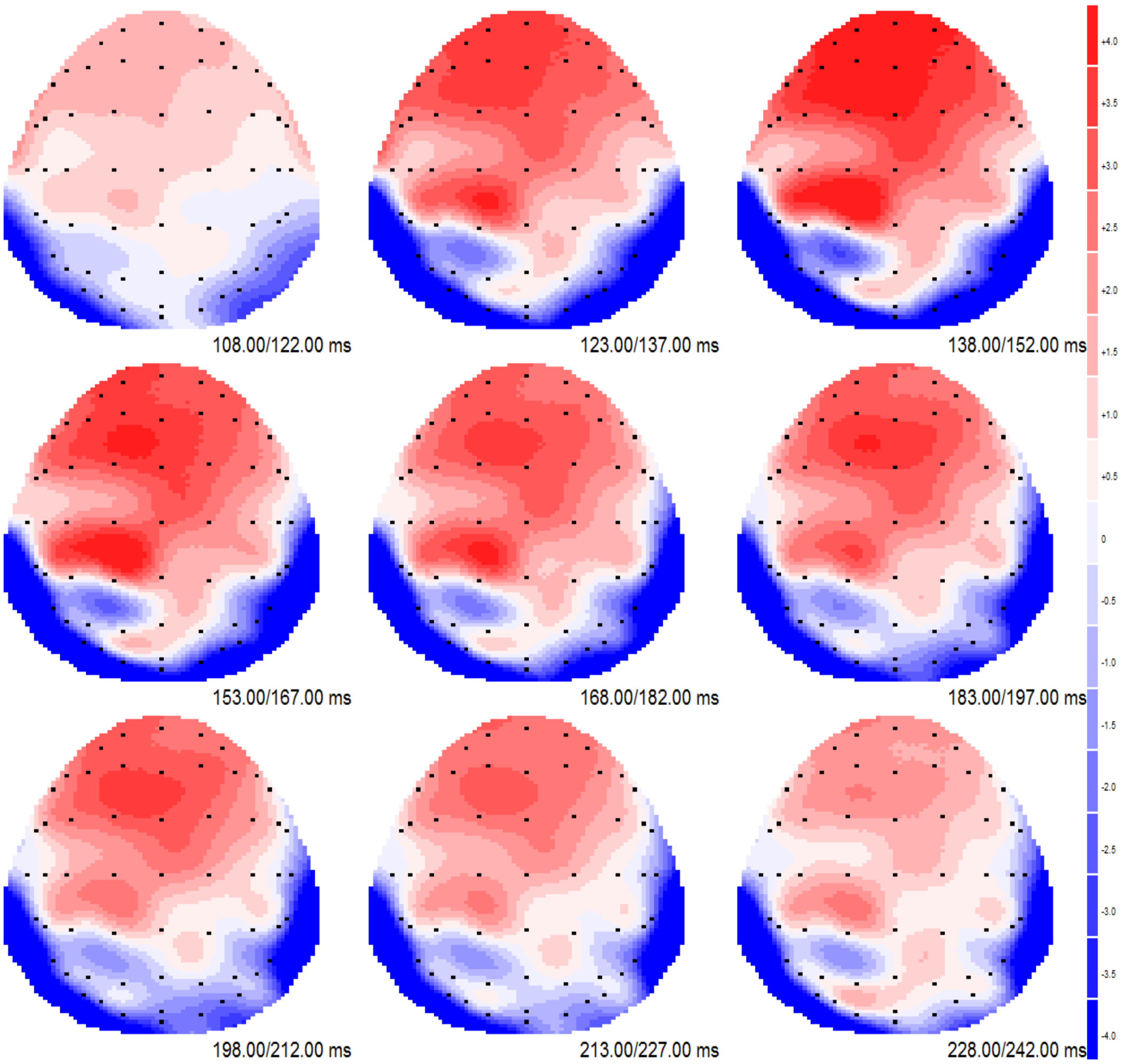

Figure 7.2: Topography highlighting two ERP components (N1 and P2) at similar latencies over time from top left (108-122ms) to bottom right (228-242ms). The colour key (right) shows positive (red) and negative (blue) inflections.

N1 Component Amplitude Analysis

The results display the findings of the N1 amplitude, explaining the overall analysis, interactions and main effects (see table 7.5).

Table 7.5:

N1 ANOVA F values, degrees of freedom, significance levels and effect size for amplitude interactions and main effects.

Interaction / Main Effect	**ANOVA**			
	F	***df***	***p***	η^2
Horizontal x Vertical x Stim x MA	1.96	2.45,68.52	.139	3.49×10^{-4}
Horizontal x Vertical x Stim	.31	2.40,69.58	.774	5.69×10^{-4}
Vertical x Stim x MA	1.00	1.99,55.67	.375	2.45×10^{-4}
Horizontal x Stim x MA	4.46	1.31,36.64	.029	.001
Horizontal x Vertical x MA	1.95	3.15,88.19	.125	5.69×10^{-5}
Vertical x Stim	1.40	1.99,57.68	.256	3.43×10^{-4}
Horizontal x Stim	2.27	1.32,38.29	.134	7.13×10^{-4}
Horizontal x Vertical	17.73	3.28,95.07	<.001	.02
Stim x MA	.22	1,28	.642	2.33×10^{-4}
Vertical x MA	2.46	1.90,53.00	.098	.008
Horizontal x MA	2.17	1.18,33.02	.148	.02
Vertical	45.54	1.93,55.97	<.001	.14
Horizontal	51.13	1.17,33.93	<.001	.02
Stim	.05	1,29	.834	4.61×10^{-5}
MA	.60	1,28	.447	.02

The 3×3×2×2 analysis showed no significant four-way interaction between horizontal, vertical electrodes, stimulus type and maths anxiety group. There was no significant interaction between stimulus type, horizontal and vertical electrodes. There was no significant interaction between horizontal, vertical electrodes and maths anxiety group. However, there was a significant interaction between maths anxiety group, stimulus type and horizontal electrodes such that both groups exhibited higher N1 amplitudes at posterior electrodes with low maths anxious individuals eliciting a higher N1 amplitude during letter observation (mean = -2.59mv, SD = 2.09) than high maths anxious individuals (mean = -1.33mv, SD = 2.81). There was no significant interaction between maths anxiety group, stimulus type and vertical electrodes.

There was no significant interaction between maths anxiety group and stimulus type. There was no significant interactions between maths anxiety group and vertical electrodes, or between MA group and horizontal electrodes. There was also no significant interaction between stimulus type and horizontal electrodes and stimulus type and vertical electrodes. There was a significant interaction between horizontal and vertical electrodes across all conditions (see table 7.6) such that higher N1 amplitudes were observed in posterior sites particularly at left and right electrodes.

There was no significant main effect of maths anxiety groups or stimulus type. However, there was a significant main effect of horizontal electrodes across all conditions and groups, such that a higher N1 amplitude occurred at posterior electrodes (mean = -1.90mv, SD = 2.37), than at centre (mean = -.41mv, SD = 2.43) and anterior sites (mean = 1.64mv, SD = 1.79). There was also a significant main effect of vertical electrodes across all conditions and groups, such that there was a higher N1 amplitude elicited at right sites (mean = -1.01mv, SD = 2.23), than at left (mean = -.66mv, SD = 2.45) and midline sites (mean = 1.00mv, SD = 2.66). Again, this is typical of a N1 displayed largely at parieto-occipital electrodes (Hopf et al., 2002).

Table 7.6:

N1 mean amplitude (mv) and standard deviation depicting the interaction between horizontal and vertical electrodes for both conditions.

	Vertical Electrodes		
Horizontal Electrodes	Left	Midline	Right
Anterior	1.27 (.04)	3.07 (.12)	.58 (.12)
Centre	-.95 (.16	1.21 (.03)	-1.50 (.07)
Posterior	-2.31 (.19)	-1.29 (.05)	-2.11 (.01)

P2 Component Amplitude Analysis

The results display the findings of the P2 amplitude, explaining the overall analysis, interactions and main effects (see table 7.7).

Table 7.7:

P2 ANOVA F values, degrees of freedom and significance levels for amplitude interactions and main effects.

Interaction / Main Effect	**ANOVA**			
	F	***df***	***p***	***η²***
Horizontal x Vertical x Stim x MA	1.84	2.90,81.15	.148	5.69×10^{-4}
Horizontal x Vertical x Stim	.25	2.89,83.75	.854	7.95×10^{-5}
Vertical x Stim x MA	1.38	1.85,51.84	.260	5.94×10^{-5}
Horizontal x Stim x MA	4.87	1.18,33.05	.029	.002
Horizontal x Vertical x MA	1.03	3.06,85.80	.383	.002
Vertical x Stim	.79	1.89,54.70	.455	3.42×10^{-4}
Horizontal x Stim	1.54	1.25,36.27	.227	8.78×10^{-4}
Horizontal x Vertical	38.08	3.17,91.88	<.001	.08
Stim x MA	.48	1,28	.494	9.99×10^{-4}
Vertical x MA	.53	1.97,55.28	.534	.002
Horizontal x MA	.25	1.16,32.49	.660	.003
Vertical	25.34	1.98,57.50	<.001	.11
Horizontal	22.47	1.16,33.77	<.001	.23
Stim	.35	1,29	.560	7.11×10^{-4}
MA	4.69×10^{-4}	1,28	.983	1.61×10^{-5}

The 3×3×2×2 analysis showed no significant four-way interaction between horizontal, vertical electrodes, stimulus type and maths anxiety group. There was no significant interaction between stimulus type, horizontal and vertical electrodes. However, there was a significant three-way interaction between horizontal, stimulus type and maths anxiety group, such that higher P2 amplitudes were observed in high maths anxious individuals overall, particularly at anterior electrodes during number observation (mean = 2.70mv, SD = 2.20) than for low maths anxious individuals (mean = 2.25mv, SD = 1.64). This was fairly similar during letter observation with high maths anxious individuals eliciting only a slightly higher P2 amplitude (mean = 2.50mv, SD = 2.14) than low maths anxious individuals (mean = 2.49mv, SD = 2.02). There was no significant interaction between maths anxiety group, horizontal and vertical electrodes. There was no significant interaction between maths anxiety group, stimulus type and vertical electrodes.

