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Cognitive Load and Working Memory Capacity; Within and Between Modality

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Submitted to the School of Psychology, College of Arts, Social Sciences and Celtic Studies as Partial Fulfilment of the Requirements for the Doctor of Philosophy Degree, Psychology.

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<tr>
<td>AWM</td>
<td>Auditory Working Memory</td>
</tr>
<tr>
<td>ACC</td>
<td>Anterior Cingulate Cortex</td>
</tr>
<tr>
<td>ANOVA/rANOVA</td>
<td>Analysis of variance (r = repeated),</td>
</tr>
<tr>
<td>WM</td>
<td>Working Memory</td>
</tr>
<tr>
<td>CL</td>
<td>Cognitive Load</td>
</tr>
<tr>
<td>CE</td>
<td>Central Executive</td>
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<tr>
<td>CDA</td>
<td>Contralateral Delay Activity</td>
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<tr>
<td>EF</td>
<td>Executive Function</td>
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<tr>
<td>ERP</td>
<td>Event Related Component, pertinent waveform derived from EEG averaging</td>
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<tr>
<td>ERD/ERS</td>
<td>Event related Synchronisation/De-synchronisation</td>
</tr>
<tr>
<td>FMRI</td>
<td>Functional Magnetic Resonance Imaging</td>
</tr>
<tr>
<td>FFT</td>
<td>Fast Fourier Transform, used to create EEG frequency bands</td>
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<tr>
<td>FMT</td>
<td>Frontal Midline Theta</td>
</tr>
<tr>
<td>HGRCT</td>
<td>Halford Graphical Relational Complexity Task</td>
</tr>
<tr>
<td>ISI</td>
<td>Inter-Stimulus Interval (ISI). This period is also known as the retention period i.e. the period the target has to kept/remembered before responding to a trial.</td>
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<tr>
<td>ICA</td>
<td>Independent Component Analysis</td>
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<td>LTM</td>
<td>Long Term Memory</td>
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<td>LTS</td>
<td>Long-Term Store</td>
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<tr>
<td>Ms</td>
<td>Milliseconds, unit of measure, generally associated with the length of time a trial lasts, or participants take to respond to tasks.</td>
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<tr>
<td>MS</td>
<td>Multiple Sclerosis</td>
</tr>
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<td>Mv</td>
<td>Millivolts, measure of amplitude of the EEG.</td>
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<tr>
<td>MCI</td>
<td>Mild Cognitive Impairment</td>
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<tr>
<td>NF</td>
<td>Neuro-Feedback, EEG intervention.</td>
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<td>NSW</td>
<td>Negative Slow Wave</td>
</tr>
<tr>
<td>PC</td>
<td>Personal Computer, refers to standard desktop computers.</td>
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<tr>
<td>PL</td>
<td>Perceptual Load</td>
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<tr>
<td>PFC</td>
<td>Pre-Frontal Cortex</td>
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<td>PET</td>
<td>Positron Emission Tomography</td>
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<tr>
<td>RC</td>
<td>Relational Complexity, Halford et al.,’s theory of Working Memory capacity</td>
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<tr>
<td>RT</td>
<td>Response Time</td>
</tr>
<tr>
<td>RI</td>
<td>Relational Integration, the process of RC.</td>
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<tr>
<td>ROI</td>
<td>Region of Interest, EEG sites pooled to correspond modes</td>
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<td>STM</td>
<td>Short-Term Memory</td>
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<td>STS</td>
<td>Short- Term Store</td>
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<td>SR</td>
<td>Sensory Register</td>
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<td>Abbreviation</td>
<td>Description</td>
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<tr>
<td>SE</td>
<td>Standard Error</td>
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<td>VWM</td>
<td>Visual Working Memory</td>
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<td>WMC</td>
<td>Working Memory Capacity</td>
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Abstract
Perceptual load and cognitive load have been assessed in the same method. However, it is proposed they have self-regulating and contradictory effects on the use of attentional resources. The difficulty of distinguishing between what is being measured is an on-going debate, centred on the allocation of limited capacity mental resources. The behavioural results from studies one and two, which looked at the reaction times to Relational Complexity based on visual, auditory and cognitive-based stimuli, underpinned the further EEG investigation based upon the differences in RT slopes over arity. RTs and errors were increased as relational complexity increased; Perceptual tasks (visual and auditory) divulge similar overall trends in RT performance, but are considerably slower and with less pronounced RT over arity slopes. This does not seem to be constant with the equivalent RT over arity slope found in the cognitive task. On these foundations, it can be concluded that the cognitive load defined by Halford is not only fundamentally different, but it may be differentiated from the effects of perceptual load measured in the analogous visual and auditory tasks. Results of the EEG experiments showed the visual RC based experiment responded well to alpha, across arity at occipital sites, as per hypothesis. The analogous auditory RC based experiment did not respond to either alpha or theta; this was not the expectation. The cognitive RC based experiment did not respond to alpha or theta, especially the latter, as synchronised FM theta over arity was expected, mainly as it was a ‘purely’ cognitive task. Limitations of the current study are discussed ranging from: issues of serially presented stimuli (auditory experiment), using time-frequency analysis, splitting up of frequency bands in lower and higher based Hz. The use of other imaging techniques namely: MEG, and the revaluation of the role of alpha in cognition. Suggestions for future research include the coupling of frequency bands and the Bayesian approach to statistical analyses.
For Katie, you are the biggest inspiration and driving force in my life, and now Onan.

I look forward to our adventures together.
Acknowledgements

This dissertation would not have been possible without the love, support and encouragement of Katie, Gabrielle and Jim. Katie who sacrificed so much, I hope in years to come I can begin to repay you. And Gabrielle for your constant unwavering support and belief in me and what I was trying to achieve. And to dad, rest in peace.

A special word of thanks to my supervisor Mark Elliott. Mark is without a doubt one of the most amazing academics I have met, and when I am not in awe of that, an all-round good person to be around. I can’t thank you enough for activating and cultivating a potential I never knew I had. Also, in NUI, as I imagine a name that graces many acknowledgement pages, Declan Coogan, for all your technical support, I thank you.

To all in the Biological Research Unit in Munich’s LMU, especially Prof. Paul Sauseng for your support in all matter’s EEG, Danke und hoffe auf ein baldiges Wiedersehen.
1.0 Introduction

1.1 What is Cognitive Load?

Cognitive load (CL) refers to the amount of mental demand imposed by a cognitive operation and research has emphasised the importance of the limited capacity of working memory (WM) (Ayres & Gog, 2009). Cognitive operations or tasks refer to the mental activities in acquiring and the subsequent processing of information (Colman, 2015). The term WM (see Chapter 3 Working Memory for detailed explanation) refers to a brain system that provides temporary storage, and manipulation of the information necessary for complex cognitive tasks (Baddeley, 1992) such as; language comprehension (Acosta, Hernandez, & Ramirez, 2017; Daneman, 1994; Gathercole & Baddeley, 1993) learning (Alloway, 2009; Gathercole & Alloway, 2008; Hulme & Mackenzie, 2014; Jaeggi, Buschkuehl, Jonides, & Perrig, 2008; Swanson & Alloway, 2012) and reasoning (Baniqued et al., 2015; Hitch & Baddeley, 1976; Kyllonen & Christal, 1990; Söderqvist, Nutley, Ottersen, Grill, & Klingberg, 2012; Staccioli, Stasiuk, & McMillan, 1997).

1.2 Effects of heavy cognitive load, more specifically: Working Memory tasks.

Below is an example of an n-Back computer-based task that’s is designed to tax CL (Figure 1 Example 1 of a Working Memory Task). A heavy CL and demand on WM typically result in error or interference in the task at hand. One of the most popular experimental paradigms has been the n-back task (Gevins & Cutillo, 1993; Jaeggi, Buschkuehl, Jonides, & Perrig, 2008; Jaeggi, Buschkuehl, Perrig, & Meier, 2010; Oberauer, 2005a; Pollack, Johnson, & Knaff, 1959; Ross, 1966), in which participants are asked to monitor the identity or location of a series of verbal or nonverbal stimuli and to indicate when the currently presented stimulus
is the same as the one presented n trials previously (Owen, McMillan, Laird, & Bullmore, 2005). Performance variability may arise for several reasons, for example, Multiple Sclerosis (MS) is known to cause difficulty in information processing (Costa, Genova, DeLuca, & Chiaravalloti, 2017). This is due to the breakdown of the fatty tissue known as myelin, which acts as a conduit in neuronal communication. Research has shown that MS patients had slower reaction times over increasing CL compared to a control group when engaging in a n-back task (Parmenter, Shucard, Benedict, & Shucard, 2006). Similarly, cognitive function decline has been observed due to the ageing process (Salthouse, 2012), which in turn would affect participants ability to engage in WM tasks such as the n-back.

Figure 1 Example 1 of a Working Memory Task. Figure 1 depicts a schematic representing a typical trial for the N-Back task. Working from the top left panel down towards the bottom right panel: A digit (here the number 2) is randomly displayed, in this case from a number range 0-9, for a predetermined period (500ms in this example). The next panel refers to the interstimulus interval (ISI), this period is also known as the retention period i.e. the period the target digit (in this case the number 2) is to be held in WM. In this example it claims the ISI can be between 500/1500ms (Ms refers to Milliseconds), the reason for toggling between the two different lengths of ISI's is that it is said to reflect extra load on WM. The panel following this shows another target digit (here it’s the number 8) following by another retention period (again between 500/1500 Ms). The final panel is the response panel. If for example, the task was using an N-Back paradigm were n is equal to 2- back, then the participant would respond positively, or perhaps respond it satisfied this criterion. Responses are usually via PC keyboard
or dedicated button box. If the task was described as n equals to 1-back which is the number 8, this would not match the digit in the response panel which is the number 2. This would result in a negative response, as it would have not matched the set-out criteria of 1-back. Researchers manipulate both the number of n-back and the ISI length in a bid to tax WM.


Example 2: Another popular paradigm which aims to tackle perceptual load is visual search. Typically, a target is shown, followed by an ISI, then the participant must respond whether the target is amongst the probes. Another visual search paradigm is to test if the memory array matches the test array, see Figure 2 for variations of this.
Figure 2. Example 2 of Working Memory Task. Figure 2 shows a typical visual search task. Panel (A) shows an example, wherein the colour stimulus between memory and test arrays is different. Panel (B) depicts an example wherein the orienting of the stimulus between memory test arrays are different. Panel (C) is an example wherein the amount of target and distractors is manipulated. From High Visual Working Memory Capacity in Trait Social Anxiety, by Moriya, J., & Sugiura, Y. (2012), PLoS ONE, 7(4), e34244. https://doi.org/10.1371/journal.pone.0034244

1.3 How to measure Working Memory load?

CL theories are generally based on the idea that WM is limited in its capacity for maintaining or processing novel information (Miller, 1958), while long-term memory (LTM) has virtually unlimited capacity (Sweller, Merrienboer, & Paas, 1998). It is claimed that only 7±2 information elements can be held in WM (Cowan, 2001), and the number decreases when information must be not only remembered but also explicitly processed (Cowan, 2005) (i.e., when elements interrelate and have to be combined, this describes serial and parallel processing of information, described later in Chapter 3). An everyday example would be the learning the grammar of a foreign language (parallel processing) is more intrinsically complex than learning individual words (serial processing) because grammar involves the interaction of several grammatical components e.g., subject, predicate, and object.

1.4 Other theories that have attempted to characterise human processing capacity.

This first example discusses Miller’s (1956) magic number 7, which could be deemed as the starting point from which modern neuroscience began to quantify CL (Fan, 2014), but first and introduction is warranted in to Shannon’s work, and earlier attempts to quantify information from a mathematical viewpoint, and how that led onto Millers discovery.
Shannon’s (1948) entropy is utilised in physics as a way of quantifying how disorderly a system is and is a central construct in Shannon’s Information Theory. Entropy’s role is to attempt to provide regularity in information. Researchers in the 1950’s and 60s have been exploring its application in cognitive processes in relation to categorisation, reasoning and learning (Cover & Thomas, 1991).

Information is the reduction of uncertainty, Information Theory moreover entropy; is a branch of mathematics on how uncertainty could be measured, handled and characterised (Shannon, 2001). Shannon’s description of the theory which has five main parts (1) information source (2) transmitter (3) channel (4) receiver (5) and destination, although originally destined for use in electrical communication (Figure 3) it is seen to be sufficiently general to use in wider areas, including cognitive neuroscience (Shannon, 2001). Within the neuroscience field the term ‘information processing system’ is used regularly to describe the brain, and ‘bit” is defined as an algorithmic measure of information introduced by Shannon (1947) in his paper A Mathematical Theory of Communication (Shannon, 2001).

Figure 3 schematic depicting information theory from The mathematical theory of communication, Shannon, C. E., & Weaver, W. (1949), Urbana: University of Illinois Press. https://doi.org/10.2307/3611062. Shannon worked for Bell Laboratories in the United States, which at the time was concerned with transatlantic telephony communication. A message travelling from
the States to mainland Europe became weak, so weak it was indecipherable. Shannon began to work on how to quantify information to address this issue. The above figure describes how the information comes from a source, the transmitter changes the message (spoken word, music etc.) into a signal, what is eventually sent over the communication channel from the transmitter to the receiver. In the case of the telephone system, the channel is the wire, the signal is the current, which varies, travelling through the wire, the transmitters/receivers are the telephones either end. The source is the person speaking. So, what was the Problem? As the message travelled through the wire across the ocean the signal became unreadable. One solution offered was to put amplifiers over stages, to strengthen the signal, this did not work, however, as it also amplified the noise (unwanted perturbation, deviations in the signal) which unfortunately accompanies every signal. Eventually, using this method, amplifying signals over and over resulted in the noise becoming greater than the signal. Shannon's solution was to convert all messages into binary digits more popularly known as 'bits'. Amplifiers were replaced by readers, which in a lossless fashion, simply read the message and repeated it. Bits are a series of zeros and ones, therefore, becoming lost in the translation of a weak signal becomes a non-issue. Further to this Shannon uses a measure of entropy, to rate how organised the information is, and how to use it in context. According to Shannon the definition of sending and receiving information strongly relies on the context, the context corresponds to the message that is expected, which is the probability of that message. Following from this, if the message is rare, the more information it has. The key point here is a measure of entropy provides a measure of the probability (p) of the information (i) and how it is contextualised. If p is the probability of the message, then its information is related to 1/p. This is not how Shannon went about quantifying it, the idea was to define information rather as the number of bits required to write the number 1/p. This number is its logarithm in base 2, which is denoted log2(1/p) From C. E. Shannon, "A mathematical theory of communication," in The Bell System Technical Journal, vol. 27, no. 3, pp. 379-423, July 1948. doi:10.1002/j.1538-7305.1948.tb01338.x URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6773024&isnumber=6773023

Examples of how Information theory can be used to attempt to understand different functions of the brain are: in neurophysiological experiments where sensory stimulus are varied, and as a result electrical activity of a neuron is recorded (explained in depth in Chapter 4), common information can be analysed to infer what the neuron is coding for (Sills, 1968). Further to this, common information from different coding schemes can be compared; for example whether the same neuronal electrical activity is common information transmission (Rieke, Warland, Deruytervansteveninck, & Bialek, 1999). Additionally, as information theory is a formal mathematical theory, common information could be compared to information processing capacity. The main concern of the theory in relation to this current research is that it offers a measure of the amount of information people can deal with.

Information theory has had a long and eminent position in the cognitive science field. After the publication of Shannon and Weaver’s book (1949), most of the psychological research demonstrated that response time (RT) in a task which required a keypress on an input device like a keyboard, was linearly related to the complexity or the amount of information
transmitted. An example of this is Hicks law (1952), and it states that a logarithmic function exists between the number of alternative responses for the participant, implying that a linear relationship exists between the RT and the number of bits of the input of the information. However, it is suggested that the use of these types of mathematical models became complicated when for example, estimates of information processing capacity displayed the ability to differ depending on the response paradigms i.e. if you compare a task which requires more familiar skills to less familiar skills (Posner, 1966).

As cognitive psychology developed in its own right, focus on information theory and RT began to dwindle and an emphasis was given to more specific mental operations involved in processing tasks (Neisser, 1967), an example is the Sternberg (1969) task, in which the key variable is the list length of the items to be stored in WM rather than explicitly stating how much information was to be transmitted (see Figure 4 as an example), and as a result of this focus on more specific processes it is suggested that the relationship between mental operations and a quantitative analysis of the amount of information that is being processed was not fully developed (Fan, 2014). This is one of the reasons, (another being it may not suitable to begin with, discussed later in chapter 3) if not the main reason the current research does not use Information Theory as a direct tool to measure WM, rather it is in line with the work of Miller (1956) in which a more discrete and arguably more simpler to operationalise measure of WM is employed. Further to this, it is suggested that as brain imaging technology and techniques improved; this disconnect between researching Information Theory and processing capacity increased (fan, 2014).
Further to Shannon’s Information Theory, concepts regarding information processing and the quantification of such may have been introduced to the field of Psychology in the identification experiments in the late 1940s (Sills, 1968), in which stimuli were presented to participants in which they then had to identify in a subsequent presentation. When stimuli were sensibility ordered according to some standard unit i.e. weight, length, tone etc. performance can be easily measured by standard statistics, the average error for example. The opposite is true, when the stimulus is not well-ordered identification cannot be readily measured with standard measurements/statistics. This suggests that the transmitted information of the latter is ideally suited to be a non-metric measure of the relatedness of the stimuli and its responses (Sills, 1968). Regardless of the method statistical analyses, it shows the debate and study of what participants were engaging in, the task itself, began in earnest.


Figure 4 modified Sternberg task. Schematic illustration of the modified Sternberg task (1966) illustrating a four-word list (low memory load condition). After an orienting cue (+), a series of words (four or eight, depending on memory load condition) is shown sequentially in the centre of a monitor screen. Following this study list and a brief retention interval, a memory cue word is shown and participants are asked to decide whether the word was in the immediately preceding list (yes) or not (no).
Cognitive Load and Working Memory Capacity; Within and Between Modality

Garner and Hake (1951) attempt to answer the simple question put forth in the identification experiments; how many stimuli can be correctly identified? While noting that the answer may lay in the margin for error, that is if a small average error is permitted, the same body of data will allow a larger number of discernible stimuli, than if a larger average error is allowed. The theorists continue to suggest that the proportion of errors may be greater in locating a point at 1 of 50 possible locations as opposed to 1 out of 10. Gardener and Hake (1951) operationalise this from looking at absolute and comparative judgements; which is said to be as a result of the comparison of perceptions. A comparative judgement is usually made with two or more stimuli; one is the standard and one is a comparative stimulus; the comparative is always compared to the standard. A simple example here may be the brightness of lights. It would be easier to compare one light (or ten lights or fifty to the standard) from another if all were presented at the same time, there is less chance of errors.

An absolute judgement, however, is to compare one light to the standard (or ten lights or fifty) from another using memory. So, in this instance, the standard only exists in the observer's memory. A simple example here would be to compare the brightness of the light when the observer can no longer see the previous light (perhaps only displayed for a moment, then masked) and can only be compared to memory. Critically, what Garner and Hake observed was that the amount of transmitted information remains the same, the question of interest might be how observers deal with this information. The same light (information transmitted) was observed in both comparative and absolute judgements but the CL was different, as errors would increase in the absolute judgement task. According to Sills (1968) as a result of this observation, a flurry of experimental activity occurred within the field of psychology, focused
on the limited transmission of information capabilities of the observer emerged, including Miller's magical number seven, plus or minus two (Sills, 1968).

So, what did Miller (1956) discover? Miller discovered a coincidence between the information capacity channel of the observer for absolute judgement tasks and that of short-term memory (STM). Miller goes on to claim that perhaps attempting to measure the information capacity of an observer using Information Theory may not be the best approach considering the way that humans assimilate and deal with information. Firstly, it is important to discuss the coincidence and just as Miller cites in his paper, the suppression of the technical details in the interest of communication, as Miller does in his work, will be adhered to here as well, as it is heavily embedded in the field of mathematics and is beyond the scope of this current work to go into detail regarding the fundamentals (for further information on the absolute judgement tasks that will be discussed here and how they were measured in bits see Pollack, 1953b, 1953a; Pollack & Ficks, 1954; Pollack, Johnson, & Knaff, 1959).

A note before a description of the absolute judgement task. Miller noted that there was a limit on the amount of information a person could deal with and calls this the channel capacity of the observer. Looking back on Shannon’s Information Theory (see figure 3), the channel was a telephone line which information travels, in this case, the channel is the STM of the observer. Generally, in these tasks, an observer has to make a judgement. Miller gives an example of a judgement and how much a ‘bit’ of information is relative to that judgement. Imagine giving a judgement of whether or not a man is less than are more than six feet tall, with the pre-existing knowledge that he is there or thereabouts, therefore it is said that the chances are 50-50 in this judgement. This judgement has two alternatives and therefore is said that one bit of information is needed. Following from this it is said that two bits of
information are required for four alternatives, three bits of information for eight alternatives, four bits of information for sixteen alternatives and five bits of information for thirty-two alternatives etc. To summarise Miller claims one bit of information is required for each binary decision, and if there are 32 alternatives; that is five binary decisions, equating to five bits, that would have to be made in succession to solve the task.

The following are some of the examples that Miller discusses in relation to absolute judgement tasks. Observers had to listen to the identities of tones which varied in pitch, a preassigned number was learned by the participant before the test began, and the goal of the participant was to respond with a corresponding number when the tone was heard. Up to fourteen tones were presented with the expectation of the participant attempting to correspond them to with fourteen numbers. The results show the participants had very little errors with two to three tones, errors were rare for four tones, errors were more frequent for five tones and for fourteen tones many errors are were made.

Miller suggests that the channel capacity of the observer for distinguishing between pitch and auditory tones is roughly $2.3$ bits, the ability to judge six tones. In other experiments, for example, judging perceived loudness it is $2.5$ bits are five tones, for taste intensity; the judgement of concentration of the salt solution, the channel capacities ($1.9$ bits) are four distinct judgements of concentrations, and in visual is experiments it ranges from $3.2$ to $3.9$ bits depending on how long the exposure of the visual target, on which a judgement had to be made results in $10$ to $15$ distinct possibilities or judgements. Based on these experiments it led Miller to his magic number 7 plus or minus two based on averages: take the average of possible judgements across these tasks: six for pitch, five for perceived loudness, four for taste and if
one goes midrange for the visual task that's 12, it equates to 6+5+4+12=27/4=6.75 absolute judgments on average.

Miller goes on to look at the multidimensional absolute judgements and comes to the conclusion that in the terms of distinguishing alternatives observers are able to deal with 6.5 alternatives on average, and this is over a wide variety of different variables that were studied. Miller suggests that there is some type of limitation built into us as part of the design of our nervous system that somehow manages to keep our channel capacities in this general range. Next Miller looks at STM task which he claims keeps within this range but more notably he also claims that the amount of bits that are measured in the transmission does not necessarily dictate the capacity of the channel of the observer rather, this is done by recoding an important but often overlooked (at least at the time) aspect of cognitive psychology, and also another reason why this current research did not measure WM in bits.

Miller’s (1956) compares the memory span task to absolute judgements tasks as a measure of STM (the term working memory (WM) had not emerged at this time, it’s generally agreed that WM is a part of STM), which is measured by the longest list of items a person can recall directly after presentation. Miller found this to be roughly 7 items, and this was recorded in stimuli with different amounts of information quantified by bit rate. A list of words compared to a list of numbers, for example, words have 10 bits on average and digits have one bit (Miller, 1956). This was a very important discovery, as quantifying STM by the number of bits that were transmitted was the more formal mathematical approach as demonstrated earlier with Shannon’s work, it was emerging that human STM did not operate in the same manner. More simply put, Miller posited that STM consisted of ‘slots’, and that these slots had the ability to store information. In addition to this, the amount of information as measured by bits, may not be the defining factor in discerning WM capacity, people tended
to ‘chunk” information together, a chunk being the largest meaningful unit of information a person can recognise (Miller, 1956) by a process of grouping together of items or words so that they can be processed as single concepts (Daneman & Carpenter, 1980).

Miller claims in a bid to increase the number of bits in a slot, observers chunked together more familiar information, this was described as ‘recoding’ the information, a process which Miller describes at the time, was one of the most important processes that humans do, and was not given enough emphasis in the research of the era. Miller claims a chunk is difficult to define, for example, a word in one’s own language may represent a chunk, where a word in a foreign language may represent many chunks, as a person deals with assimilating it or even just attempting to pronounce it. This current research aligns itself with that of Miller’s, in that it attempts to measure WM capacity in relation to the number of familiar recognisable chunks of information, in this current research participants are asked to search for rectangles, with simple variations, listen for whole sounds from musical instruments rather than unfamiliar or odd stimuli that participants can retain in WM, rather than the formal mathematical measure in bits, as this measure may not be as suitable to the end goal of measuring WM.

1.5 What is the research question?

Perceptual load (PL) and cognitive load (CL) have been treated in the same manner (Wenger & Fitousi, 2010). However, it is suggested that PL and CL have independent and conflicting effects on the dispersal of attentional resources (Fitousi & Wenger, 2011). It is claimed that PL is moderated by factors such as the size of the display and amount of distractors (as shown in Figure 2, for example in the visual search task), and CL is moderated (as described with Figure 1 when, within the n-back paradigm, 1-back is increased to 2-back, in turn increasing WM load) by the dynamics of WM load (Fitousi & Wenger, 2011), this
demonstrates the difficulty of distinguishing between what is being measured, and is an on-going debate, centred on the allocation of limited capacity mental resources. It is here that this proposed research will contribute to the field by using the analysis of the electroencephalogram (EEG) to answer these questions.

The EEG was chosen to capture physiological data in this research due to its ability to record neural activity in milliseconds (Ms) and neural oscillations, a physiological measure obtained by the EEG (explained in depth chapter 4). These oscillations have been said to be strong indicators of cognition (Cohen, 2017). The overarching goal is to attempt to isolate CL in WM tasks physiologically, achieved by quantifying and controlling for the perceptual components in both visual and auditory modalities, revealed by analysing the neural oscillations, the residual cognitive component. The novel aspect of this work is both the use of the EEG combined with the multi-modal approach and employment of the RC construct, which is claimed to be a more definitive measure of WM.