There was no significant interaction found between maths anxiety group and stimulus type. There was no significant interaction between maths anxiety group and horizontal electrodes and maths anxiety group and vertical electrodes. There was also no significant interaction between stimulus type and horizontal electrodes and stimulus type and vertical electrodes. However, there was a significant interaction between horizontal and vertical electrodes across all conditions and groups (see table 7.8) such that higher P2 amplitudes were elicited anterior and centre midline sites.

There was no significant main effect of maths anxiety groups or stimulus type however, there was a significant main effect of horizontal electrodes across all conditions and groups, such that higher P2 amplitudes were identified at anterior electrodes (mean = 2.48mv, SD = 2.00) than at centre (mean = 1.62mv, SD = 1.70) and posterior sites (mean = .54mv, SD = 1.85). There was also a significant main effect of vertical electrodes across all conditions and groups, such that there was a higher P2 amplitude at midline electrodes (mean = 2.32mv, SD = 2.44) than at left (mean = 1.29mv, SD = 1.62) and right sites (mean = 1.04mv, SD = 1.64).

Table 7.8:

P2 mean amplitude (mv) and standard deviation depicting the interaction between horizontal and vertical electrodes for both conditions.

	Vertical Electrodes		
Horizontal Electrodes	Left	Midline	Right
Anterior	2.10 (.02)	4.07 (.06)	1.28 (.03)
Centre	1.28 (.01)	2.33 (.09)	1.26 (.05)
Posterior	.48 (.11)	.55 (.22)	.58 (.15)

7.3.3: Gamma activity

To analyse Gamma band activity, data was corrected for ocular artefacts and then fast Fourier transformed (cosine 10% taper). This was converted to power (μV^2) to observe frequency contribution over time. In the previous two studies within this research, the earliest response time was used as a parameter for the spline fit, in order to rule out artefact contamination from muscle movement. For example, the earliest response time in the previous study was 741ms. A spline fit was applied to data to make 512 data points to fit with the frequency analysis parameters. As there no response needed in this study, it permitted the full duration, from presentation of stimulus until the appearance of the next fixation point. As stimulus presentation had duration of 2000ms and inter-trial intervals were pseudo-randomised between

2000-4000ms, a spline fit was applied so that frequency was measured over 4096ms. Data was then extracted from the gamma frequency band (35-70 Hz). Using electrodes across temporal and parietal regions based on *a priori* assumptions, (T3/T7, C3, C4, T4/T8, T5/P7, P3, P4, T6/P8), a 2 (high/low MA group) x 2 (letter/number) x 2 (anterior/posterior electrodes) x 4 (left/midline left/midline right/right electrodes) mixed factorial ANOVA was conducted to identify any interactions and main effects (see table 7.9). The analysis included the Greenhouse-Geisser correction to ensure type I error rates were not inflated (Greenhouse & Geisser, 1959) as neurophysiological data is rarely homogenous.

Table 7.9:

Gamma activity ANOVA F values, degrees of freedom, significance levels and effect size for interactions and main effects.

Interaction / Main Effect	**ANOVA**			
	F	***df***	***p***	***η^2***
Horizontal x Vertical x Stim x MA	3.12	2.12,59.22	.049	.003
Horizontal x Vertical x Stim	.45	2.18,63.08	.654	4.19×10^{-5}
Vertical x Stim x MA	1.01	1.64,45.85	.359	1.54×10^{-4}
Horizontal x Stim x MA	3.80	1,28	.061	.004
Horizontal x Vertical x MA	2.52	2.10,58.79	.087	.01
Vertical x Stim	.50	1.70,49.18	.581	7.60×10^{-4}
Horizontal x Stim	2.97	1,29	.095	.004
Horizontal x Vertical	.32	2.16,62.55	.741	.004
Stim x MA	5.15	1,28	.031	.02
Vertical x MA	1.83	1.89,52.96	.172	.01
Horizontal x MA	.62	1,28	.436	.004
Vertical	.94	2.04,59.07	.397	.007
Horizontal	15.03	1,29	.001	.12
Stim	2.85	1,29	.101	.01
MA	.83	1,28	.369	.03

There were no significant four-or three-way interactions (see table 7.9). There was a significant two-way interaction between condition and MA group, such that higher gamma activity was experienced for number, but not letter, in high maths anxious individuals than in low maths anxious individuals (see table 7.10). There were no other two-way interactions. There was a significant main effect of horizontal electrodes, such that there was a higher power of gamma in temporal and central regions (Mean = .02 μV^2, SD = .04) than parietal (Mean = .01μV^2, SD = .01). There were no other main effects.

Table 7.10:

Mean power (μV²) and standard deviation depicting the interaction between condition and MA group.

	Maths Anxiety	
Condition	Low	High
Number	.01 (.02)	.03 (.05)
Letter	.01 (.02)	.01 (.02)

7.3.4 Analysis Summary

This section will highlight and summarise the significant ERP amplitude findings for each component and the separate gamma frequency analysis. The summary will include significant main effects and interactions of ERP amplitude and gamma activity. Main effects of horizontal and vertical electrodes and interactions between horizontal and vertical electrodes will be ommitted due to their clear findings on where components spatially appear, which is consistent with previous research.

The P1 showed a significant interaction between stimulus type and horizontal electrodes such that higher P1 amplitudes were elicited at posterior electrodes particularly for letters than for numbers.

The N1 showed a significant interaction between maths anxiety group, stimulus type and horizontal electrodes such that both groups exhibited higher N1 amplitudes at posterior electrodes with low maths anxious individuals exhibiting a higher N1 amplitude during letter observation than high maths anxious individuals.

The P2 component showed a significant interaction between horizontal, stimulus type and maths anxiety group, such that higher P2 amplitudes were observed in high maths anxious individuals overall, particularly at anterior electrodes during number observation than for low maths anxious individuals, whereas this was fairly similar during letter observation with high maths anxious individuals exhibiting only a slightly higher P2 amplitude than low maths anxious individuals.

Finally, the gamma activity results showed a significant interaction between stimulus type and MA group, such that higher gamma power was elicited during number in high maths anxious individuals than in low maths anxious individuals.

7.4: Discussion

This study set out to compare ERP differences across high and low maths anxious participants during the observation of number and letter, and to identify gamma power differences between the two groups during the observation of number and letters. It was hypothesised that high maths anxious individuals would elicit different gamma power for numerical over letter based stimuli whereas low maths anxious individuals will show no difference between stimulus sets. This section will describe and explain significant results for each ERP component (P1, N1 and P2) and the gamma frequency analysis.

7.4.1 P1 Component Analysis

The P1 component, typically responsible for contrast perception (Odom et al., 2004), showed a significant interaction between horizontal electrodes and stimulus type, eliciting a higher occipito-parietal P1 amplitude for letters over numbers. It is likely that this was generated due to letters being physically larger than numbers in some instances (W or M being larger than 8 or 9). Pattern contrast differences can affect the amplitude of the P1 (Odom et al., 2004) which is likely why the higher P1 amplitude was elicited for letters, being that contrast differences would have been more varied.

A higher P1 amplitude was also elicited at posterior right and left electrodes, which was identified by the significant interaction between horizontal and vertical electrodes, as well as the significant main effect of both horizontal and vertical sites. As shown in the previous studies and literature, this is typical of a P1 eliciting at posterior sites soon after the signal from perceiving the visual stimulus is sent to the occipital lobe (Itier & Taylor, 2002; Luck et al., 2000; Odom et al., 2004).

7.4.2 N1 Component Analysis

As stated in earlier chapters, the N1 is typically described as a component associated with visual recognition of stimuli. A significant interaction was found between horizontal and vertical electrodes, whereby a higher N1 amplitude was identified at occipito-parietal left and right sites, which is indicative of an N1 component (Hopf et al., 2002). An interaction was also found between horizontal electrodes, stimulus type and MA group which identified a higher N1 amplitude for low maths anxious individuals at posterior sites. Those with HMA also experienced a lower N1 at parietal sites for number whereas letters elicited a higher N1 amplitude. This may have been elicited in high maths anxious individuals due to increased attentional bias towards number (the perceived threat) as shown with other high anxious populations (Bar-Haim et al., 2007a). The task required very little demand which would likely enable a large contribution of alpha activity to the ERP when individuals are awake and relaxed (Handy, 2005). In high maths anxious individuals the lower N1 amplitude is likely due to the reduction of alpha contribution caused by attentional bias to number as a threat.

7.4.3 P2 Component Analysis

The significant interaction between horizontal and vertical electrodes, as well as the significant main effect of both horizontal and vertical electrodes, indicated a higher P2 amplitude at anterior sites, particularly across midline electrodes. This is consistent with previous research noting a central P2 peak is mainly related to the allocation of attention resources (Li, Li, & Luo, 2005; Smith, 1993; Szucs, Soltesz, Jarmi, & Csepe, 2007). This supports the current localisation and latency findings of the P2 component. The P2 component is seen around 200ms and whilst it shows similar features of a P3 in terms of amplitude, it tends to be elicited for attention to more simple visual stimuli (Luck & Hillyard, 1994).

A significant interaction was found between horizontal electrodes, stimulus type and MA group. Both elicited higher P2 amplitudes in anterior electrodes however, high maths anxious individuals showed a higher P2 amplitude for numbers over letters. Based on the P2's function (allocation of attention resources), high maths anxious individuals could have shown a higher P2 amplitude linked to attention and vigilance to the more threatening stimulus. This is supported by research noting that the P2 amplitude increases for target stimuli (Luck & Hillyard, 1994). Whilst numbers were not described as a target to high maths anxious individuals, they arguably provide more attentional resources to these stimuli due to their perception of them as a threat. This leads to the analysis of gamma activity in response to the processing of attention and threat.

7.4.4 Gamma activity Analysis

The previous studies identified that high maths anxious individuals produce higher power of gamma activity, particularly in response to more threatening mathematical situations. Whilst study three (Chapter 6) endeavoured to identify control stimuli, the amount of maths-based tasks may have increased anticipation and threat before stimulus presentation occurred. As gamma activity can also represent attention and working memory activity (Hughes, 2008; Müller et al., 2000; Tallon-Baudry et al., 2005) alongside anxiety and threat, it was important to alleviate the task demand to exclude the need for working memory resources. A simple task involving the viewing of stimuli was used to identify basic threat perception differences during the observation of numbers and letters. This could have also be interpreted as attentional differences however, due to high anxious populations eliciting increased attentional bias towards a threat (Bar-Haim et al., 2007a), i.e. numbers in the present study, this is still related to threat processing. This was also used to examine MA on a larger spectrum, including number anxiety.

Gamma activity results showed a significant main effect of horizontal electrodes showing higher gamma power at anterior sites. This main effect is likely due to the central and temporal sites eliciting higher gamma power for attentional processing in the fusiform gyrus (Tallon-Baudry & Bertrand, 1999). Previous research also supports this, noting higher power of gamma activity at temporal than at parietal sites during worry (Oathes et al., 2008). This is consistent with research noting the close link between temporal lobes and the amygdala (Swanson & Petrovich, 1998), associated with worry and anxiety (Davis, 1992; Young et al., 2012).

One of the main findings of this study was the significant interaction between condition and MA group. Overall, it was found that equal levels of gamma power were experienced by both high and low MA groups during the observation of letters. Low maths anxious individuals also experienced similar power during the observation of numbers. However, high maths anxious individuals showed significantly increased power of gamma activity when viewing numbers. This implies that high maths anxious individuals show increased levels of attentional bias to a perceived threat, i.e. viewing numbers. This also shows that the effect happens regardless of calculation or verification demand.

This has implications for more ecologically valid settings, a link between gamma activity and the social implications of MA may be observed. For example, adding up a pile of change, calculating a shopping bill or even the perception of time, are items typically measured on adult MA scales (e.g. MAS-UK, MARS and sMARS) and are rated as anxiety-inducing by those with HMA. The current results imply that high maths anxious individuals show increased attentional bias towards number, perceiving them as threatening. This could further support why high maths anxious individuals consistently avoid maths based situations.

It also provides further insight into Maloney et al's. (2011) working memory deficit theory, due to the lack of manipulation of numbers required. Maloney et al. (2010) argued that there was a working memory deficit in high maths anxious individuals because they still experienced delayed reaction time and reduced accuracy even when very little working memory resources were in demand during a numerical distance effect task. This means that high maths anxious individuals acquire a low-level deficit in numerical processing inhibiting the development of higher mathematical skills. Whilst the current study used no performance measures, the theory of a working memory deficit seems unconvincing when little working memory resources are in demand during observation. Similarly, there is no need for higher mathematical skills during number observation. Instead, the processing of threatening stimuli may slow and reduce accuracy in response to behavioural tasks observed in previous MA studies. It is likely less associated with a lack of working memory resources and more relevant to consider a threatening or phobic related response after recognition has taken place. In other words, neurophysiological mechanisms involved before answering a mathematical problem (which relies on working memory) such as the P1 (contrast perception), N1 (recognition of stimulus), P2 (attention) or P3 (processing), may contribute but are less involved in these behavioural effects. It is the perception of a threatening stimulus, which draws attentional resources, that causes delay and inaccuracy identified in behavioural measures.

Lyons & Beilock's (2012) research implies that it could also be anticipation that plays a role in poorer accuracy and increased reaction time. They show that high maths anxious individuals show increases in activity associated with threat detection and often experience pain but this wasn’t seen during maths performance, rather, anticipation caused this. This shows that high maths anxious participants may experience activity stimulating pain pathways in response to anticipating maths or even a numerical based task. This could indicate why behavioural tasks show an increase in reaction time and decrease in accuracy, as seen in the current body of research; prior to the task pain pathways may activate promoting an avoidance towards maths tasks. Future research in this area should also identify points of gamma power change over time. This could then inform whether anticipation of task or viewing of number (prior to stimulus presentation) produces higher power of gamma activity than post recognition.

However, at the moment the link between higher gamma power and anticipation remains weak. Conducting an event related band amplitude analysis would allow the understanding of each frequency band’s contribution to the production of the ERP. This would enable the analysis of how the power of gamma contributes to this and can be measured prior to stimulus onset. This could then inform us as to when the increase of gamma activity occurs and if it is related to anticipation rather than recognition. Furthermore, it would outline whether there is an association between gamma activity and the experience of pain accompanying threat related stimuli.

A limitation of this study could be the use of letters that may be construed as roman numerals and therefore number related, e.g. I, V, X. An option could be to remove all letters that may be mathematically associated with a form of number or maths to avoid confounds however, achieving this target would be difficult due to the amount of letters used to represent different forms of maths problems in education. For example; algebra ($a^2 + b^2 = c^2$), axes of graphs (x, y, z), equations ($A = \pi r^2$), Roman numerals (I, X, V) and Greek letters (α=1, β=2). Letters I, O and S may also look like 1, 0 and 5 however, all of these were kept in so as not to exclude numbers or letter from the study, which would likely reduce the amount of data and comparison between the two digit types.

7.4.5 Summary

The results from this study have implications for those suffering with MA and provide some explanation as to why high maths anxious individuals avoid maths related situations. Current MA research associates high maths anxious individuals with avoidance behaviour (Ashcraft, 2002), typically evading maths related situations including jobs and education. High maths anxious participants in this study indicated that higher rates of gamma activity that may be associated with attention and threat during the observation of numbers.

The use of number in this research provides further support for a nomenclature shift in MA. Based on the above results, there is a stronger support for a modification of MA definitions. The increase in gamma activity in only the number observation condition could represent higher levels of attention and threat perception in high maths anxious individuals. This similar activity was also seen in the previous studies where those with HMA showed increased power of gamma activity towards more threatening stimuli. If this is the case across all levels of numerical and arithmetical observation and processing, then it shows a need for an inclusive definition of MA covering these points.

In conclusion, previous research has defined MA as a "feeling of tension, apprehension, or fear that interferes with math performance" (Ashcraft, 2002, p.1). However, this does not mention simple observation of number or viewing maths without the need for a response. It may be that this needs to include the processing of maths rather than performance. Based on previous assumptions, that number anxiety is the *sine qua non* to MA (Kazelskis, 1998), and the results generated from this study, an aspect of number anxiety may need to be included in an updated definition or recognised separately.

This study has identified an interesting finding to take forward into future research. The implication that the mere observation of number increases threat related sensations in high maths anxious individuals has a large impact on MA research and future directions. The current body of research has identified increases in gamma activity associated with attention, threat and anxiety, but needs to be taken further by identifying when this occurs in high maths anxious individuals. It has also highlighted the need to change definitions of MA to incorporate the processing of arithmetic and number, if not the observation of this. Future research should also consider the measurement of gamma activity power pre and post-stimulus onset to identify fluctuations in gamma band power and how this may relate to behavioural responses.

Chapter 8: General Discussion

8.1 Introduction

The previous four chapters form the body of research in this thesis and have presented results outlining their collective novel contribution to research into MA. This chapter will begin by summarising this research, with a brief outline of each study along with their rationale (based on gaps in previous research) and the main findings. It will position the current research alongside existing research and go on to outline the implications of the overall findings for MA research more broadly. Finally, the chapter will conclude by acknowledging the limitations of the research and will make recommendations for the direction(s) of future research in this area.

8.2 Summary and evaluation of the research

The research presented in this thesis explored the electrophysiological correlates of MA and aimed to identify if these were consistent with the typical behavioural effects seen i.e. poorer accuracy and increased reaction time, seen in high maths anxious individuals. Previous research using EEG with ERPs identified MA differences at frontal sites including the prefrontal cortex (Lyons & Beilock, 2011; Sheffield & Hunt, 2006; Young et al., 2012), associated with anxiety (Davidson, 2002; Engels et al., 2007). Whilst this area of the brain is prevalent in neurophysiological research concerning MA, posterior regions associated with maths processing are generally absent. This series of empirical studies collected data from posterior regions to identify a neurophysiological signature associated with sites related to the processing of mathematical stimuli (Barnea-Goraly et al., 2005; Eliez et al., 2001; Kiefer & Dehaene, 1997; Ku et al., 2010; Pinel & Dehaene, 2010; Schmithorst & Brown, 2004; Tang et al., 2006a). In all four studies ERPs were extracted from EEG data to analyse electrical activity from central, temporal, parietal and occipital regions in order to identify where and when the interference of MA affects maths processing. In studies two, three and four frequency analysis was also used to identify the power contribution of the gamma band. This section will continue by summarising the findings of each study.