1.6 Why is the research important?

It is very important to maintain the optimal CL to achieve the maximum efficiency and productivity of limited cognitive processing capabilities (Jackson, Kleitman, & Aidman, 2014; Korol, 2002). For this reason and for proper measurement, a real-time non-invasive measurement of CL is very important (Paas, Tuovinen, Tabbers, & Van Gerven, 2003); with behavioural experiments one can understand something about how the stimuli are processed, but no physiological responses are recorded, which hamper the ability to link behaviour and brain function, which in turn lessens the ability to understand how information is processed. (Shriram, Sundhararajan, & Daimiwal, 2013).
The primary aim of this thesis is to investigate if the Relational Complexity (RC) metric could help disentangle PL from CL, achieved by (1) creating analogous perceptual tasks both auditory and visual and comparing them to a cognitive task. WM load will be manipulated across all experiments, allowing for analysis of an interaction between WM load and mode (perceptual versus cognitive). An ancillary aim (2) will be investigated if perceptual processing affected processing the cognitive task. The research proposed here will focus on CL and limited WM capacity deriving behavioural and electrophysiological measures. Additionally, research of this kind has the potential to help aid in the diagnosis, monitoring and subsequent treatment of cognitive disorders associated with age-related cognitive decline, MS and dementia to a name a few. It also can influence the design and implantation of EEG based therapies like Neurofeedback.

1.7 Relational Complexity Theory Introduction

According to the RC theory of Halford, Wilson and Phillips (1998), a suitable definition for WM capacity limitations is best derived when regarding the complexity of the relations between information that allows for parallel processing. Parallel refers here to the processing of multiple pieces of information at the same time and is distinct from serial processing which refers to the processing of individual pieces of information one after the other (see Chapter 3.3 for a debate on this). In the Halford et al., (1998) interpretation, complexity make-up has a theoretical and mathematical foundation (described later) and is understood as the essential characteristic of Working Memory Capacity (WMC) limitations. It is important to note that in opposition to RCT, previous research in this area has in general, focused on the number of items or chunks of discrete information that can be held in WM as a measure of WMC (Halford, Baker, McCredden, & Bain, 2005).
1.8 Introduction to the Relational Complexity metric

To directly measure RC, Halford et al., (1998) devised the RC metric. This metric pertains both to the structural assets of a given problem and to individual processing capacity and assumes an isomorphic relationship between the two. The metric bases itself on RC as this refers to the number of related pieces of information, it also corresponds to the arity of relations, between information within the same cognitive representation (Perret, Bailleux, & Dauvier, 2011). The metric is broken down as follows; in logic, mathematics and computer science, the arity of a function or operation is the number of arguments or operands the function or operation receives (Vialar, 2016, p.693). A unary relation takes one argument (A:B), a binary relation takes two arguments (A:B::C:D), a ternary relation takes three arguments (A:B::C:D::E:F), and so on. Relations of increasing arity are more complex; A unary relation is less complex than a binary relation, which is, in turn, less complex than a ternary relation and so on. As arity increases, so too does the RC. A quaternary relation (A:B::C:D::E:F::G:H) is found to be the most complex that healthy adults can process, although under optimal conditions a small number of people can process quintenary relations (Halford et al., 2005). Processing capacity is not all or none; increased complexity produces an increase in errors and decision times, rather than sudden catastrophic failure (Halford et al., 2005). This is meaningful, in the sense that the process under scrutiny is analogous to stimulus complexity up unto limits in processing capacity. Consequently, the RC metric is a prospective measure of the efficiency of the underlying brain mechanisms involved.

1.9. Why is there a need for the RC task? Plus, a critique of the theory
Attempts to quantify information processing has been embarked upon since Miller in the ‘50s (See Miller, 1956), in which it is claimed that the number of discrete items that humans can hold in short-term memory is 7, assessed by using simple recall. Cowan's (2001) claim is that WM capacity is close to 4 items. Halford et al., (2005) claim that processing limits in humans have been at best estimated theoretically and that many of these estimates are estimates in Visual Working Memory (VWM). There has not been in their view, an effective empirical determination of processing capacity. Halford et al., (2005) acknowledge that the assessment of human processing can be difficult due to the number of strategies available to deal with the processing load. Although these strategies are valuable in other settings, they must be controlled for to determine the underlying processing capacity. Halford et al., (2005) contend that the Halford Graphical Relational Complexity Task (HGRCT) can achieve accurate measurements of WMC. The opposition to RC theory mainly comes from child development literature; this researcher acknowledges the lack of studies related to typically developed adults. Gentner and Markman (1997) maintain that increases in WMC are not just down to increases in RC, and RC cannot by the isolated marker of cognitive development and that relational knowledge is just as important.

Sternberg and Smith (1988) posit a good example of relational knowledge is children’s development coming from the scrutiny of object categorisation and the relations between objects. As a result, it was found that the ability to deal with this relational knowledge was hierarchical, starting with the ability to discern object similarity i.e. the child knowing that a red ball and a red Apple has the same shape and colour. After this, a higher order relationship between objects was observed in older children, for example, a ball can roll on the ground, a toy car can roll on a table top. A higher-order relation than that would be that the ball can
cause a person to trip and the toy car can cause a vase to fall over for, thus indicates a more mature level of relational knowledge (Goswami, 1998, 2010, 2013). A similar age-dependent increase in relational knowledgeability was found in research with children and basic mathematical ability (Baroody, 1999).

Challenges to RC theory’s ability to be a good indicator child development come from RC theory claiming infants only deal with the here and now representations (e.g. hiding a toy/object permanence) and cannot go beyond this. Evidence suggests they can (infants 4-5 months) and are capable of being surprised by ‘impossible physical situations’ (floating toy), this it is claimed infers a cause and effect ability/relation (Goswami, 1998). It is not expected that developmental research into RC theory will affect this current study, as the current research is recruiting adults only.
Chapter 2

2.1. A detailed description of the Halford Graphical Relational Complexity Task

Halford et al., (2005) claim that the HGRCT attempts to probe human information processing limits by manipulating the conceptual complexity displayed in graphically displayed statistical interactions. The task necessitates participants to endeavour to understand graphical exhibitions of interactions (two, three and four-way), which entail a corresponding number of variables to be processed. Explicitly, these graphical interactions necessitated participants to choose whether or not greater/smaller (i.e. $>$, $<$) would be the appropriate conclusion of the finishing sentence in a verbal explanation accompanying interaction.

The theory underpinning RC suggests that the quantity of information essential for processing in a distinct cognitive step can be condensed into fewer, larger units by conceptual chunking, or by segmentation into lesser subtasks that can be processed serially (Halford et al., 1998). Halford et al., (2005) claim conceptual chunking and segmentation are constrained in their graphically displayed interactions because of the necessity to process the variables together. Put simply, in the HGRCT a participant must look at one area of the graph, carry out a calculation, for which serial processing is required, resulting in a number that must be held in working memory. The process is repeated in another area of the graph in which another variable is calculated and held in WM. In a binary relation, one would have to perform a calculation on both of these variables held in WM, in a ternary relation one would have to perform a calculation on three variables and so on. As the interactions increase from binary to ternary, chunking and segmentation are controlled for; as the binary interaction must be solved before the ternary, the ternary before the quaternary and so on. The cognitive process cannot be grouped or broken down to smaller subtasks as a result of this serialised structure.
The HGRCT is illustrated in Figure 5. Here, participants are asked to calculate/compare differences in bar heights on a graph mentally. This calculation results in a number because of a binary interaction, to begin with, about an accompanying narrative (which type of cake people prefer, not used in this study, graphs are modified to replicate the steps, without the use of the narrative, as piloting proved it to be confusing). Figure 5 (A-C) on the next page depicts the modified version used in this study.
Cognitive Load and Working Memory Capacity; Within and Between Modality

A

Binary = 25-60
Ternary =
Quaternary =
Result = 25 < 60

B

Binary = 55-40, 40-65
Ternary = 15 25
Quaternary =
Result = 10 < 25

C

Binary = 20-10, 20-40, 65-0, 30-40
Ternary = 10 20 65 10
Quaternary = 10 55
Result = 10 < 55
2.2. How does this task differ from traditional WMC tasks?

In the HGRCT, participants are asked to interpret graphically displayed statistical interactions. The main difference from traditional WMC tasks such as the N-Back task is that;
when engaging in the HGRCT, all independent variables need to be considered together, this means that the unary interaction needs to be solved before the binary can be solved before the ternary can be solved and so on. The reason for this is so that grouping together of information to aid recall, or break down into littler subtasks is controlled, normally done by chunking and segmentation as described earlier, and thus conceptual complexity is directly determined by order of the interaction, the goal of the task.

2.3. What does the HGRCT claim to have found?

A relationship is found between the number of variables to contend with as a result of the order of these interactions, the quantity of variables increases as the order of interactions increases. Halford and colleagues claim there is a significant decrease in accuracy and increase in time to resolve the task from a binary, ternary and quaternary level of interaction, with quinternary resolved at chance level.
Chapter 3 Working Memory

3.1 Overview and purpose of the chapter

The term Working Memory (WM) was first used in 1960s by Miller and colleagues in a very influential book looking at the structure of behaviour (Miller, Galanter, & Pribram, 1960) and was subsequently adopted by Atkinson and Shiffrin's (1968) WM model and then into the Baddeley and Hitch's (1974) WM model, the gold standard of there respective eras. The following describes models of memory. It is not possible to describe memory literally, and it is not possible to observe individual neurons and the physiological functions of these neurons (not yet anyway) during the memory process (Foster, 2002). In a bid to understand memory, mental models are constructed. These models are metaphors to help understand, test, build upon and explain how research attempts to explain the concept of memory (Foster, 2002). A brief overview of WM models will be provided, which will culminate into how RC was eventually adopted as one of the processes in modern models of WM. According to Henry (2012), the original WM model originates from Baddeley (1986) and Baddeley and Hitch (1974), with the revision some years later Baddeley (2000, 2007,). Baddeley (2010) describes how the WM model came to be after an examination into the link between STM and LTM, which involved scrutinising the most popular model of the day (the 60s and 70s) the Atkinson Shiffrin model. The focus will be given to these two models. Other advances in the field will be referenced back to these models. To begin with, a history of earlier attempts to understand, and eventually fractionate memory is given, one assumes the starting point to be one were memory is one single entity.
3.2 The fractioning of memory into subcomponents

Studies in philosophy suggest that as far back as 2000 and more years ago, attempts were made to understand human memory. Aristotle in his treatise of the soul came up with what is sometimes referred to as the storehouse metaphor, all humans are born as a blank slate and begin to store memories, making memories was likened to making impressions in wax (Duschinsky, 2012).

Yate's (1966) book the Art of Memory, looks at how memory was understood from ancient Greece, the Middle Ages and Renaissance times, were notions put forth included there were two sorts of memory; material memory, this resides within us and is useful for every day, and artificial memory needed for daily learning, accumulating as life goes on.

In the 19th century William James (1842-1910) known as one of the founding fathers of modern psychology made a distinction between primary and secondary memory, which equates to STM and LTM as described in modernity. In this, the infancy of memory research, the primary memory was in charge of cognition whilst the secondary consolidated memory (Vianna et al., 2000).

The 19th century saw the start of modern experimental psychology as we know it and investigations into memory were a part of the zeitgeist. William James and Wilhelm Wundt (1832-1920) spearheaded memory research. James suggested a distinction for primary and secondary memory which eventually turned into STM and LTM whilst positing the notion of neural plasticity long before it was demonstrated (Berlucchi & Buchtel, 2009). Wundt had devised his own associate model of memory in his bid to explore the boundaries of
consciousness, he wondered how many elements could be held in consciousness after a brief exposure to stimuli, this he referred to as the scope of attention (Capenter, 2007), this can be described as an early attempt to test memory capacity. Interestingly, Wundt’s experiment which involved the recollection of letters following fixation at a central point, resulted in the average of three and a maximum of six and, as shown by Miller these falls within the range of the magic number 7 +/- 2. Wundt’s paradigm involving the scope of attention was replicated in the 1960s with Sperling's iconic research (see Sperling, 1960).

It is suggested that Hermann Ebbinghaus (1850-1909) is credited with the first scientific approach to the study of memory in the 1880s (Murre & Dros, 2015). Ebbinghaus’s experimental work included a list of nonsense syllables that were compared with proper words. The idea was to create combinations of syllables he had not seen before in a bid to measure learning for the first time, the learning of novel information. The criteria he set out was to recall the list perfectly two times in a row, this criterion was necessary he claimed in studies of how long a memory lasts, as it shows the memory is fully formed. A retention period, the period between observing the test syllables and the recall test was experimented with, often varying between several minutes to several days. After retention, the test was measured in savings made, that is if the task took 20 trials to learn the list the first time, and took 10 trials the second times, the savings made were 50% (Ebbinghaus, 2013). Note the introduction of the term trials, criterion, measure etc. all used in today’s research. As a result of his experiments, Ebbinghaus charted the amount of forgetting, the forgetting curve and later the learning curve (Murre & Dros, 2015).
Richard Semon’s (1859-1918) work through the early 1900s through to the 1930s was based on the idea of an engram, which suggests that every psychological state has a corresponding physical state, a memory left, a permanent trace as it were on cellular material (Schacter, Eich, & Tulving, 1978), an early indicator of research linking memory to its physical correlate. FC Bartlett (1886-1969) introduced the term recall, which involved the serial reproduction technique: first the participant reads a story, recalls it to a second participant, and the accounts are compared, third participant reads the second participant version and so on. In another version, the repeated reproduction technique involves the researcher reading aloud a story twice, a 15 minute delay was given and participants attempted to recall the story: over different time periods, Bartlett wanted to see how the story would be attended over the time periods and what would be omitted and/or added to make the story comprehensible (Bergman & Roediger, 1999), one could say this was an introduction into the fallibility of memory. The 1950s saw psychology and neuroscience begin to weld together, as surgical and technical advances started to pave the way for new research into uncharted territory. Wilder Penfield (1891-1976) was a neurosurgeon whose research using electrical probes to stimulate the brain resulted in maps of the brain cortices, that led to the summonsing of memories as flashbacks after stimulating parts of the temporal lobe (Hogan & English, 2012).