The first study aimed to evaluate the extent to which ERPs could be used to identify MA group differences in relation to the typical behavioural effects seen in previous research concerning MA (e.g. Ashcraft & Kirk, 2001; Ashcraft & Krause, 2007; Ashcraft & Moore, 2009; Faust et al., 1996). This differed from previous research by analysing components at sites associated with the processing of maths. It was noted that this could contribute to the understanding of typical effects of MA seen in behavioural studies (Ashcraft & Krause, 2007), whereby high maths anxious individuals often display poorer accuracy and increased reaction time, when confronted with maths based tasks.

Behavioural analyses showed that high maths anxious individuals displayed poorer accuracy and increased reaction time overall. Four ERP components were identified and separate analyses were conducted on each. The P1 component indicated a lower amplitude for high maths anxious individuals during addition, than low maths anxious individuals. The P1 component is representative of contrast perception therefore, the discrepancy is likely due to the length of the stimuli (Odom et al., 2004) as addition stimuli contained an extra digit. In a similar interaction, high maths anxious individuals elicited a larger N1 amplitude for addition than multiplication, assumed to be caused by the extra digit within the addition problems. As high anxious individuals attend to more threatening stimuli (Rinck et al., 2003), in this case a larger maths problem, it is thought that they showed attentional bias towards addition due to the inclusion of the extra digit.

Previous research has identified that most anxiety disorders have flawed visuospatial attentional processing when presented with threat-relevant information (Weierich et al., 2008). In support of this assertion in the current research, high maths anxious participants had a significantly lower P3 amplitude at right anterior right sites compared to low maths anxious participants. High maths anxious individuals also displayed higher P3 amplitudes at left centre sites, attributing the application of phonological language techniques in the left hemisphere (Tang et al., 2006) to cope with maths processing. This technique is likely used to cope with maths tasks by applying phonological resources in the left hemisphere and reducing the amount needed for visuospatial processing in the right hemisphere. The N400 component amplitude, which fluctuates based on task difficulty (Atchley & Kwasny, 2003; Jost et al., 2004), was also lower in high maths anxious individuals. This was thought to be associated with fewer working memory resources available to verify complex answers, due to anxious intrusive thoughts consuming these (Hunt et al., 2014).

To summarise the first study, current theories outlining the relationship between MA and working memory state that the necessary working memory resources needed to complete the primary task, are instead consumed by anxious intrusive thoughts, causing poorer accuracy and increased reaction time (Hunt et al., 2014). Previous studies have shown that the increases in anxiety, which consumes needed working memory resources, are consistent with ERP differences in frontal and prefrontal regions (e.g. Jones et al., 2012; Sheffield & Hunt, 2006; Young et al., 2012). Therefore, it was hypothesised that regions associated with maths processing would be affected showing ERP differences in amplitude and latency in high maths anxious individuals. Evidence of the typical behavioural effects were identified between MA groups, whereby those with HMA had significantly poorer accuracy and increased reaction time than those with LMA. However, there were no main effects showing differences between MA groups in ERP activity at sites associated with maths processing.

Study one provided an extension to previous research but identified few ERP posterior amplitude and latency differences between MA groups, despite the observed behavioural differences (poorer accuracy and increased reaction time). It may have been that the task requirement was too easy to elicit differences in areas associated with maths processing. The study used a verification task which is consistent with other neurophysiological research into MA (Sheffield & Hunt, 2006; Young et al., 2012). However participants may have guessed without needing to calculate and it is suggested that a calculation task may have highlighted these differences instead. It is also suggested that the neurophysiological differences may not be distinguishable in ERP analyses when specifically observing maths processing, which identified one of the pitfalls when applying this method to posterior regions in the maths anxious brain.

The aim of the second study was to build upon the methodology and findings of study one by increasing the task difficulty. The verification task in the previous study enabled participants to have a 50% chance at being correct by guessing. The second study addressed this shortcoming by changing the verification paradigm, where one answer was presented (correct or incorrect), to include four answers (one correct and three incorrect). Behavioural findings were in line with previous research (Ashcraft & Krause, 2007), whereby high maths anxious individuals performed significantly slower overall. This study also used ERPs to remain consistent with the research area, but also included the first instance of frequency analysis. This was used to analyse gamma band power due to its association with the processing attention and threat (Jensen et al., 2007; Luo et al., 2007a; Maratos et al., 2012; Müller et al., 2000). The ERP analyses showed no main effects and only one interaction concerning MA across all components. The *post-hoc* N1 component showed lower amplitude for high than low maths anxious individuals. As the N1 is associated with recognition rather than processing (Vogel &

Luck, 2000), it is not enough to justify the significant behavioural differences between MA groups in this study. This warranted the exploration of further analyses to identify why the behavioural results had been inconsistent with current ERP expectations. Frequency analysis, measuring the power of the gamma band, was used to investigate further. The analysis revealed significant main effects between MA groups, with high maths anxious individuals eliciting higher gamma power overall. This provided a significant addition to the research area and further neurophysiological support for the theory that high maths anxious individuals perceive maths as threatening and are more vigilant towards it (Lyons & Beilock, 2012). This study identified an interesting finding however; in order to take this further, a replication of this study was needed with changes to the stimulus groups. The following study needed to account for a lack of a non-numerical task therefore, study three incorporated a control condition to test this theory as well as building on the foundation of this study and the novel frequency findings.

Study three used a non-numerical task alongside three numerically based tasks. There was no significant main effect of MA for accuracy but this was likely because scores were similar (with high maths anxious individuals displaying slightly lower accuracy) in all conditions except complex addition. Nevertheless, high maths anxious individuals did show a significantly longer reaction time than those with LMA, again supporting previous findings in the current and previous behavioural research (Ashcraft & Krause, 2007). Despite this, ERP component analyses showed no main effects or interactions concerning MA group differences.

Once again, the frequency analysis highlighted a significant main effect of MA with high maths anxious individuals eliciting significantly higher power of gamma overall. When exploring the stimuli and MA interactions further, the *post-hoc* ANOVA identified significant differences between MA groups in every condition except the compound word task. This highlighted that those with HMA had a significantly higher power of gamma than those with LMA in all maths based conditions. High maths anxious individuals experienced lower power of gamma, not only during compound words but also within the simple addition condition, likely due to the gamma-band's involvement in attention. For example, to high maths anxious individuals, a sum with two 1-digit addends would seem less threatening than a sum containing at least one 2-digit addend. This suggested it may be the initial observation of maths stimuli that generates this increase in gamma activity through attentional bias therefore, heightening threat perception. This is in line with attentional bias theory, whereby anxious individuals dedicate increased attention towards a perceived threat (Bar-Haim et al., 2007a; Rinck et al., 2003;

Yiend & Mathews, 2001). However, as gamma is also associated with working memory (Jensen et al., 2007) it could be that the power differences were memory and not threat-based, being that those with HMA would need increased effort to complete the primary task (Eysenck et al., 2007). It was considered that the increase in gamma power in high maths anxious individuals, across study's two and three may have been due to the need for working memory resources. To rule out working memory's involvement in the following task, the next study removed the need to verify or calculate maths.

The final study removed any task demand by only requiring observation of single digit numbers and letters. This was used to relieve working memory demand due to complex stimuli having a potential effect on previous gamma power results. ERP analyses showed significant interactions between horizontal electrodes, stimulus type and MA at the N1 and P2 components. The lower N1 amplitude for high maths anxious individuals in posterior sites during number presentation was likely a decrease in alpha activity, lowering the ERP amplitude, due to higher levels of attention. The P2 represents a similar finding whereby the higher amplitude in high maths anxious individuals, at anterior sites during number presentation, represents an increase in allocation of attentional resources. The increase allocation of attention resources supports that high maths anxious individuals do show an attentional bias towards numerical stimuli. There were no other significant interactions or main effects of MA across all components.

The gamma frequency analysis identified the same power of gamma for letter observation across groups however; high maths anxious individuals elicited significantly higher gamma power during the observation of number. This implied that high maths anxious individuals display greater levels of attention and threat perception towards number, even when no calculation or verification of task is needed. It is likely that the high maths anxious individuals have a delayed reaction time and poorer accuracy, seen in the preceding studies, due to an anticipatory effect (Lyons & Beilock, 2012). This also supports research noting high maths anxious individuals self-reported increase in intrusive thoughts (Hunt et al., 2014), whereby it may not be the presentation or doing maths itself, but the anticipation and threat of being faced with something that triggers anxiety.

Overall, in this body of research the behavioural analyses have been consistent with previous MA studies whereby a longer reaction time and poorer accuracy was typically identified in high maths anxious individuals. The ERP findings in the studies are also consistent with previous research concerning maths processing, in terms of localisation and latency. However, it was expected that differences between MA groups would be seen in regions associated with maths processing, which did not occur in ERP analyses. The frequency analyses in study's two, three and four identified higher power of gamma in high maths anxious individuals for maths and number related stimuli. As gamma activity is associated with attention and threat perception it was theorised to be because high maths anxious individuals show attentional bias to a perceived threat. This identified a novel measurement for MA and recognises it as a similar construct in the brain to other anxious disorders.

The following section will contextualise the research findings outlining what the results mean for maths anxious individuals and how this relates to the MA research area.

8.3 Contextualising the research

Previous research had explored activity in the maths anxious brain enabling the identification of locations and stimuli triggers in high maths anxious individuals (Jones et al., 2012; Lyons & Beilock, 2012; Sheffield & Hunt, 2006; Suárez-Pellicioni, Núñez-Peña, & Colomé, 2014; Suárez-Pellicioni, Núñez-Peña, & Colomé, 2013; Young et al., 2012). These studies have been useful in evaluating appropriate analyses and methods. For example, using ERPs, previous research has shown discrepancies between high and low maths anxious individuals in frontal lobes, associated with consumption of necessary working memory resources (Lyons & Beilock, 2011). However, there had been little research associating the typical behavioural effects with the underlying neurophysiological maths processing. The current research analysed sites concerning maths processing, in an effort to understand how these regions might be associated. ERP analyses showed few differences between MA groups identifying one of the pitfalls in this method used in previous investigations. Significant amplitude differences were found between stimulus types, and localisation which were consistent with previous visual maths processing research, but few differences were identified between MA groups. Alongside these results, the research also identified a new method of analysis for comparison across MA groups. The introduction of frequency analysis to measure gamma power supports that high maths anxious individuals elicit attentional bias and threat perception (Lyons & Beilock, 2012) in measures of brain activity similar to other high anxious individuals (see Bar-Haim et al., 2007 for a review).

Furthermore, it was noted that previous studies have tended to use arbitrary methods of identifying high and low maths anxious groups, such as median splits or quartile methods. This research provides further support for the use of cluster analysis as a novel method of distinguishing high and low maths anxious individuals which provides a statistical method based on participants' responses to questions rather than using these arbitrary methods.

Whilst behavioural measures identified poorer accuracy and increases in reaction time in high maths anxious individuals during maths tasks, in the current and previous research, little evidence had been shown as to how this is associated in areas of maths processing. The behavioural results in study's one, two and three typically showed poorer accuracy and increased reaction time in high maths anxious individuals, consistent with previous behavioural research (Ashcraft & Kirk, 2001; Ashcraft & Krause, 2007; Ashcraft & Moore, 2009; Faust et al., 1996). Current explanations note that these effects are due to a consumption of working memory resources by anxious intrusive thoughts. However, the same gamma power increases in high maths anxious individuals were also seen during the final study, whereby greater levels were observed for numbers rather than letters. If this significant increase can occur during simple observation of number, with little working memory demand, then this could outline another process involved in contributing towards these behavioural effects. It is possible that the reaction to number and maths could be an anticipatory one. This assertion is supported by Lyons & Beilock's (2012) research who found that high maths anxious individuals showed activation in pain pathways associated with the anticipation of maths processing.

High maths anxious individuals may experience this anticipatory fear of maths due to previous poor experiences, such as poor teaching experiences in early education (Mata, Monteiro, & Peixoto, 2012; Petronzi, 2012). The anxiety based theory proposed by Jensen et al. (2007) supports why high maths anxious individuals have a tendency to avoid exposure to maths based situations, in order to avoid these feelings. For example, if an individual experienced high anxiety during a previous maths related situation, causing encoding to occur whilst high levels of gamma activity trigger, when recalling this at a later stage the pathways that were originally encoded will reactivate eliciting the same anxious symptoms. This leads into the study four and its implications for those suffering with HMA. Participants showed higher gamma power associated with increased attention and threat. This shows that high maths anxious individuals perceive threat at the observation of number rather than maths calculation. If the simple observation of number triggers an anxious reaction, it provides further support for why those with high maths anxious avoid maths-based situations (Ashcraft & Krause, 2007).

These findings imply that high maths anxious individuals perceive numerical stimuli as threatening which would suggest that threat perception could be alleviated partly using cognitive behavioural therapy. This would be consistent with the same measures that treat phobia, for example social phobia, which involves irrational threat perception, (Emmelkamp, Mersch, Vissia, & van der Helm, 1985; Gould, Buckminster, Pollack, Otto, & Massachusetts, 1997; Heimberg et al., 1990; Jerremalm, Jansson, & Öst, 1986). Phobias are based on an illogical fear much like MA could be considered and therefore, treatable using this process, which would tackle the underlying issues rather than combatting the symptoms experienced before a maths related task. This also supports Ashcraft's (2002) prediction that neural activity in MA research will likely bear a resemblance to other negative phobic states. The frequency results also reinforce previous intervention routes for high maths anxious individuals stating that MA is threat based (Hembree, 1990). Furthermore, this also enables the novel use of frequency analysis to identify gamma power as a measure of attentional bias and threat detection. Based on the above results, the measurement of the gamma band for those with MA reinforces the use of cognitive behavioural therapy based interventions, to relieve threatening feelings and shows that this activity can be acquired from regions associated with maths processing. This analysis could be applied alongside MA pre and post-measurement intervention tools, as they also work on the assumption that MA is threat related. However, it may be useful to firstly identify the parameters for how MA is defined.

The introductory chapters noted that there was scope for a nomenclature shift within the definition of MA. This was recognised due to the amount of cognitive, behavioural and psychological tasks that measure MA whilst employing numerically or arithmetically based tasks (Ashcraft & Kirk, 2001; Faust et al., 1996; Krinzinger et al., 2009; Maloney et al., 2011, 2011; Suárez-Pellicioni et al., 2013b; Young et al., 2012). These tasks further the understanding of MA processes however, they do not necessarily represent anxiety towards maths, rather towards number and arithmetic processing. Whilst some research in MA has employed maths tasks, including algebra and fractions (e.g. Lyons & Beilock, 2011, 2012; Tsui & Mazzocco, 2006), a substantial number use tasks that are simpler than mathematics. Furthermore, MA scales direct towards evaluation, observation and social aspects of MA, but many items included in these reflect anxiety towards number or arithmetic, rather than mathematics (e.g.

Hunt, Clark-Carter, & Sheffield, 2011; Suinn, Taylor, & Edwards, 1988; Suinn & Winston, 2003). The findings within this thesis, particularly in the final two studies, note that high maths anxious individuals show threat perception towards number and arithmetic stimuli, even when there is little task demand or response required, supporting a definition change. This implies that those with HMA would not just avoid maths related careers or education, but would want to avoid situations where numbers were involved, to evade feeling threatened. MA is currently defined as "feelings of apprehension and tension concerning manipulation of numbers and completion of mathematical problems in various contexts" (Richardson & Suinn, 1972, p.551). It is proposed that the definition of MA should also include aspects of observation based on the current findings, being that no manipulation was required in the final study.

8.4 Limitations of the research

Whilst the research question aimed to identify how neurophysiological ERP differences (in amplitude and latency) underpin behavioural effects (accuracy and reaction time) in those with MA, a combination of the temporally based methodology alongside one with an excellent spatial resolution may have also been useful. Combining fMRI and EEG simultaneously in the current studies may have helped to understand, not only when the rise in gamma frequency occurs (see future directions below), but also a localisation of how this affects other areas. This could link the current research on gamma activity to the brain activity discrepancies observed at frontal sites in previous research concerning the neurophysiological processing of MA (e.g. Sheffield & Hunt, 2006).

A further limitation of the research (in study one) was that stimuli correctness was not measured as a variable. Previous research has investigated activity during the presentation of correct or congruent answers against incorrect or incongruent answers, noting that brain activity differs when an unexpected answer is given (Suárez-Pellicioni et al., 2013). Applying this measurement may have produced different ERP activity when incongruent answers were presented rather than the expected answer. This may have also supported that larger answers are considered more threatening due to the amount of attention resources given to stimuli in those with HMA. In the latter studies, where four answers were presented, eye tracking could have been employed to determine which stimuli were considered more threatening. Previous neurophysiological research measuring anxiety has noted, using eye tracking, that high anxious individuals typically attend to more threatening stimuli (Nelson, Purdon, Quigley, Carriere, & Smilek, 2015; Shechner et al., 2013). This has also been shown in MA research, whereby significant positive correlations were shown between MA score and fixations on specific digits in two-digit addition problems (Hunt, Clark-Carter, & Sheffield, 2015). Hunt et al., (2015) note that that this correlation was stronger for fixations and dwellings on first digits than any other digits, promoting a stimulus-driven approach. In other words, participants with HMA will have focused more on the tens digits (the digits making the problem seem larger) rather than the unit digits, which would have promoted a goal-directed approach leading to better task performance instead. Applied in the current research, this technique could have supported the notion that larger maths problems and answers were considered more threatening than smaller. Furthermore, this has implications for understanding attentional control theory within MA processing. As stated in previous chapters Eysenck et al's. (2007) attentional control theory states that those with higher levels of anxiety tend to focus on more fearful stimuli. Specifically, it has been shown that those with HMA also typically attend to stimuli that are considered more threatening. For example, in the two-digit addition verification task mentioned above, Hunt et al. (2015) showed that high maths anxious individuals focus more on ten digits than unit digits. This demonstrates their lack of inhibitory control to attend to relevant aspects of the stimuli (unit digits), that would increase response time and overall performance and instead focus on the larger irrelevant (ten digits) information.

Similarly, further increasing the difficulty of stimuli may have also provided differences in activity. As stated above, the majority of stimuli used in MA research and measurement tend to focus on numerical or arithmetical tasks. The use of more complex maths task, rather than the arithmetically based stimuli (employed in the first three studies) may have identified ERPs as a more useful tool for identifying differences in maths processing at the posterior sites associated with maths processing.

A further point to consider is the level at which participants can be considered truly high maths anxious. Individuals on the majority of BSc courses will have needed to achieve a GCSE level maths grade of C or above. Participants in this study, whilst reporting high levels of MA, may not be high maths anxious to the same extent as those that will actively avoid maths processing in everyday life. This has been a sample used in previous research investigating the neurophysiological aspects of MA (e.g. Jones et al., 2012; Sheffield & Hunt, 2006; Suárez-Pellicioni et al., 2013), but the effects identified in the current studies may have increased exponentially if the sample was comprised of individuals that steered away from further education due to a fear of maths. Whilst this could be seen as a downside to the participant group, it could also explain why ERP effects were not as heightened as expected. Furthermore, gaining participants at university level would likely prevent acquiring dyscalculic individuals rather than those with just MA. This could have had a greater chance of skewing results being that this disorder comprises alterations of brain structure and activation (Kucian & Aster, 2014).