The emergence of the field of neuropsychology and the biological basis for theories relevant to encoding: the process of breaking down/assimilation information so that it can be understood (see Melton 1963) led Carol Lashley (1890-1958) to two and half decades of research into the mapping memory trace (engrams) in laboratory rats, moreover the attempt to pinpoint their origin, only to discover that they are not localised to a single area of the brain, rather distributed widely across areas. Lashley (1951) observed that in complex sequential behaviour such as playing the piano, it could not be executed by sending a signal to one part
of the brain, waiting for a response then sending another waiting for a response, and so on. There was quite simply was not enough time for the neuronal signals to travel back and over in this manner. Lashley posited that an essential, hierarchical organised programme (referring to a memory system) was responsible. It is argued that this guided the study of motor behaviour ever since, and made Lashley a pioneer of neuroscience before the term was ever used, it is claimed Lashley purposely avoided theoretical research at the time, in a bid to link the psychological phenomenon with biology, without the added bias of existing non biological theories (Lashley, 1951; Rosenbaum, Cohen, Jax, Weiss, & van der Wel, 2007).

Continuing in neuroscience research as early as 1949, Hebb's rule emerged: neurons that fire together, wire together (Hebb, 1950). This rule states that the encoding forms memories, as these neuronal connections related to memories are established through repeated use, they become associated with one another, so activity in one group of neurons facilitates the same activity in another group; this is the neuronal basis for memories (Hebb, 1950).

The 70's expanded upon the neurology behind encoding and consolidation, long-term potentiation and neural plasticity, for example work with sea slugs which bolsters Hebb's rule, helping to identify at a molecular level the changes during learning and the role of the neurotransmitters (Kandel, 1976, 1978; Kandel, 2009; Kandel, 2012). Consolidation refers to memories which are stored for a longer period (Clopath, 2012); one might not remember one parked the car a week ago, but one could the day of a wedding, these memories are, thought to be stored in connections between neurons, called synapses, which can vary in strength (Clopath, 2012). The greater the synapse strength the clearer the memory, your wedding day memories would be greater than your average day's memories. Short-term neuronal plasticity
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refers to a change in synaptic strength lasting a few minutes, were early and late long-term potentiation lasts from two to ten hours (Clopath, 2012).

The end of the ’60s saw the Atkinson Shiffrin model (1968) which posited a multi-store model of memory. In this model, information passed in a linear fashion from store to store and has been described as an information processing model, analogous to a computer, in that there is an input, a process and output. These types of computer brain analogies were very popular since the advent of the PC in the 50s and 60s (See Broadbent, 1954, 1958; Deutsch & Deutsch, 1963; Treisman, 1969).

The Atkinson Shiffrin model consisted of physical structures, which did not vary, the sensory register, the short-term store (STS) and the long-term store (LTS). Each store had control processes. These processes can and do vary depending on the situation. The situation refers to in this case refers to the type of information, the amount of information and experience and knowledge of the observer (Atkinson and Shiffrin, 1968)(see Figure 6).
Firstly, external input enters the sensory register (SR). The main concern of the SR is the amount of sensory information that needs to be handled, and what proportion needs to be dealt with. Some of the control processes that could be used here are; scanning the information as it enters the SR, a related attention process; attends to the which information transfers to the STS, and the process of matching incoming information to the LTS to aid identification (Atkinson Shiffrin, 1968). The duration of the information in SR is roughly between 250 to 500 Ms, its capacity is large, encompassing’s sensory experience. Encoding here involves
different stores for each sense for example Figure 6 Shows the visual sense for example (Atkinson Shiffrin, 1968).

Attended to information flows from the SR to the STS, the STS is referred to as WM in this model. Control processes in the STS are search, recognition, recall and rehearsal. The duration of information in the STS is up to 18 seconds, the capacity as suggested earlier by Miller is 7+ or -2 items, and the encoding process is mainly auditory/rehearsal. The rehearsal process, the repetition of information allows for the transfer of information to the LTS if this repetition does not occur the information is forgotten through displacement. The rehearsal buffer (see Figure 7 on the next page) consists of slots (posited by Miller (1956) which can only hold so much information before it decays, and/or is displaced by another item of information (Atkinson Shiffrin, 1968).
To maximise the performance of the buffer, one must put all efforts into rehearsal and not engage in any other resource draining activities (Atkinson Shiffrin, 1968). Examples of resource-draining processes that might be occurring could be that the rate of information input could be too high, resulting in attempts to organise new information encroaching on the rehearsal process that is already underway (Atkinson Shiffrin, 1968). In addition, new complicated information may just simply be ignored, this is in a bid to keep the buffer
unchanged, requiring no additional strain on resources (Atkinson Shiffrin, 1968). In reference to the LTS, it is claimed the generation of information, and information capacity is mainly unlimited, and encoding process is mainly but not limited to semantic, as it can be visual and auditory as well (Atkinson Shiffrin, 1968). The main reason for the elaboration on this model at this juncture is thinking of memory in terms of metal models, stores, information capacity, buffers etc will not seem like strange concepts in subsequent descriptions.

Craik and Lockhart (1972) put forth the Levels of Processing model and suggest that the strength of memory traces are due to the depth of the processing of information. The depth of the information results in the depth of the memory, which is a direct result of the meaningfulness extracted from attending/processing the information, rather than how the analysis was performed on it. Craig and Lockhart's model is unlike the Atkinson Shiffrin model in that it does not rely on physical structures, instead, it focuses on how the act of processing forms new memories. Processing according to Craik and Lockhart (1972) is done in three ways (1) shallow processing; which consists of two subcomponents, (a) structural processes and (b) phonemic processing and (2); deep processing. Shallow processing is concerned with the processing of the sensory-perceptual features of the stimuli, encoding the physical qualities, phonemic processing attends to the sound attributes. Shallow processing involves maintenance rehearsal, repeating the task to hold in STM for short durations. Deep processing engages elaborate rehearsal, this is a more in-depth meaningful rehearsal, it involves linking associations, images and meanings leading to stronger memories. The model is focused more on the encoding process rather than the physical structures of memory (Craik & Lockhart, 1972).
Returning to the multicomponent models, brain disorders/brain dysfunction studies demonstrated that these types of models are reliable (Baddeley, 2010). One famous case being patient HM. Following brain surgery to treat epilepsy, patient HM could not form ongoing memories, but could however retain information in STM (Squire, 2009). This showed a disassociation physiologically between impaired LTM and preserved STM (Baddeley 2010), these findings and others with similar brain damage studies led to memory loss been viewed as the succession of storage systems, in which information flows from the environment, into temporary buffers before entering a limited STM store, which culminates in LTM. The Atkinson Shiffrin model demonstrates this but according to Baddeley (2010), it ran into two problems, (1) the assumption that the mere maintenance of material in STM would generate long-term learning. This Baddeley claims is incorrect, an example given is processing a word based on its appearance or sound as opposed to its context, emotion or meaning, would hamper long-term learning. (2) The study of patients with a very specific short-term deficit, i.e. with a non-functioning STM, according to the Atkinson Shiffrin model these patients would not be able to learn as information simply lost. Furthermore, if the STM encompassed the WM processes, as betrayed in the model, the day-to-day cognitive dysfunction would be apparent. This proved not to be the case as patients with brain injuries can recover and can continue with fairly normal routines including, for example, driving a taxi, secretarial duties etc. (Baddeley 2010).

Baddeley and Hitch (1974) attempted to address this paradox by attempting to disrupt STM capacity on cognitive demand tasks, with a concurrent activity like remembering a phone number for example or a random list of numbers. The idea being, as the sequence of numbers increased, the remaining capacity in STM would be significantly reduced, and performance significantly or catastrophically disrupted. A consistent effect of performance deteriorating was
detected but was not as detrimental as expected. The unitary model of working memory was abandoned as it could not explain these results but instead, a multicomponent model was drafted, probably the most influential to date (Baddeley, Hitch, & Allen, 2018). This multicomponent model differed from the Atkinson Shiffrin model as a replacement of a single system for WM with at least three separate systems: attentional control (central executive), phonological loop, and a visual-spatial sketchpad (Baddeley 2010). This model left behind the notion of a series of successive stages of processing, to a model capable of parallel processing across the subsystems. Another component, the episodic buffer was added later (Baddeley 2010). A detailed description of the models follows.

The concept of a STM store was replaced with the WM construct, and allocated four components: a neutral modality component that bears resemblance to attention (1) the central executive (2) a subvocal articulation and speech-based component: the phonological loop (3) a visual and spatial processing component: the visuospatial sketchpad, and (4) a component to the integration of information from long-term memory, the fourth component the episodic buffer, was added later (Baddeley, 2000).
Baddeley (2007) states “working memory is the temporary storage system under attentional control that underpins our capacity for complex thought”. Henry (2012) reminds us how loaded this quote is, as it contains several important points, temporary storage refers to what is being dealt with in the here and now, under attentional control suggest that the person chooses were to direct their attention, and underpinning complex thought suggest that WM is the bedrock for higher order thinking and reasoning (Henry 2012). An everyday example is provided by Goldstein (2011) for WM and its processes. WM is a cognitive function required to stay focused on tasks, deals with interferences and keep the individual aware of what is happening around them. The phonological loop is used to deal with auditory information and is composed of two components, the phonological store and the articulatory rehearsal process, the latter is responsible for rehearsing information so that it is kept in the former, so the information is not forgotten. An example given is studying for an exam, the student would repeat information out loud in a bid to remember the information, dates and theorists for
example. Another example is, repetition helps a phone number to be stored in LTM (Goldstein, 2011).

The visuospatial sketchpad handles and manipulates visual information. In addition, it is responsible for the creation of visual images in the mind in the absence of physical stimuli (Goldstein, 2011). An example of the visuospatial sketchpad in action would be retracing your steps if you misplaced something, visual scenes would be re-enacted in your mind to help remember.

Both the phonological loop and the visuospatial sketchpad are under the control of the central executive, it decides which information is handled by what part of the WM. It directs and prioritises attention. When all these components work in unison, the individual can reason, problem solve, read, discuss, comprehend etc. It is a lifelong, and constant process (Goldstein, 2011).

The episodic buffer which is added as a third slave system (Baddeley 2000) to the central executive interacts with all of the subcomponents of WM and claims to add a sense of time. The sense of time helps to explain why memories can be recalled as a coordinated sequence of events rather than random sequences (Baddeley 2000). Another justification used for the episodic buffer is that it addresses the binding problem, that is how multiple modalities form together to create a single experience i.e. seeing an object moving and hearing the sound that goes with it (Baddeley 2000). It offers a multidimensional code that can be read by all of the subcomponents of WM i.e. the phonological loop, the visuospatial sketchpad and a central executive. Making the perception of the event coherent (Byrne, 2008; Gathercole & Alloway, 2008)
3.3 Serial vs parallel processing debate:

At this juncture, before moving on to how RC eventually became part of modern WM models, it is important to discuss issues in the literature related to WM which are the serial versus parallel processing debate and the motor WM debate. Although the current research does not control explicitly for either, in saying this Halford (2005) claims the HGRCT is a parallel processing task. However, it is important to note these debates and their importance in the literature and were attempts to control for either or has been used currently.

Serial processing can be defined as strictly sequential, without the successive processing times of items/objects from distinct subsystems (subsystems here refers to for example to constructs like the visuospatial sketchpad), the next item or object is not processed until the previous is dealt with. In opposition, parallel processing is assignable to any processing of several items/objects or subsystems at the same time, processing can finish on different objects at different times (Townsend, 1990).

The question as to what constitutes serial from parallel processing was the foundation of perceptual psychology in the late 19th century, and lay dormant until the 1960s, with the advent of the resurgence of information processing, referred to as the architecture issue. Arguably beginning with the work of Sternberg in the 1960s (Williams et al. 2014).

Sternberg assessed high-speed scanning in human memory. Participants studied a list of symbols, kept them in STM and were tasked with responding if a test symbol was absent or present in tests array. As the mean length of the symbol list increased, so did the RT. Results suggest that an internal serial comparison mental component is at play, between 25-30 symbols (Sternberg, 1966).
Visual search tasks (Figure 2) have an important role in the serial versus parallel debate. Generally, these tasks involved a visual target to be retained in WM, which participants attempt to find in the search array. The target will be absent/present in half the trials. As the set size varies it increases/decreases WM load. Researchers then plot the time it takes to detect the target as a function of the set size, results show RT’s increased linearly with set size, suggesting a serial search was conducted (Townsend 2014).

However, it was shown that parallel WM models could mimic serial WM models and vice versa. This becomes known as model mimicking (Townsend, 1990 for a review). In addition to this Narbutas, Lin, Kristan and Heinke (2017) state in the last five decades, visual search has been employed to experimentally study human processing of a complex scene. However efficient more straightforward searches i.e. searching for a green circle amongst red ones and inefficient searches (more difficult searches) i.e. target distractor needs to be determined based on local features, for example, N among M’s, also conjunction searches, when the target and distractors have to be discriminated by two or more features i.e. search for orientation colour of a target against distractors with similar feature; both the serial and parallel search is in these scenarios, result in the same function over time, in that it mean RT’s cannot distinguish between parallel and serial searches (Narbutas et al., 2017).