8.5 Directions for future research

With the effects of MA providing significant disruption to everyday life with those who suffer from it, it is suggested that how and when the increase in gamma power contributes to this should be further investigated, in an effort to understand MA mechanisms in more depth. Noting gamma activity increases along ERP waveforms may help identify when they begin, leading to a possible explanation of how this relates to the poorer accuracy and increased reaction time in high maths anxious individuals. A replication of this study could accomplish this by taking a longer pre-stimulus interval and running an event related band amplitude analysis along the full length of the ERP breaking it down into individual band contributions. This would likely indicate areas of increased gamma activity and could further support Lyons & Beilock's (2012) research by noting whether rises in gamma activity occur as part of anticipation, pre-stimulus onset.

This could also identify other contributing processes to the behavioural increase in reaction time. It was hypothesised early on in this thesis that amplitude of ERP components would reflect accuracy differences and latency would underpin reaction time. High maths anxious individuals tended to show increased reaction time on maths based tasks, however across all studies, no significant latency differences occurred, suggesting that the increase in reaction time could be a result of processes occurring later but up to the button press. Again it will be of use to use event related band amplitude to identify when increases in gamma power occur along the ERP latency window.

As stated in the limitations above, the combination of spatial and temporal methods would have been of use to further understand the localisation as well as latency measures here. Indeed, the use of EEG and source localisation or fMRI is of interest for future research. It is suggested that these methods are combined in order to confirm whether the gamma band activity elicited in studies two, three and four, manipulates the amygdala shown in previous anxiety research. It has been outlined that gamma activity is responsible for this (Luo et al., 2007a; Sato et al.,

2011) and that the amygdala is implicated in the maths anxious brain (Lyons & Beilock, 2012). Confirming that the gamma band is linked to amygdala activity within MA processing would enhance these results and provide additional contribution and support for the wider MA research area.

A further path for future research is to identify the extent that increases in gamma power occur in children with MA, being that simple number observation elicited higher gamma power in adults. Recent research has identified MA effects in children (Krinzinger et al., 2009; Mazzocco, Feigenson, & Halberda, 2011; Wu et al., 2012) even in those as young as four years old and once formed, is maintained throughout education (Petronzi, 2012). A simple EEG paradigm could be applied in school settings using portable equipment to test the power of gamma in young children. It would be relevant to identify whether simple observation of number triggers this at an early age or whether it is more complex maths that leads to the negative perceptions of number indefinitely. Based on previous research, it is theorised to develop due to a lack of motivation (Ashcraft & Krause, 2007; Ashcraft & Moore, 2009), applying testing formats which remove any practical applications of maths (Geist, 2010), or unhelpful parenting or teaching methods which pass on negative attitudes towards maths (Beilock et al., 2010; Swetman, Munday, & Windham, 1993). These suggest that doing maths, rather than observation, contributes to the development of MA which leaves two theories about the observation of number and increases in gamma power in high maths anxious individuals: Either children develop MA early during number comprehension causing an early disdain and fear of number or that MA promotes threat towards all numerically based tasks even if individuals were originally happy when learning simple forms. The former links the current research to Jensen et al.'s (2007) theory, stating that an early encoded anxious experience (for example, during maths learning) could promote the same anxious feelings when confronted with a similar task. It is likely that this will inhibit any foundation being formed to learn higher order maths skills and eventually create an avoidance of future maths based careers and education. The investigation of gamma activity at a young age could provide an answer in response to these proposed theories and may offer a deeper understanding of the development and signatures of MA within the brain.

8.6 Conclusion

This thesis has reported four experimental studies designed to investigate the neurophysiological correlates of MA. Specifically, this aimed to identify how the behavioural effects of MA (increased reaction time and reduced accuracy) may have been underpinned by underlying mechanisms in the brain. It was originally thought that this could be identified using ERPs to measure fluctuations in component amplitude and latency in regions associated with the processing of maths within the brain. Whilst some effects involving MA were found, the main MA discrepancies in brain activity were identified from the frequency analysis. The gamma frequency band has been associated with threat perception and attention in previous research. Indeed, it is associated with the amygdala (responsible for the processing of these emotional responses) and has been explored in research concerning other forms of anxiety. These areas had not previously been brought together to explore gamma-band power's involvement in the maths anxious brain, nor had this band of activity been observed in any previous MA research. The novel frequency analyses consistently showed greater gamma power in high maths anxious individuals when confronted with numerically based tasks, whereas those with LMA had significantly lower gamma power. This was confirmed when employing a non-numerical task alongside numerically based ones, whereby high maths anxious individuals elicited a reduced power of gamma to less threatening stimuli. Finally, it was shown that high maths anxious individuals perceive basic numerical stimuli as threatening, even when there is no task demand to consume working memory resources. It is suggested that this novel measurement of brain activity in this area of research be explored further to understand when and how this activity may influence performance and reaction time in maths anxious individuals.

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Appendices

Appendix i: Reference site justification

The selection of an EEG reference site has always been a critical choice for the study of electrical brain activity (Hagemann, Naumann, & Thayer, 2001; Qin, Xu, & Yao, 2010; Yao, Wang, Arendt-Nielsen, & Chen, 2007). Whilst there are many methods to choose from, some more frequently used than others, each have their own advantages and limitations which will be discussed here.

The Common Vertex Reference method has been developed over time with the reference site being placed on the tip of the nose, the neck and even the big toe to try and tackle the issue of a low electrical activity site. However, it has been found the electrical activity exists everywhere on the body surface therefore site Cz is more frequently used. This provides the advantage of low electrical activity in the central region (Schomer & Silva, 2010) and, the fact that there is a lack of muscles in this area, prevents artefact contamination. However, reference contamination can occur if the common reference is in the field of interest. Moving the site to a more preferable one may be considered an advantage however, it has been shown that different sites can yield different power for the same target (Lehmann, 1984).

A second method is known as the average reference. This encompasses getting the average voltage of all electrodes across the scalp creating a virtual reference. This method demonstrates absolute voltage at each electrode site (Luck, 2005) with no reliance of an electrically neutral reference site. The main disadvantage with this method is that the average reference works on the basis of a sphere. Besides the knowledge that the head does not represent a spherical shape, it is impossible to cover the entirety of the head in electrodes due to the face and neck (Luck, 2005) resulting in an inaccurate representation of an average reference.

One of the more traditional methods of referencing EEG has been either linked ears or mastoids. This was primarily due to the thought that no electrical activity would come from these areas and so would act as electrically neutral reference cite. However, research has shown that little electrical activity can be obtained at these sites. Luck (2005) notes that when choosing a reference method there are three key factors that should be met: Due to the lack of a completely neutral site a comfortable and convenient reference should be chosen. Secondly, avoid a reference site that is biased towards a single hemisphere e.g. left or right mastoid/ear, as this can distort the voltage between hemispheres. Thirdly, Luck (2005) advises that the same reference should be consistent across all participants given that each referencing method can alter the appearance of ERP data.

Although this has been the dominant method for referencing EEG and considered outdated, recent ERP research in the area of maths processing has shown the use of linked mastoids and ears as a reference (Heine et al., 2011; Paulsen et al., 2010; Prieto-Corona et al., 2010; Wang et al., 2007; Zhang et al., 2012; Zhou et al., 2006). Therefore, linked mastoids meet the 3 criteria, stated above, in that they show no bias towards individual hemispheres and are fairly comfortable as oppose to the tip of the nose or using ear clips. Similarly, the use of a commonly used reference method is advantageous particularly when comparing data across laboratories. Luck (2005) further supports this by arguing that with all things considered "this is the best reference scheme for the majority of ERP experiments in the area of cognitive neuroscience" (p.108). Nevertheless there are also disadvantages to this method, Hagemann et al. (2001) state that the presence of the ear can sometimes result in uneven spacing of the electrodes and that the ear canal can cause severe conductance imhomogenities.

A final method to consider as a reference is Current source derivation (CSD) which has been used as an alternative to relying on voltage measurements. It estimates the density of sources and sinks across the scalp generated by the electrical activity of the brain (Hagemann et al., 2001) permitting a reference free method. The Laplacian method of CSD is worked out by the sum of the potential differences of the surrounding 4 electrodes on the x and y axis. However this method can only work if they are situated at an equal distance from the target electrode in the centre. This method is the most appropriate due to the absence of a reference site however, it is not ideal for measuring the electrodes on the outer electrode system. Similarly, this method tends to attenuate distributed sources and due to the nature of alpha activity showing wide distribution, CSD may remove alpha that will likely be of interest.

Based on the above suggestions the linked mastoids are the most appropriate reference method mainly because it meets Luck's (2005) suggested 3 key factors and is still used currently in ERP studies relevant to this area of research.

Appendix ii: participant recruitment forms (brief, consent, demographics, MAS-UK (five sample items), debrief)

Participant Invitation

Dear participant

You are invited to take part in a research project involving mathematical processing in adults as part of my PhD research. This research is supervised by Paul Staples, Dr Ian Baker and Professor David Sheffield.

You will be asked to fill in a short questionnaire called the Maths Anxiety Scale – UK (MAS-UK) which involves rating how anxious you would feel in certain mathematically based situations. This should take no longer than 5 minutes to complete and you will be rewarded with 1 participation point for your time. You may then be invited to continue with the second part of the study at a later date based on your MAS-UK score. This will involve the recording of electrical brain activity whilst you conduct word and maths tasks.

It should be noted that if you consent to the first part of the study it does not mean you have consented to the second part. You may withdraw your data at any time and up to two weeks after you have completed this form. If you have any questions or queries do not hesitate to contact Michael Batashvili via my email at: **m.batashvili@derby.ac.uk** or Paul Staples at: **p.staples@derby.ac.uk**

Please fill in and tick where appropriate and then return the forms to the researcher

Record Number (The first two letters of your Last Name and the last 3 digits of your phone number) For example, if your name was Dominic Smith and your phone number ended in 234, your record number would be = SM234. If you wish to withdraw from the study please quote this number when contacting the researcher.

Record Number: _ _ _ _ _

Gender **Male** ☐ **Female** ☐

Which hand do you consider to be dominant? **Right** ☐ **Other** ☐

Do you have Dyslexia? **Yes** ☐ **No** ☐

Age: ____

Email address _ **(contact details are needed in case you are invited to the next part of the experiment).**

I agree to being contacted at a later stage if I am chosen for part 2 ☐

I understand what the study topic is and I consent to taking part in this study:

Sign here _ _ _ _ _ _ _ _ _ _ _ _ _ _

Date: _ _ / _ _ / _ _ _ _

	How anxious would you feel in the following situations?........Please circle the appropriate numbers below.				
	Not at all	Slightly	A fair amount	Much	Very much
Having someone watch you multiply 12 x 23 on paper.	1	2	3	4	5
Adding up a pile of change.	1	2	3	4	5
Being asked to write an answer on the board at the front of a maths class.	1	2	3	4	5
Being asked to add up the number of people in a room.	1	2	3	4	5
Calculating how many days until a person's birthday.	1	2	3	4	5

Debrief

Thank you for completing the MAS–UK. Your participation is greatly valued.

Recently researchers have become increasingly interested in maths anxiety (MA) and its effects on the brain (Jones et al., 2012; Young et al., 2012). Ashcraft (2002) defines MA as "a feeling of tension, apprehension or fear that interferes with maths performance" (p.1).

Research suggests that individuals with anxiety including MA have intrusive thoughts that slow down calculation. The memory system has limited resources available for task performance and these intrusive thoughts use up these necessary resources however, this is yet to be tested in an adult population.

To date there are only a few limited electroencephalography (EEG) studies that examine MA (Jones et al., 2012, 2012) therefore, additional EEG studies measuring timing and activity levels during maths processing are needed.

Depending on your MAS-UK score you may be invited to the second part of the study involving EEG. You will be contacted via email if this is the case. Please note that there is no obligation to participate in the second study if you do not wish to.

Once again, if you have any questions or queries do not hesitate to contact me via my email at: **m.batashvili@derby.ac.uk** or Paul Staples at: **p.staples@derby.ac.uk.** If you wish to withdraw from the study please quote your record number when contacting the researcher.

Thank you for your time,

Michael Batashvili (Postgraduate researcher and associate lecturer in psychology)

If you feel you may want some information or advice about Maths Anxiety or related areas you can contact your student support centre:

http://www.derby.ac.uk/ssis/student-support-centres

Please write your Record Number here and take this sheet:

_ _ _ _ _

Appendix iii: EEG study invitation

Dear Student,

Recently you completed a survey as part an ongoing study looking at maths anxiety. I would like to take this opportunity to invite you to take part in the next phase of this research.

This would involve you coming into the University (Kedleston Road site) for approximately 2 hours. During this time you will be asked to complete a series of word and maths problems whilst recordings of brain activity are taken.

You will be entered into a prize draw to receive vouchers. First place will get £30 in vouchers and second and third will receive a £10 voucher each, for participating in this study.

There is no obligation to take part but if you could let me know if you would or would not like to I would be very grateful and it will help me with booking lab space. Please contact me via email at this address: m.batashvili@derby.ac.uk

Alternatively, if you cannot participate in the study I would be grateful if you could let me know.

Best wishes,

Michael Batashvili
University of Derby postgraduate researcher and associate lecturer in psychology

Appendix iv: EEG consent form

Dear Participant

You will be participating in a study where word and mathematical tasks will be presented to you on a screen whilst EEG data is recorded. You will be asked to calculate and answer the questions that appear on screen. Before this you will be asked to fill in an anxiety questionnaire.

Please remember that you will have the right to withdraw at any time during the study and up to two weeks after you have completed the study.

If you have any questions or queries do not hesitate to contact me on 01332 592019 or at m.batashvili@derby.ac.uk

Thank you for your consideration,

Michael Batashvili (Postgraduate research student and associate lecturer in psychology)

This is a consent slip regarding the study.

Please tick where applicable:

I have read the study information and have had a chance to ask questions, and I understand what will be involved in the EEG study. Please sign here: _ _ _ _ _ _ _ _ _ _ _ _ _

I consent to participating in this experiment ☐

I am Male ☐ Female ☐

I am Right Handed ☐ Left Handed ☐

Age ____

Date ____________

Please enter your unique code created previously from the earlier questionnaire _ _ _ _ _ _ _ _

Appendix v: State-trait anxiety inventory, five sample items in total

SELF-EVALUATION QUESTIONNAIRE STAI Form Y-1

Please provide the following information:

Name Date

Age Gender (*Circle*) **M F**

5. I feel at ease **1 2 3 4**

7. I am presently worrying over possible misfortunes............ **1 2 3 4**

16. I feel content **1 2 3 4**

SELF-EVALUATION QUESTIONNAIRE STAI Form Y-2

Please provide the following information:

Name Date

Age Gender (*Circle*) **M F**

23. I feel satisfied with myself... **1 2 3 4**

39. I am a steady person... **1 2 3 4**

Appendix vi: EEG debrief

Debrief

You have just taken part in an electrophysiological study. The aim of this research was to observe different patterns of electrical brain activity when solving maths and word. It is theorised that those with high maths anxiety may process maths tasks in different ways to those with low maths anxiety although this has yet to be tested with this type of study.

Previous research suggests that multiple areas of the brain are involved and numerous imaging studies provide evidence that arithmetic processing is supported by structures at the rear of the brain over both hemispheres (Barnea-Goraly et al., 2005; Mayer et al., 1999). Whilst there is neurophysiological evidence in this area, a more careful and sensitive analysis of the amplitude and timing of maths processing in individuals is needed. This is why we have used EEG (electroencephalography). Findings from the present study could help in identifying the differences between those who have high and low levels of maths anxiety or other maths difficulties and the way they process these stimuli, improving future research and chances of support.

Thank you for your time. Your participation is greatly valued. If you have any questions or queries I would be happy to answer them. You can contact me at **m.batashvili@derby.ac.uk** or Paul Staples at: **p.staples@derby.ac.uk**
Please remember you still have the right to withdraw up to two weeks from now. If you wish to withdraw from the study please quote this number when contacting the researcher. If you feel you require some extra advice or support that I cannot provide then simply go to this website for the University of Derby's Student support services: **http://www.derby.ac.uk/student-support-and-information-services/ssis-general/student-support-information-services/student-support-centres**

Thank you,

Michael Batashvili (Postgraduate researcher and associate lecturer in psychology)

Appendix vii: Example BATCH file code for processing of ERP data

```
# Tcl BATCH file for ERP analysis of exp.
# Initially written by Michael Batashvili (c) 2012 with the help of Dr Ian Baker.
set PATH "C:\\Documents and Settings\\syssupport\\Desktop\\Acquired
Data\\Study_4&1\\Analysis\\Study_4\\Recoded\\"; # Path for Analysis machine
set file "3" ;# This file can be re-named each time in order to perform this programmed
analysis on any core CNT file in the above directory path
set cnt .cnt
set eeg .eeg
set avg .avg
set ev2 .ev2
set corr corr
set reref _reref
set LD _LD
set OAR _OAR
set fil   _fil
set base _base
set AR _AR
set type1 _type1
set type2 _type2
set ERP _ERP

OPENFILE "C:\\Documents and Settings\\syssupport\\Desktop\\Acquired
Data\\Study_4&1\\Analysis\\Study_4\\Recoded\\3.cnt" ;# opens the inital cnt file
REFER N N N { M1 M2 } {C:\\Documents and Settings\\syssupport\\Desktop\\Acquired
Data\\Study_4&1\\Analysis\\Study_4\\Recoded\\3_reref.cnt}; # rereferences to linked
mastoids
OPENFILE "C:\\Documents and Settings\\syssupport\\Desktop\\Acquired
Data\\Study_4&1\\Analysis\\Study_4\\Recoded\\3_reref.cnt"
ARTCOR POSITIVE 10 30 400 VEOG LDR+CNT {ARTRED.LDR} "C:\\Documents and
Settings\\syssupport\\Desktop\\Acquired
Data\\Study_4&1\\Analysis\\Study_4\\Recoded\\3_reref_LD_OAR.cnt" Y N; # applies the
ocular artefact reduction
```