The WM capacity issue (one of the main goals of this current research is to measure this) is a crucial one in the comparison of serial to parallel models. However quite astutely Townsend notes in a serial search model, by definition is a limited capacity model because attention and effort is devoted to one item at a time, and since parallel models can produce indistinguishable RT slopes from serial, perhaps this renders efforts to differentiate between the two types of models moot (Townsend, 1990; Townsend & Fifić, 2004; Williams, Eidels, &
Townsend, 2014). The current study assumes Halford’s (2005) stance in that the HGRCT is a measure of parallel processing.

Arguably, the most influential serial search theory is guided search (Wolfe, 1998) and suggest a two-stage process. First is a parallel process stage and uses saliency maps of the visual scene. These maps focus on how distinct properties of the scene are compared to other items properties (more on how this influences the current study in the discussion section see Chapter 12). The saliency maps guide the serial search, the second of the processes. It is suggested this model explains how efficient searches operate as features that are highly salient and are easier to find as opposed to inefficient searches were saliency is low, and where search is not guided and becomes random (Wolfe & Cave, 1999).

On the other side of the coin, the Biased Competition Theory (Desimone & Duncan, 1995) is one of the most influential of the parallel search theories. It is argued that information processes in the visual field are done through the ventral stream; the ‘what’ system responsible for object recognition, and the dorsal stream; the ‘where’ system responsible for the projection of the object to the relevant visual systems (Ungerleider & Haxby, 1994). Participants struggle with multiple objects presented simultaneously as they have to deal with large amounts of information, the perceptual stimulus is then prioritised to make for a more efficient search (Desimone & Duncan, 1995). Prioritisation is done through the model’s five main rules (1) objects presented at the same time will compete for resources at a neural level, so the competition begins. (2) stimuli that activate neurons in the same cortex or moreover, the same area of the cortex will be in a more intense battle for resources, competition increases. (3) competitive interactions can influence bias in one stimulus over another due to the feedback bias. An example of feedback bias could be top-down feedback; when one stimulus could be
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more relevant to the situation, i.e. if one was asked to match a round shape to test an array of shapes, square shapes would lose the limited attentional resource battle to other round shapes. Another example of feedback bias is bottom-up; refers to the stimuli structure form its basic components upwards: one stimulus could stand out due to novelty (4) feedback bias is not purely spatial, it can be down to features that stand out due to the relevance like colour for example (5) top-down bias is said to originate in the PFC, deriving from this brain structure (Desimone, 1998). Top-down processing is generally regarded as past experience, knowledge and expectations which influenced the sensory information required by the participant (Gaspelin & Luck, 2018).

Beck and Kastner (2009) state Bias Competition Theory consists of three basic principles (1) that there is competition for representations in the visual system from your own perspective (2) this competition is influenced by bottom-up or top-down processing (3) and this competition is integrated across brain systems. A basic example given is observing a crowd to find a particular face. First, not all of the faces can be processed at the same time, second, there is selectivity, one can filter out all of the necessary information to focus on a single face. An internal neural template takes care of matching the stimulus, this template is integrated across brain systems (Beck & Kastner, 2009). Again this current study assumes Halford et al’s position that there RC paradigm has controlled for serial processing and acknowledges that competition bias exists for stimulus, at not just the design stage of a task, but an inherent biological level.
3.4 Motor Working Memory Debate

WM is not restricted to cognitive tasks, the practising of motor skills can lead to demands on a limited WM, they include; the correction of errors to improve a skill, complex sequence of movements such as dancing, or the implementation of instructions from a coach. However, the influence of motor skills acquisition and WM remains unsubstantiated (Buszard et al., 2017).

The process of coordination both on a cognitive task and a motor task is known as dual tasking, as is claimed that one negatively affects the other in terms of task completion time and accuracy (Schott & Klotzbier, 2018), this is known as cognitive-motor interference and is included in the underpinning of limitations in cognitive abilities (Watanabe & Funahashi, 2014). Cognitive motor interference has been studied with participants while walking (Al-Yahya et al., 2011) as a result of having MS (Learmonth, Pilutti, & Motl, 2015; Postigo-Alonso et al., 2018) stroke victims (Dennis et al., 2009; X.-Q. Wang et al., 2015) and interference with daily tasks such as crossing the street (Janouch et al., 2018), all suggesting a drain on cognitive resources while engaging in a motor task.

Bolstering cognitive-motor interference Kiyonaga, Dowd and Egner (2017) suggest that recent findings show that visual WM relies on the same attentional resources and sensory substrates as attending perceptually to the external visual stimuli, they claim neuroimaging studies has shown activation in the same cortices resulting in a subsequent trade-off between internalised (i.e. WM demands,) and external (visual, perceptual) attentional demands. Therefore, it is important to note that during the tasks in the current study, motor WM operationalised in this case by a button press on the computer keyboard may be adding load to the auditory, visual and cognitive WM load.
The current study involves response via keyboard (see methods Chapter 8). According to De Kleine and Van der Lubbe (2011), the execution of motor sequences becomes faster with practice. In their study key button presses in go/no-go task were examined. Results show that familiar sequences were executed faster than unfamiliar sequences, in turn lessening the demand in visual WM. In relation to the current study, button response was kept the same (made familiar) across experiments i.e. visual, auditory and cognitive. In addition, practice was given (see methodology Chapter 8) before the experiment proper, in line with the research cited above, the practice sessions should have controlled for the unfamiliarity for the participant at the beginning of each experiment when responding via button press at the keyboard computer, which in turn should have lessened the WM load in the corresponding tasks, and not affected, or at the very least lessened the effect of the result of the outcome variable.

Before moving on to how RC became an integral part of current WM models, this current research acknowledges the issues related to the serial vs parallel processing and motor WM debates, and realises the capacity to adequately test and subsequently analyse for issues related to these debates is beyond the scope of this current study

3.5 How RC Became Part of Contemporary WM Models

The emergence of theories of Relational Integration (the process of RC) in recent literature aids in underpinning its significance. Oberauer (2005a) suggests that WM is a system of forming temporary relational schemes or binding. Upon inquiring into the finite ability for binding, Oberauer suggests the ability to memorise these bindings are age-dependent, and numerous studies (Hedden & Park, 2003; Henkel, Johnson, & De Leonardis, 1998) have demonstrated this with older adults.
Based upon the inquiries of tasks burdens of various indicators of WM capacity and reasoning skills, Oberauer argues in all of these tasks, the establishment and maintenance of bindings in WM could be a mutual limiting factor. Oberauer, Süß, Wilhelm and Wittmann (2008) bolster this claim by positing that the primary goal of WM is to integrate information, and from there create new representations based on this information. Oberaur et al., conclude that the capacity of the building and the subsequent maintenance of these bindings is the common denominator between engaging in complex reasoning and problem-solving tasks and utilising WM.

3.6 Relational Integration/Complexity and the Development of Theories in Working Memory

Upon charting the evolution of WM, one can see the significance of RC is further supported, especially with the body of literature that surrounds WM capacity. As discussed, the concept of an STM store was replaced with WM and allocated four components in the central executive, the phonological loop, visuospatial sketchpad and the episodic buffer (Baddeley & Hitch, 1974; Bower, 1974). As part of the central executive comes executive processes or functions, which have been identified namely as inhibition, updating and shifting (Miyake et al., 2000), these processes reside in the Prefrontal Cortex (PFC) (Best & Miller, 2010)

It is claimed an intact PFC is required for WM (fuster, 2015). The PFC is situated directly behind the eyes and the forehead, it is responsible and said to dictate our personality, It is claimed to have a neural representation of our goals, competition or distraction is fended off within the PFC by competing goals and alternate values (Grawe, 2007). Probably the most
famous case in relation to discovering the role of the PFC comes from a patient with brain damage, Phineas Cage. Described as a young reflective, determined and goal orientated man. Following a construction accident, a metal rod pierced straight through his left PFC. Cage survived, and changed into what was described as a selfish, rude and abstinent man. His well-balanced mind was replaced with a childless intellectual capacity different from before the accident (Ratiu, Talos, Haker, Lieberman, & Everett, 2004).

Over time the PFC has been divided into functionally distinct regions: the dorsolateral PFC, the orbitofrontal cortex and the ventral medial PFC. The dorsolateral PFC is the topmost part of the PFC and is responsible for higher-order cognition like decision-making and risk evaluation (Luo, Ye, Zheng, Chen, & Huang, 2017) strategy (Yamagishi et al., 2016) causal role of stress regulation in WM tasks (Bogdanov & Schwabe, 2016) to name a few.

The orbitofrontal cortex is known to also have a role in cognitive processing, but because of the close connection to the limbic system is said to claim a more emotional role in decision-making, thought of like a convergence of sensory and emotional information (Schore, 2014).

The ventral medial PFC is responsible for piecing together the big picture in relation to decision-making from various brain structures including: olfactory systems (Zald & Andreotti, 2010), amygdala (Bechara, Damasio, Damasio, & Lee, 1999) temporal lobes (Verfaellie, Wank, Reid, Race, & Keane, 2019) and thalamus (Motzkin, Philippi, Wolf, Baskaya, & Koenigs, 2015).

The EEG’s spatial resolution limitation (see chapter 4 and limitation section in Chapter 12) does not allow for individual sections of the PFC to be compared, thus the review is abrupt.
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(for an in-depth view of the role of the PFC (see Fuster, 2008, 2015). More particular areas related to WM have been revealed within the PFC. Participants engaged in tasks that directly taxed this triad of executive processes using Positron Emission Tomography (PET). This imagining technique was used to highlight which brain areas were activated in each of these executive processes, and these activations then compared. As a result of this, it was revealed that each executive process had a corresponding and different area within (PFC). Moreover, all processes showed activation connected with selective attention (right intraparietal sulcus), switching and integration (left superior parietal sulcus), and monitoring and temporal organisation (lateral pre-frontal cortex) (Collette et al., 2005).

The general view for many years was that the PFC stored task relevant information in WM, recently this view has been challenged in that the role of the PFC is to actively attend to sensory information, rather than just store it. FMRI studies, an imaging technique with high spatial resolution has claimed the same sensory neurons are activated with sensory information in WM and represented in the sensory environment in the first instance (Lara & Wallis, 2015). Once again, and important to this study, and because of the poor spatial resolution within the EEG recording environment, as opposed to the PET or FMRI, the current study is unable to tackle the issue of which area of the PFC is responsible for storing or attending to information. Therefore, this study aligns itself with Fuster’s (2008) basic premise, that an intact PFC is needed for WM tasks, and focusses on WM capacity based on EEG electrodes placed over major lobes of the brain rather than precise locations of WM processes.

Cowan (1988) proposed the Embedded Process Model (Figure 9) and here WM is described as keeping mental representations in an accessible state. This model operates in a
two-tier system; one tier houses the ‘focus of attention’ this is a part of one’s conscious awareness and is said to hold up to four pieces/chunks of information. The other tier is limited by time and is called ‘active memory’, which can, for example, activate LTM and is unlimited in that regard. The central executive is tasked with controlling the information pathway to the focus of attention, described as automatic recruitment of attention mechanism directs information straight to active memory, with the ability to bypass the focus of attention. Additionally, it would appear that Baddeley’s model dealt with information maintenance using the episodic buffer, this is taken care of with activation of representation in LTM, according to Cowan (Holyoak & Morrison, 2005).

Figure 9  Shows Cowan’s Embedded Process Model, complete with the Focus of Attention, LTM and Activated STM components, as well as a Central Executive. From Working memory, by Baddeley, A. (2010). Current Biology, 20(4), R136–R140. https://doi.org/10.1016/J.CUB.2009.12.014
An addition of Cowan’s model the ‘Working Memory Concentric Model’ is proposed. Three functional areas make up this model: the limitless capacity activated part of LTM, the region of direct access (Cowan’s focus of attention), again adhering to the claim of the ability to hold four items/chunks of information, and finally the focus of attention, which holds and hones in on one item/chunk of information (Oberauer, 2002).

Further to this, a multi-domain approach is posited about WM. One of these domains is content related, dealing with language, visuospatial and numerical information, aligning itself with Cowan's domain-specific slave systems. The other domain is functionally linked and is claimed to have three categories which encompass most of the functions carried out by WM namely: simultaneous processing and storage, supervision and coordination (Oberauer, Suss, Wilhelm & Wittman, 2003).

Oberauer et al., posit that the simultaneous storage and processing function was the principal definition of WM as a whole. This notion came from efforts to distinguish WM from the STS by addition of a processing element. The supervision function similarly oversaw executive processes comprising of monitoring and selecting activations and procedures (selecting relevant and disregarding irrelevant ones) of ongoing cognitive processes and actions. Most relevant to RI and RC is the third category proposed which is the coordination of information elements into structures, the idea being that WM assists in building these new relations amongst elements, and to integrate these relations into structures, i.e. to make them coherent cognitions. In the opinion of Oberauer (2002) this is prominent in the research by Halford et al., (1998).
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Further revisions by Oberauer et al., (2008) of their WM model, stemming from their research into predictors of intelligence and WM capacity, propose that WM contains three major cognitive functions: concurrent storage and processing (refers in general to the accepted definition of WM capacity), Relational Integration (refers in general to the accepted definition of coordination) and supervision (which refers to in general the accepted processes associated with executive processes). Results from Oberauer’s research show that evidence supports the notion that mutual sources of variance of WM capacity and reasoning abilities stem from the ability to form and maintain structural relations i.e. Relational Integration (RI) (Oberauer et al., 2008)

3.7 Implications of Relational Integration

Regarding reasoning and problem solving the implications of RI are far-reaching (Chuderski, 2014; Dauvier, Bailleux, & Perret, 2014; Parkin, Hellyer, Leech, & Hampshire, 2015). WM has been described as a workspace where retrieval representations are created, in which semantic memory plays an important role in the interfacing between analytical and non-analytical processes in higher cognition (Halford, Wilson, & Phillips, 2010) directly associated with transitive inference, which is said to underpin reasoning by analogy (Andrews & Bohadana, 2018). Analogical reasoning is a vital part of higher cognition, and one that demonstrates the properties, i.e. mapping and retrieval of relational processes. Additionally, in dealing in relational knowledge reasoning by analogy utilises structure consistent mapping, compositionality and systematicity, more simply put, these are tools needed to overlay information onto existing schemas (Halford, Wilson & Phillips, 2010). A schema is a pre-planned set of concepts, which usually contain social information. Schemas classify knowledge
for example into a chain of events, situations, existing knowledge, relationships etc (Ensar, 2015).