OPENFILE "C:\\Documents and Settings\\syssupport\\Desktop\\Acquired Data\\Study_4&1\\Analysis\\Study_4\\Recoded\\3_reref_LD_OAR.cnt"
FILTER_EX BANDPASS ZEROPHASESHIFT 1 24 30 24 x x x N FIR { ALL } "C:\\Documents and Settings\\syssupport\\Desktop\\Acquired Data\\Study_4&1\\Analysis\\Study_4\\Recoded\\3_reref_LD_OAR_fil.cnt" ;# applies the bandpass filter
OPENFILE "C:\\Documents and Settings\\syssupport\\Desktop\\Acquired Data\\Study_4&1\\Analysis\\Study_4\\Recoded\\3_reref_LD_OAR_fil.cnt"
CREATESORT SORT165
SORT165 -TypeEnabled T
SORT165 -TypeCriteria 10,20,30,40 ;# ensures that both the four conditions are used in the epoching sort
EPOCH_EX PORT_INTERNAL "" N -100 700 N Y Y N N SORT165 "C:\\Documents and Settings\\syssupport\\Desktop\\Acquired Data\\Study_4&1\\Analysis\\Study_4\\Recoded\\3_reref_LD_OAR_fil_ep.eeg" ;# takes -100 to +700 ms and epochs all four conditions
DELETESORT SORT165
OPENFILE "C:\\Documents and Settings\\syssupport\\Desktop\\Acquired Data\\Study_4&1\\Analysis\\Study_4\\Recoded\\3_reref_LD_OAR_fil_ep.eeg"
BASECOR_EX2 PRESTIMINTERVAL x x N N { ALL } "C:\\Documents and Settings\\syssupport\\Desktop\\Acquired Data\\Study_4&1\\Analysis\\Study_4\\Recoded\\3_reref_LD_OAR_fil_ep_base.eeg" ;# baselines corrects to the pre-stimulus interval
OPENFILE "C:\\Documents and Settings\\syssupport\\Desktop\\Acquired Data\\Study_4&1\\Analysis\\Study_4\\Recoded\\3_reref_LD_OAR_fil_ep_base.eeg"
ARTREJ_EX REJCRITERIA Y x x Y -75 75 Y Y { FP1 FPz FP2 AF3 AF4 F7 F5 F3 F1 Fz F2 F4 F6 F8 FT7 FC5 FC3 FC1 FCz FC2 FC4 FC6 FT8 T7 C5 C3 C1 Cz C2 C4 C6 T8 TP7 CP5 CP3 CP1 CPz CP2 CP4 CP6 TP8 P7 P5 P3 P1 Pz P2 P4 P6 P8 PO7 PO5 PO3 POz PO4 PO6 PO8 CB1 O1 Oz O2 CB2 } ;# rejects any epochs with artefacts at -75 to +75 mV on all channels except for
VEOG, HEOG, M1 and M2
PAUSE ;# Will pause the BATCH file until the Resume button is pressed. This is in order to allow manual inspection for any artifacts the automated rejction routine has missed

SAVEAS "C:\\Documents and Settings\\syssupport\\Desktop\\Acquired Data\\Study_4&1\\Analysis\\Study_4\\Recoded\\3_reref_LD_OAR_fil_ep_base_AR.eeg" ;# saves the artifact rejection files

CLOSEFILE "C:\\Documents and Settings\\syssupport\\Desktop\\Acquired Data\\Study_4&1\\Analysis\\Study_4\\Recoded\\3_reref_LD_OAR_fil_ep_base.eeg" ;# closes the baseline correction file

OPENFILE "C:\\Documents and Settings\\syssupport\\Desktop\\Acquired Data\\Study_4&1\\Analysis\\Study_4\\Recoded\\3_reref_LD_OAR_fil_ep_base_AR.eeg" ;# begins the averaging for the Letter (Type1) stimulus

CREATESORT SORT168

SORT168 -TypeEnabled T

SORT168 -TypeCriteria 10

AVERAGE_EX TIME Y AMPLITUDE 10 COSINE PRESTIMINTERVALNOISE x x POSTSTIMINTERVALSIGNAL x x SORT168 "C:\\Documents and Settings\\syssupport\\Desktop\\Acquired Data\\Study_4&1\\Analysis\\Study_4\\Recoded\\3_reref_LD_OAR_fil_ep_base_type10.avg"

DELETESORT SORT168

CREATESORT SORT168

SORT168 -TypeEnabled T

SORT168 -TypeCriteria 20

AVERAGE_EX TIME Y AMPLITUDE 10 COSINE PRESTIMINTERVALNOISE x x POSTSTIMINTERVALSIGNAL x x SORT168 "C:\\Documents and Settings\\syssupport\\Desktop\\Acquired Data\\Study_4&1\\Analysis\\Study_4\\Recoded\\3_reref_LD_OAR_fil_ep_base_type20.avg"

DELETESORT SORT168

CREATESORT SORT168

SORT168 -TypeEnabled T

SORT168 -TypeCriteria 30

AVERAGE_EX TIME Y AMPLITUDE 10 COSINE PRESTIMINTERVALNOISE x x POSTSTIMINTERVALSIGNAL x x SORT168 "C:\\Documents and Settings\\syssupport\\Desktop\\Acquired Data\\Study_4&1\\Analysis\\Study_4\\Recoded\\3_reref_LD_OAR_fil_ep_base_type30.avg"

DELETESORT SORT168

CREATESORT SORT168

```
SORT168 -TypeEnabled T
SORT168 -TypeCriteria 40
AVERAGE_EX TIME Y AMPLITUDE 10 COSINE PRESTIMINTERVALNOISE x x
POSTSTIMINTERVALSIGNAL x x SORT168 "C:\\Documents and
Settings\\syssupport\\Desktop\\Acquired
Data\\Study_4&1\\Analysis\\Study_4\\Recoded\\3_reref_LD_OAR_fil_ep_base_type40.avg"
DELETESORT SORT168
CLOSEALL
```

Appendix vii: Example BATCH file code for processing of gamma activity data

```
# Tcl BATCH file for gamma FFT analysis
# Written by Michael Batashvili (c) 2013.
set PATH "F:\\Work\\Study_4\\Analysis\\Study_4\\Recoded\\Gamma_FFT"; # Path for Analysis machine
set file "30" ;# This file can be re-named each time in order to perform this programmed analysis on any core CNT file in the above directory path
set cnt .cnt
set eeg .eeg
set avg .avg
set ev2 .ev2
set corr corr
set reref _reref
set LD _LD
set OAR _OAR
set fil   _fil
set base _base
set AR _AR
set type30 _type30
set type30 _type40
set ERP _ERP


OPENFILE "F:\\Work\\Study_4\\Analysis\\Study_4\\Recoded\\30_reref_LD_OAR.cnt" ;# opens the inital cnt file after rereference and OAR
CREATESORT SORT236
SORT236 -TypeEnabled T
SORT236 -TypeCriteria 10,20,30,40
EPOCH_EX PORT_INTERNAL "" N 0 741 N Y Y N N SORT236 {F:\\Work\\Study_4\\Analysis\\Study_4\\Recoded\\Gamma_FFT\\30_reref_LD_OAR_fft_ep.eeg}
DELETESORT SORT236
```

OPENFILE
"F:\\Work\\Study_4\\Analysis\\Study_4\\Recoded\\Gamma_FFT\\30_reref_LD_OAR_fft_ep.eeg"
SPLINEFIT 512
{F:\\Work\\Study_4\\Analysis\\Study_4\\Recoded\\Gamma_FFT\\30_reref_LD_OAR_fft_ep_4096spline.eeg}
OPENFILE
"F:\\Work\\Study_4\\Analysis\\Study_4\\Recoded\\Gamma_FFT\\30_reref_LD_OAR_fft_ep_4096spline.eeg"
BASECOR_EX2 PRESTIMINTERVAL x x N N { ALL }
{F:\\Work\\Study_4\\Analysis\\Study_4\\Recoded\\Gamma_FFT\\30_reref_LD_OAR_fft_ep_4096spline_base.eeg}
OPENFILE
"F:\\Work\\Study_4\\Analysis\\Study_4\\Recoded\\Gamma_FFT\\30_reref_LD_OAR_fft_ep_4096spline_base.eeg"
CREATESORT SORT237
SORT237 -TypeEnabled T
SORT237 -TypeCriteria 10
AVERAGE_EX FREQUENCY Y POWER 10 COSINE PRESTIMINTERVALNOISE x x POSTSTIMINTERVALSIGNAL x x SORT237
{F:\\Work\\Study_4\\Analysis\\Study_4\\Recoded\\Gamma_FFT\\30_reref_LD_OAR_fft_ep_4096spline_base_type10.avg}
DELETESORT SORT237
CREATESORT SORT238
SORT238 -TypeEnabled T
SORT238 -TypeCriteria 20
AVERAGE_EX FREQUENCY Y POWER 10 COSINE PRESTIMINTERVALNOISE x x POSTSTIMINTERVALSIGNAL x x SORT238
{F:\\Work\\Study_4\\Analysis\\Study_4\\Recoded\\Gamma_FFT\\30_reref_LD_OAR_fft_ep_4096spline_base_type20.avg}
DELETESORT SORT238
CREATESORT SORT238
SORT238 -TypeEnabled T
SORT238 -TypeCriteria 30

AVERAGE_EX FREQUENCY Y POWER 10 COSINE PRESTIMINTERVALNOISE x x POSTSTIMINTERVALSIGNAL x x SORT238 {F:\\Work\\Study_4\\Analysis\\Study_4\\Recoded\\Gamma_FFT\\30_reref_LD_OAR_fft_ep_4096spline_base_type30.avg}

DELETESORT SORT238

CREATESORT SORT238

SORT238 -TypeEnabled T

SORT238 -TypeCriteria 40

AVERAGE_EX FREQUENCY Y POWER 10 COSINE PRESTIMINTERVALNOISE x x POSTSTIMINTERVALSIGNAL x x SORT238 {F:\\Work\\Study_4\\Analysis\\Study_4\\Recoded\\Gamma_FFT\\30_reref_LD_OAR_fft_ep_4096spline_base_type40.avg}

DELETESORT SORT238

CLOSEALL