The importance of relational knowledge is acknowledged in cognitive linguistics (Carriedo et al., 2016; Gentner, 2016). Relational representations components identified in linguistics are structural alignment (the learning of meanings and grammar), attainment of verbs (framing or slotting in) (Halford et al., 2010). Another equally important cognitive process is categorisation, which contains many properties of RI (Halford et al., 2010), for example, parenthood is often categorised by its relationship to its offspring and vice versa. Yet another cognitive process is planning which is contingent on creating sequences of actions or operations that alter the current state into a goal state while the concurrent action is performed on representations (Halford et al., 2010). As part of planning another important cognitive process is a strategy, employing numerous elements and their relations to form templates, all in a bid to navigate to the goal state (Halford et al., 2010).
Chapter 4 The Electroencephalogram

4.1 A Typical EEG Setup

Hans Berger (1929) discovered that he could place an electrode on a participant's head, measure the electrical activity of the human brain from the scalp, amplify that signal, and plot the change in voltage over time (see Figure 10 on the next page, a modern day EEG setup). This recording of electrical activity is known as the electroencephalogram (EEG) (Luck, 2005). The EEG is a very coarse measure of electrical activity associated with cognitive and perceptual tasks (even just the presentation of stimuli elicits an EEG response), but through averaging techniques, and more complicated techniques (arguably the technique for this current study) it is possible to extract which component of the EEG is associated with certain stimuli at a certain time, and then make comparisons (Luck & Kappenman, 2012).
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Figure 10 Typical modern day EEG setup. Usually in a specially designed and electronically shielded laboratory. The experimenter sets up the EEG cap on the participants head, which collects the electrical recordings from 64 electrodes, it then sends the signal to the headbox amplifier/digitiser to the data acquisition PC which stores the EEG recording for analyses later on. At the start of the experiment the experimenter loads the task onto the stimulus presentation PC, which has a video splitter to duplicate the screen for the participant to interact with the task via the screen in the chamber. The response is given by the participant via response box, mouse, keyboard etc. Codes are sent between the stimulus presentation PC and the data acquisition PC, each code represents each stimulus, codes are digitally marked on the EEG, the researcher can recognise each stimulus by its code, then conduct analyses on the time the marker was sent, or certain times before and after (epochs) and analyse the EEG around the marker. From The Oxford Handbook of Event-Related Potential Components, by Luck, S. J., & Kappenman, E. S. (2012). New York: Oxford University Press.

The following looks at an example of handling an EEG epoch (a predefined length of time of the EEG, usually in milliseconds) and then averaging in an Event Related Potential
(ERP) experiment, ERP is used in this example as it is a very popular technique. The purpose is to gain an overview of the process before a detailed explanation of the process in this current study is given. Once the EEG is captured by the data acquisition computer the process of averaging out the data can begin. Below is an example of an oddball paradigm task, in which the aim is to present participants which a serious of Xs and O’s. For the sake of simplicity of this explanation Figure 11 (on the next page) shows what type of EEG waveform is extracted after averaging the signal from many epochs related to each the X and the O, i.e. different stimuli, from one electrode site. There are usually 64 electrodes used in modern EEG research. The subsequent analysis is an ERP analysis, used in this example, but not in the current study.
Figure 11 shows an example of averaging from an epoch of the EEG. The overall aim here is to average and result in a pertinent waveform. The EEG contains the signal of interest plus noise. The researcher finds this signal by averaging over many trials, the noise is eventually averaging out, leaving a waveform. The waveform has distinct figures, peaks and troughs which have been named (N1, P1, P3 etc.) which then can be compared to the averaged trials and existing data sources. The figure above, in the top panel, shows EEG recorded from a single electrode site, in this case, Pz, it shows how epochs of the EEG have sectioned out at the time of the onset of the Xs and O’s. These sections are based on the marker codes sent for either the X or the O. On the left-hand side of the panel below it shows four of the X trials and the EEG associated with them, and two of the O trials and the EEG associated with them. The right-hand panel shows the average of the waveforms for the X and the O. From An introduction to the event-related potential technique, by by Luck, S. J., (2014), cambridge: MIT Press.
The current study is concerned with sending marker codes, averaging and epochs just as in the example set out in the above. The difference is the main concern is not averaging the epoch to extract a pertinent waveform, rather its to average an epoch in a certain frequency band to obtain an average voltage (exact design of the experiments are described in chapter 7). Firstly the preprocessing stage is described.

4.2 Preprocessing of EEG data

Traditionally, the first part of the analysis of the EEG data is signal averaging. In this case, the averaging of selected time segments know as epochs, which in this case are 1000ms before the response in all of the tasks, the dependent variable is MilliVolts. Each epoch is averaged under its relevant condition, these independents variables are described in full see chapter 9.

There are several types of artefacts that can contaminate the EEG recording, stemming from blinking facial movement, eye potentials etc. The two main approaches used to deal with this are: one can detect large artefacts on a trial-by-trial basis and simply exclude manually them from the averaging process (artefact rejection) and the other is artefact correction. An example of artefact correction dealing with eye movements is when eyes blink or move voltages are created which will transmit to the scalp electrodes, one way to correct for them is to calculate this propagation factor and omit it from the averaging process (see Luck, 2005). In the EEG frequency range, the mingling of brain fields at the scalp electrodes is basically linear. The skull lessens brain potentials and defined as the time from stimulus onset to the point of maximum positive amplitude within this same epoch (Luck 2005).
Simply rejecting EEG epochs contaminated with artefacts results in the loss of a considerable amount of data. Often, regression is used in the frequency or time realm and is performed simultaneously on both the EEG and the Electrooculographic recordings, but the latter also contains brain activity, so regressing these out leads to loss of data. Also, because many sources of noise including muscle, electrode and so on don’t have a reference channel, typical regression methods cannot be used to remove them (Luck & Kappenman, 2012; Luck, 2005).

Independent Component Analysis (ICA) attempts to tell the researcher what independent components make up the data collected (Makeig, Jung, Bell, Ghahremani, & Sejnowski, 1997), and has been shown to be more preferable and a statistically stronger method (Jung, Makeig, Humphries, Lee, Mckeown, Iragui & Sejnowski, 2000). The ICA method has been used in this current study. For a review of artefact rejection methods and other instances of data contamination including technical aspects like line noise from existing powerlines in the room where the recordings take place, biological artefacts including muscular, cardiac, eyeblink and eye movement see Kanoga and Mitsukura (2017) and Figure 12.
Figure 12 depicts the observed raw EEG signal (far right), in the panels on the left starting from the top one can see what an observed EEG signal is comprised of; the EEG signal; the signal of interest, then artefacts which is noise or unwanted signals which can comprise of eye movements, eye blinks, muscular and cardiac noise (diagram is colour coded). The whole idea is to capture the EEG signal and subtract the added noise. It is worth noting then; some or all of this types of noise can be present, and through flat out rejection of parts of the EEG, mathematical algorithms such as the ICA and averaging, an average representation of EEG signal of interest will present itself. From Review of Artifact Rejection Methods for Electroencephalographic Systems, by Kanoga, S., & Mitsukura, Y. (2017). In Electroencephalography. InTech. https://doi.org/10.5772/68023.

According to Onton and Makeig (2006) ICA has been likened to the ‘cocktail party effect’ when a partygoer is trying to focus in on one conversation in a noisy room. The EEG attempts to record spatially smeared brain singles in a problem known as a blind source separation. ICA based artefact correction attempts to separate and remove artefacts from the EEG by employing linear decomposition. It assumes that (1) the time series recorded on the scalp are constant spatial mixtures of temporally independent cerebral artefacts, (2) the potentials arising from different parts of the brain, scalp and body is linear at the electrodes, and (3) that transmission delays from these sources the electrodes are insignificant. These assumptions are reasonable providing enough data is imputed (EEG software like Brainvison will tell the researcher if not). ICA uses spatial filters derived by the algorithm so doesn’t
require a reference channel for each source. When the independent time courses of the different artefact and brain signals are extracted from the data, artefact corrected EEG signals can be established by eliminating the contributions of the artifactual sources. Each independent component (IC) is recognised with an activity time course (its 'activation') and a set of relative strengths of its projections (by volume conduction) to the recording electrodes (its 'scalp map'). Likening IC activities across participants, demands clustering of similar IC’s based on mutual dynamic and/or spatial features, displayed on a two-dimensional digital image (Makeig, Jung, Bell, Ghahremani, & Sejnowski, 1997; Onton & Makeig, 2006)

4.3. Capturing Neural Oscillations, the Basics.

The continuous (also called spontaneous) EEG signal is composed of oscillations in various frequencies, which are assumed to reflect information representation and transfer within and across neuronal assemblies (Klimesch, Schack, & Sauseng, 2005). This oscillatory frequency information has long been neglected as most of the neurocognitive EEG research focused on ERP indices. ERP’s reflect brain responses to certain events and are calculated by averaging the continuous EEG signal over many trials, so that the oscillatory background activity, plus noise, the latter is cancelled out in the pre-processing stages. In the past two decades, however, the growing interest into how functional networks in the brain are formed and interact with each other has moved the dynamics of brain oscillations again into the focus of attention (Antonenko, 2010). The current study focusses on these oscillations.

Traditionally, brain waves fall into four main categories; Delta waves (measure below 4 Hz), Theta waves (4-7 Hz), Alpha waves (8-13 Hz), and Beta waves (13-38 Hz). Additional categories have been added, Sensory Motor Rhythm (SMR) ranging around the 14 Hz mark,
and Gamma waves (39-100 Hz) (Cohen, 2014). After the preprocessing of the data, the EEG epochs are selected (details of which are in chapter 9). The next part of the process is to use a mathematical equation known as the Fourier transform, its role to break down complex EEG signals in less complex sine waves, and then displayed digitally in a spectral feature (Cohen, 2014) (Figure 13). The reason why the Fourier transform is carried out is that the complex signal can be compared. It is difficult to compare a complex signal to another complex signal, but when it is broken down into its component parts (Figure 14), comparisons can be made against these components (Cohen, 2014). The components in this case are the various frequency bands named above. The continuous EEG signal is composed of oscillations in various frequencies (derived from the Fourier transform), which are assumed to echo information representation and transfer, within and across neuronal assemblies (Klimesch et al., 2005). These oscillations are characterised by their frequency, amplitude and phase, which can be extracted from the EEG recording using a time-frequency analysis (Cohen, 2014).

The time-frequency analysis comes from: the time domain feature, utilised by the time stamping of the stimulus from the presentation PC to the EEG amplifier, in which the researcher will be able to calculate the keyboard button response from the participant after the stimulus is presented (Roach & Mathalon, 2008). Frequency refers to the number of occurrences of a repeating event per unit of time, as indexed by the EEG recording (Luck, 2005). The amplitude is the strength of the electric potential, more specifically the measure of its change over a single period. The phase feature refers to the sinusoidal utility that is the mathematical curve that indicates a smooth repetitive oscillation (Cohen, 2014). An oscillation in this sense is recorded by the EEG and can be defined as the regular variation in magnitude about a central point, especially that of an eclectic current or voltage, in which the EEG is recording (Roach & Mathalon, 2008).
Figure 13 shows the result of a Fourier analysis which decomposes a complex EEG signal into less complex sine waves, these sine waves based on their amplitude can then be assigned into their corresponding frequency bands.

Figure 14 an example of the spectral feature of various frequency bands derived from a Fourier transform. It shows the amplitude of the delta, theta, alpha, beta and gamma frequency bands. Subsequent analyses of frequencies bands can be conducted by extracting the band of interest. In this current study, it will be theta and alpha the reasons for the selection of these two bands is described in depth later.
Chapter 5. Existing Relational Complexity Tasks, and Neuroimaging techniques that explore them

5.1 General Purpose of Neuro Imagining Techniques
This section looks at existing RC tasks in the visual, auditory and cognitive domains. Moreover, it will look at what neuroimaging/recording techniques were used and what these techniques contributed. In addition, it will be shown that attempts were made to spatially segregate or localise certain processes related to RC and WM using these techniques. These studies will give a foundation to the current approach, which has attempted to acquire physiological data in a bid to isolate visual, auditory and cognitive RC processes using EEG, by examining neural oscillations. Typically, ERP studies are plentiful in this area, as opposed to the examinations of oscillations. ERP studies, other approaches and examples of existing studies which have attempted to examine RC within the visual, auditory and cognitive modalities are given.

5.2 Visual RC and Neuroimaging Studies
According to Agam and Sekuler (2007) at a physiological level, little is known about the mechanisms of WM and which WMC rely on. On a theoretical level, there would appear to be in general, two types of models which attempt to assess the interactions between perception and memory. These are (1) the embedded model; the idea that WM is a specialised set of buffers utilised in the event of storing information (see Baddeley, 1992; Baddeley, 2000) under the command of the central executive. Limited capacity here is discussed in the terms of a limited amount of synchronisation and time decay, with the PFC being responsible for this (Fuster, 2008). An alternative view is to treat WM as an ‘emergent property’ (Dempere-Marco, Melcher, & Deco, 2012; Postle, 2006) which ties together existing neural mechanisms with specialised roles i.e. sensory perception and LTM activation. In the case of visual stimuli, it is
proposed that when the stimuli disappear from sight, VWM is achieved by prolonged activation in the service of attention, of the same occipital and parietal regions, which are thought to mediate visual perception (Agam & Sekuler, 2007). In either case with the embedded and emergent models, the PFC it seems does not provide the neural substrate for memory storage, but rather it mediates for attention (Baddeley, 1992; Baddeley, 2000).

Contrary to this, more recent studies follow up and ask whether PFC stores past sensory information or is it actively dealing with rehearsal or other aids (Eriksson, Vogel, Lansner, Bergström, & Nyberg, 2015). The results of their analysis suggest synchronised gamma oscillations support the latter, an active storage component in the PFC (Polania, Paulus, & Nitsche, 2011).

ERP Studies have shown that most people can hold on average, four active representations in VWM (Cowan, 2001, 1998, 2005). ERP’s examining the maintenance of information in WM use the Negative Slow Wave (NSW) component, and for example, in a study looking at visuospatial and verbal stimuli, the amplitude of this wave was seen to increase as memory load increased (Ruchkin, Canoune, Johnson, & Ritter, 1995; Ruchkin, Johnson Jr., Canoune, & Ritter, 1990). Furthermore, the NSW was maximal at the parietal temporal sites for the visuospatial material and the frontal sites for verbal material, this finding of scalp topography differences according to the type of information being held in VWM has been replicated for example; a more posterior distribution for spatial memory tasks and a more frontal for object memory (Mecklinger & Müller, 1996). Further to this, trials in which a large NSW was observed during the retention period resulted in participants successfully remembering the information when tested (Li, Chan, & Luo, 2010; Luck & Kappenman, 2012); these findings suggest that this activity (NSW) is important in WM tasks.
Contralateral Delay Activity Component (CDA) attempts to measure the current contents of WM (Luria, Balaban, Awh, & Vogel, 2016). It is a phenomenon seen in EEG recordings when people perform visual WM tasks, for example when they look at pictures presented on a screen, in various locations and need to remember what they have seen for some short period (Woodman, 2010). What happens in this situation is that a large negative electrical wave is seen over the opposite (contralateral) side of the head relative to the side where the picture is shown, lasting as long as the picture needs to be held in mind (Woodman, 2010).

Studies using ERP techniques have provided a useful way of measuring delay activity in WM tasks. One reason for this may be that due to the high temporal resolution of Event Related Potentials (ERP’s) which allows for the isolation of activity during the retention period of WM tasks (Woodman, 2010), which in turn permits gleaning of information about the timing of brain processes recruited for WM tasks. ERP’s provide valuable information about the fast brain dynamics subservient to cognitive functions such as attention and WM (Barceló, 2003).

Luria, Balaban, Awh and Vogel (2016) combine NSW, ERP and CDA techniques and observe a large NSW during the retention period in the to be remembered information in a visual search task. The same task demonstrated a relationship between the set size of the search array and the resting amplitude of the CDA. Similarly, the maintaining of the current focus of WM also is reflected by CDA amplitudes (Berggren & Eimer, 2016).

5.3 The interplay between WM, visual perception and RC

Phillips, Takeda and Singh (2012) acknowledge the need to integrate many sources of information to deal with complex cognitive tasks and relate their study to visual search (see chapter 1 for examples of visual search), moreover, feature search incorporating RC. As a
reminder, visual search can be described as a perceptual task requiring attention that usually relies on an active scan of the environment for a particular object or feature (Pashler, 2016), known as the target in many experimental paradigms, among other objects or features, generally referred to as distractors (Horowitz & Wolfe, 1998; Wolfe & Horowitz, 2017). Feature search can be described as ‘disjunctive’ or ‘efficient search’ as part of a parallel process. Disjunctive search describes when the properties of the target and the distractors are outstandingly different in so far as shape, size, colour etc. Conjunctive search, on the other hand, is when the target and the distractors share similarities in more than one visual search, e.g. size, colour, shape etc. (Treisman & Gelade, 1980).

5.4. Example of an Existing Visual RC task

In their study Philips et al., (2012) participants were tasked with resolving three search display arity conditions; (1) unary, (2) binary, (3) ternary, where the targets and distractors in each display where set uniquely identifiable features (one, two, three respectively). As an example, the display set for the binary condition was four colour, orientation and frequency triples (Red, 90, 0-gap)–target, (red 45, 0-gap), (blue, 90, 0-gap), and (blue, 45, 0-gap)–non-targets.

For the unary, binary and ternary conditions, there were three-dimension conditions associated with the colour (C), orientation (O) and frequency (F) feature dimension(s) that uniquely identified the target. Examples of all arity-dimension conditions labelled 1C, 1O, 1F, 2CO, 2CF, 2OF, and 3A are shown in Figure 15. In total, there were seven conditions (see Figure 16 for trial layout).
Figure 15, Example display sets for each arity-dimension condition. In each case, the target is the (red, 90, 0-gap) object. The procedure was as follows (see figure 16); each trial had four periods in the following order: (1) fixation that lasted 1500ms, participants had to stare at a point in the middle of the screen. (2) Target display for 1000ms, (3) delay, 1500ms, similar screen to the 1st periods (4) search display, 2500ms or until a key was pressed whichever came first. During the search display participants had to identify the target location in one of the four quadrants of the screen (Figure 15) and press the corresponding pre-allocated key on the keyboard which they would have had a chance to practice before recording started.


Phillips et al., (2012) discuss whether frontal or parietal synchrony is involved in the integration of information, and claim further investigation is required. They do however posit that cognition might rely on a complex cognitive system to support binding within the PFC (see Oberauer, 2009), and the parietal synchrony is involved in feature integration.

5.5. Limitations of this task

Philip’s et al., (2012) acknowledge limitations in their task. Firstly, they claim their task design was influenced by category theory. This theory brings into question the reliability of their task by way of a constant. A constant is said to reduce task difficulty. For example, keeping the same target in mind as above; red, 90 degrees and 0 gaps, in Figure 15’s top left-hand panel, a constant in all conditions is the rectangular shape, this lessens load while searching, one does not have to deal with other shapes. In binary condition the rectangular shape is constant, the colour is held as a constant (red) and so it lessens the load to look for matching orientation. In a ternary condition the shape, colour and orientation are held constant thus lessening the load to search only for the feature dimension, o-gap in this example (this refers to feature/conjunction searches, discussed in chapter 3.2 and chapter 12 conclusion).
5.6. Proposed new Visual RC task

This proposed research plans to modify and extend the aforementioned work by Philip’s et al., (2012) in order to create a visual working memory task that extends closer to the proposed processing capacity of four variables to be processed in parallel. In Philip’s et al., (2012) study they employed three dimensions to the target namely; colour, orientation and frequency, equating to a ternary relation. This research adds another layer of complexity; hatch/pattern. The introduction of this fourth variable will allow for the creation of a quaternary target in the visual search. An example of a binary target would be for the participant to hold in WM a target based on its colour/orientation, a ternary target based on its colour/orientation/feature dimension and a quaternary target based on its colour/orientation/feature dimension/hatch.

5.7. Auditory RC and Neuroimaging Studies

Research findings suggest that Auditory Working Memory (AWM) relies on the interplay between attentional and sensory neural systems. EEG provides sufficient temporal resolution to distinguish between the encoding, maintenance and retrieval processes in AWM (one of the main advantages of the EEG over MRI for example). Research on the mental operations of stored sounds appears to be limited, with the majority focused on the maintenance aspect of AWM. WM operations include selection of one stored item over the other, updating the content of WM (referred to as the focus of attention earlier) and inhibiting distractors (Bledowski, Kaiser, & Rahm, 2010). Frontoparietal activation is thought to occur when engaging shift of attention of objects held in WM, and temporal and parietal activations help distinguish between spatial and category related cues/targets, while updating of AWM and
mental transformation are thought to display increased activation in frontal and temporal theta power and increased frontal-temporal theta phase synchrony (Kawasaki, Kitajo, & Yamaguchi, 2010).

There are some studies which evidence differences in specific tasks in relation to ERP response during the encoding phase of AWM tasks. For example, Anourova et al., (2001) investigated recordings during auditory location and pitch match to sample tasks to see if the same type of potential was evoked. Results showed in the match condition the N1 latency was shorter and the amplitude larger in the location task compared to the pitch, in addition in relation to neural substrates loci, the N1 elicited during the match condition in a location more medially (middle) to the origin of the N1 component than that of the pitch task. This indicates partial segregation of the neuronal mechanisms involved in the processing of spatial versus non-spatial auditory information. Most of the studies in this area seem to focus on the short-term retention of acoustic information, reflected by sustained ERP deflections where topography varies after the onset of task-relevant features. An example being frontal central NSW which reflects topographical distinction resulting from posterior activations (Guimond et al., 2011). The topographical differences between the location processing and sound frequency in AWM marry up to the model of ERP evidence of ventral and dorsal streams being involved in different components of AWM proposed by Kaiser and Lutzenberger (2003), and the evidence provided for sound location, which appears to be handled by more posterior, parietal-occipitotemporal regions (Alain, Arnott, Hevenor, Graham, & Grady, 2001).

5.8. The interplay between WM, auditory perception and RC

There are not many studies, as far as this researcher can tell that investigate auditory RC directly, one study did, albeit with children and a lower level of arity. Stevens and Gallagher (2004) investigated RC and relational shift in children. Relational shift refers to the change in
the ability in developing children relating to analogical reasoning, where the child begins to focus less on the perceived similarities, and more on RC when engaging in tasks.

5.9 Example of an existing RC Auditory task
In order to achieve this, pitch and duration (temporal) values were utilised to create two note perceptually similar (e.g. the melodic contour, the patterns of ups and downs in the pitch) sequences, this mimics a unary relation, and a four-note relationally similar sequence, which conforms to a binary relation. The participant then had to discriminate between a combination of tone and frequency patterns, according to a rule. An example being, was the first note lower than the second note in n trials? (Stevens et al., 2004).

5.10. Limitations of task
Stevens et al., (2004) mention implementing auditory WM tasks at ternary and quaternary levels and posit that these tasks were not included in their task for three reasons (1); ternary tasks often include transitive inference tasks, which it is claimed are controversial in current literature regarding lineage in relation to child development. As this research does not intend to tackle development research, it should not be a problem, from a theoretical point of view. (2) Ternary tasks can be decomposed into two binary tasks and be solved at this level, this refers to the aforementioned segmentation, a cognitive shortcut often employed, which this proposed study will attempt to control for by adhering to Halfords principles and designing tasks where at all possible, the unary needs to be solved before the binary before the ternary etc. (3) It is suggested that when working with auditory stimuli that RC can become confounded with stimuli and task length, again relevant to this study, to control for this adherence to existing EEG studies regarding task length, in the area will be observed.
5.11. Proposed RC Auditory Task
In this current research, auditory tasks will be constructed that are analogous with visual tasks in that they exhibit perceptual load and require WM to complete in terms of RC. In order to achieve Relational Complexity, it is proposed to use timbre/pitch/amplitude and noise values to create a musical note. This allows for the creation of a quaternary target stimulus which participants would be expected to match in a proceeding array of serially presented auditory stimulus. This extends upon the aforementioned study by Stevens et al., (2004) in which they created a stimulus just based on duration and pitch, thus not reaching a level of complexity which would tax a typical adult participant. In this study, an example of a binary target stimulus would be one based on the timbre/pitch, a ternary target would be timbre/pitch/amplitude, and a quaternary target would be timbre/pitch/amplitude and noise.

Apart from the aforementioned HGRCT task, there is no previous task published that specifically targets the cognitive only aspect of WM directly targeting RC. Therefore the same in-depth analysis given to visual and auditory tasks cannot be given, instead, the relationship between WM, cognition and neuroimaging studies will be observed.

5.12. Cognitive RC and neuroimaging studies
As stated, earlier Halford (2005) and associates claim that most of the research carried out in this area focus in VWM i.e. the perceptual component and not the cognitive aspect, which has been addressed. It is here this proposed research will make a major contribution. The next section will deal with research mostly from fMRI techniques, which attempt to explicitly focus on RC.

5.13. The interplay between WM, Cognition and RC
The following discusses the integration of information; referred to as Relational Integration. This cognitive process is responsible for the binding together of mental
representations into more complex assemblies (Chuderski, Andrelczyk, & Smolen, 2013), and therefore is a fundamental part of RC. fMRI was employed in a bid to locate the areas of the brain involved in high-level relational reasoning. Compared to control, the performance was assessed on a non-verbal reasoning task. Task difficulty was manipulated by the addition of distractors. The difficulty was held constant in the RC task. The results showed activation in the parietal and dorsolateral prefrontal cortex (PFC) with increased complexity/addition of distractors. Moreover, at high levels of RC, the involvement of the left anterior PFC was noted. In summation, this evidence suggests coping with general difficulty is distinct from interfering complex relations among stimuli (Chuderski et al., 2013).

In a similar vein, it is claimed that the integration of relations, which is claimed underpins cognitive complexity, relies on an intact PFC (Fuster, 2008). The capability to keep and control information relies on the PFC (Fuster, 2008). Moreover, Robin and Holyoak (1995) contend that the PFC in relation to explicit relational representations is responsible for their creation, and subsequent maintainance, which in turn guide thought and action (Gazzaniga, 1995). Activity in the frontopolar cortex is claimed to deliver an unclouded insight into the basic functional processes; this is in comparison to other parts of the PFC that may be activated (Poldrack, 2006). Further to this, it is claimed that activation in the frontopolar cortex (Broadman’s area 10) is functionally both more discriminating and less ambiguous than more posterior areas of the PFC, as it’s triggers have been shown to be dependently aroused by participants engaged in tasks that involve or depend on some sort of relational reasoning (Christoff et al., 2001; Kroger et al., 2002).
The use of pictorial analogy tasks has demonstrated that analogical reasoning is closely linked to RC (Cho, Holyoak, & Cannon, 2007). It is posited that reasoning by analogy depends heavily on RI and the resolution of interference (Cho et al., 2010). Attempts have been made to ascertain the neural basis for analogical reasoning using event-related fMRI. Participants engaged in nonverbal analogy tasks to be resolved on one of three relational dimensions. On half of the trial’s interference was introduced. Results displayed amplification in the lateral PFC including the lateral frontal pole of each hemisphere, with the need to integrate the new (from 1-3) relational dimensions (Cho et al., 2010). Activation was amplified in the lateral PFC and not in the frontal pole when interference was part of the task’s resolution. Areas were recognised in the central and inferior frontal gyri, which were exclusively related with both processes; furthermore, a fractional overlap was observed in this area for both the component processes (Cho et al., 2010).

5.14 Proposed new Cognitive Task
The task for this research will be a modified version of the Halford Graphical Relational Complexity Task (HGRCT). The task its self as it stands may not be suitable for the EEG environment. For example, the text which accompanies the graph could be potentially confusing for the participant (extensive piloting has shown this) and cause artefacts which the EEG will pick up. This study will modify the graphs to exclude the text and substitute them for practice rounds. This was operationalised in the piloting phase by creating a laminated version of each of the conditions, asking the participant to solve them with an erasable whiteboard marker. Participants practised until they were able to complete the task with ease. This training then transferred to the experimental trials, in which the graphs had to be solved without the aid of the training materials, in one’s head. Halford (2005) claims the narrative helped explain
what the task was about, this can be achieved by explaining the logic behind the task in more simple terms, and in diagram form (as above). Also, visual angle and screen resolution and other laboratory settings will be accounted for. Participant response will be recorded for speed and accuracy in relation to the time domain feature, utilised by the time stamping of the stimulus from the presentation PC to the EEG amplifier, in which the researcher will be able to calculate the keyboard button response from the participant after the stimulus is presented. In this case, the epoch recorded from the EEG will work in reverse, from the response via the keyboard back.
Chapter 6 Proposed EEG analysis

6.1. EEG Analysis Introduction

At present, it is believed that electrical activity in the brain generates at least four distinct rhythms (Delta, Theta, Alpha and Beta). Two of these oscillatory components of the continuous EEG have been reported as sensitive to task difficulty manipulations—alpha and theta (Klimesch, 1999; Klimesch et al., 2005). Klimesch et al., (2005) review the functional significance of theta and upper alpha oscillations and suggest under time-frequency analysis scrutiny, upper alpha oscillations show similar physiological reactivity as one would find with theta in WM tasks. It is postulated that when attention is focused on a stimulus, whether this is visual, auditory, tactile, or cognitive, the alpha waves routinely disappear or are significantly reduced in amplitude. This occurrence is commonly called alpha blocking but is also denoted as arousal, activation and desynchronization, as first described by Berger (Salamon & Post, 1965).

Sterman et al., (1993) analysed EEG data obtained from 15 Air Force pilots during air refuelling and landing exercises performed in an advanced technology aircraft simulator and found a progressive suppression of alpha with increasing amounts of CL. Gevins et al., (1998) examined changes in cortical activity during spatial and verbal WM tasks in eight participants and observed lower alpha activity in the difficult as compared with the easy task version.

By contrast, theta activity increased in magnitude with higher task difficulty. Similar results were reported by Gevins and Smith (2000) in a comparably large sample of 80 participants. The difficult version of a spatial WM task elicited lower alpha but higher theta activity than the easier task condition. These results suggest that alpha and theta oscillations are differentially related to task difficulty. As task difficulty increases, alpha activity decreases
(desynchronizes), whereas theta activity increases (synchronizes), which can be measured.

6.2. Event-related Desynchronization (ERD)/Synchronization (ERS)

Measurement of this synchronising/de-synchronising activity is discussed. Because brain wave behaviour varies as a function of age and volume (Niedermeyer & Silva, 2005) and individual differences (Klimesch 1999), it was proposed to analyse the changes in the EEG signal induced by a certain event or task rather than looking at the absolute power of a given frequency band. A well-established rate-of-change measure for oscillatory EEG dynamics is event-related (de-) synchronization (Pfurtscheller & Aranibar, 1977). It reflects the percentual decrease (event-related desynchronization; ERD) or increases (event-related synchronization; ERS) in-band power during a test (activation) interval compared with a baseline (reference) interval (Pfurtscheller & Lopes da Silva, 1999).

The ERD/ERS index for alpha and theta has also turned out to index different levels of task difficulty in a wide variety of tasks, ranging from motor (Pfurtscheller & Berghold, 1989) to cognitive tasks (e.g., Neubauer, Fink, & Grabner, 2006). For instance, Neubauer and Fink (2003) presented 58 participants with three one-digit numbers and asked them to indicate whether the triplet matches a specific rule or not (e.g., "Is the first digit the largest?"). They found that the amount of alpha ERD increased with higher task difficulty, even though significant differences were only observed between the easiest and the more complex task conditions. Stipacek, Grabner, Neuper, Fink and Neubauer (2003) investigated the sensitivity of alpha ERD to different memory components and increasing levels of memory load. Participants had to solve a STM task and a WM task, each with five levels of memory load. They found a linearly increasing ERD in the upper alpha band with ascending CL. ERD/ERS
index is one measure for the alpha and theta, another when looking at theta alone is absolute power of Frontal Midline Theta (FM theta).

6.3. Frontal Midline Theta

The frequency band associated the most with mental effort and WM is Theta. Originally reported in rat hippocampus during exploratory and alert behaviour (Onton, Delorme, & Makeig, 2005). It has been suggested that the coordination of WM processes, is revealed in frontal midline theta (FMT) oscillations, this region, in turn, controls other brain areas. Additionally, it has been shown that with ageing, substantial changes are shown in this frontal region (Kardos, Tóth, Boha, File, & Molnár, 2014). A study tasked with attempting to show this age-related functional connectivity, used participants who were both young and old (18-21, 60-71 years old), tasked with remembering sample stimuli, with varying WM loads, whilst recording simultaneous EEG. Results showed the retention period in WM tasks, across varying loads displayed FMT influences ability, relative to associated regions of interest (ROI’s); coupling with frontotemporal for maintenance and frontoparietal for WMC, was age-dependent (Cummins & Finnigan, 2007; Kardos et al., 2014).

A match to sample task in which WMC was manipulated by content (heavy load) and retention in WM (low load), was varied from 1-3 items. Results displayed higher FMT for the high load versus the low load versus the healthy controls (Griesmayr et al., 2014). Increase in FM theta (4-8Hz over medial frontal brain areas), as recorded by the EEG is a said to reflect an energy efficient temporal coordination system, an actual physical representation of cognitive processing (Berger, Omer, Minarik, Sterr, & Sauseng, 2014). Sustained enhanced FM theta
reflects active maintenance of information and it is claimed FMtheta alerts the need for more attentional resources. This is for example in contrast to the suppression of upper alpha (10-13 Hz) over posterior brain areas, which reflects processing of information from semantic long-term memory (LTM) (Berger, Omer, Minarik, Sterr, & Sauseng, 2014). The oscillatory correlates were examined between WM and STM and upper alpha and FM, exploiting a verbal delayed match to sample task. Participants had to either preserve a string of four consonant letters (maintenance) or re-arrange them according to alphabetical order (semantic manipulation with LTM access). An unadulterated WM manipulation condition was attempted where participants had to re-arrange the consonants backwards as presented on the screen (backwards manipulation without LTM access). It was hoped this would enable segregation of WM retention the manipulation thereof in WM. It was concluded that oscillatory activity in the upper alpha frequency does not clearly index semantic long-term memory and its application in WM. Therefore, one specific oscillatory frequency band was not identified as the interfacing mechanism between WM and semantic STM (Berger, Omer, Minarik, Sterr, & Sauseng, 2014).

6.4 FMT WM/cognitive load specifically.

On one hand it has been claimed that FMT reflects focussed attention (Rajan et al., 2018; Scarmeas et al., 2009; Weber & Doppelmayr, 2016; Wisniewski, Iyer, Thompson, & Simpson, 2018), and that little or no studies attempt to capture mental calculation processing i.e. arithmetic, subtraction etc. (Ishii et al., 2014), on the other hand, it is claimed that cognitive tasks which are complex, such as arithmetic, episodic encoding, retrieval, error processing, active monitoring and WM (Hsieh & Ranganath, 2014), the latter being the focus of this current study rely on a PFC that is well coordinated (Fuster, 2002), and that research in the area shows a convergence of evidence that Frontal Midline Theta (FMT), has an important role in the
resolution to these tasks (Gärtner, Grimm, & Bajbouj, 2015). The difficulty of knowing what the actual function of these oscillations, or more specifically what role they serve, is continuing to cause debate (Cavanagh & Frank, 2014). One of the leading approaches is that FMT firsts acknowledges the need for cognitive control to start, the impending CL is coming, then activates and triggers other regions of the brain, that are required for task resolution (Cavanagh & Frank, 2014).

An example of an investigation of other/grouping of regions of the brain being activated during task resolution comes from a study where participants engaging in a Stroop task (Hanslmayr et al., 2008). The ERP’s displayed amplified fronto-central negativity around 400 Ms for incongruent items in dissimilarity to congruent and neutral items. Source localization analysis exposed that a source in the anterior cingulate cortex (ACC) contributed the most to the difference (Hanslmayr et al., 2008). Time-frequency analysis presented that theta oscillations (4–7 Hz) in the ACC amplified linearly with cumulative interference and that phase coupling between the ACC and the left PFC was lengthier for incongruent items likened to congruent and neutral items (Hanslmayr et al., 2008). These effects occurred at approximately 600 msec. Conclusions made were interference in the Stroop task manifests itself at around 400 Ms and mainly activates the ACC. Thereafter, sustained phase coupling between the ACC and the PFC occurs, probably reflecting the employment of cognitive control mechanisms (Hanslmayr et al., 2008).

FMT power displayed an increase when WM was manipulated from easy to difficult for participants engaged in a matching task (Gevins, Smith, McEvoy, & Yu, 1997). The difficult tasks involved whether the letter stimulus in every trial matched the spatial location or verbal identify of the stimuli which happened three trials previously. The easy condition
meant participants recognise either a letter of spatial location, held constant over numerous trials (continuous search). This resulted in four conditions, four WM loads; verbal easy, verbal difficult, spatial easy and spatial difficult. FMT topography from EEG analysis of the tasks revealed theta power correlated with task difficulty, its larger amplitude in more difficult tasks and increase in practice trials, in both verbal and spatial tasks (Gevins, Smith, McEvoy, & Yu, 1997).

Auditory ERS/ERD was examined with participants with a Mild Cognitive Impairment (MCI), arising from the onset of Alzheimer’s disease, to matched controls (Caravaglies, Muscoso, Maria, & Costanzo, 2014). Spontaneous EEG was recorded in the resting state and the auditory ERP’s were recorded. Theta response was analysed from the omitted tones to present tones against the resting state. Results showed that MCI patients had a weaker ERS (increase in theta power) than their matched controls. This is possibly due to weaker activations and/or depletion of theta oscillatory units (Caravaglies et al., 2014)

For comparative purposes to this study, it is necessary to discuss FMT in relation to WM across varying WM loads, if possible those that pertain to CL, and where it attempts to reach or surpass WMC, would be an advantage. In a study, participants engaged in a classic Sternberg paradigm whilst EEG was recorded, consisting of a low/high memory load. Results showed a significant main effect for memory load for both absolute theta power band (4-6Hz) and relative Theta power (divided by the sum of the power in other frequency bands). Additionally, a significant increase in memory load (low versus high) was reported. Behavioural results suggested that participants performed well in the task, perhaps not a reflection of WMC (Zakrzewska & Brzezicka, 2014).
In one study evidence for a relationship between EEG alpha, correlates and performance on memory tasks was sought using a modified Schneider’s and Shiffrin’s memory search paradigm, varying attentional demands (mapping conditions) and task difficulty (set size). It is suggested by Klimesch et al., (1999) that most studies relating to alpha correlates are indeed not related to memory processes. The overview is that when compared to a resting period, alpha desynchronises, indicative of localised brain activation, in a variety of perceptual and motor tasks. Additionally, Klimesch et al., claim the power within the alpha band tends to reduce with special cognitive tasks such as recognition, classification and reading also when attentional demands are high. Klimesch, Schimke and Pfurtscheller (1993) suggested that alpha alone might not be able to classify or disentangle perceptual from cognitive load.

6.5 Task related/Dependent Frequency Modulation

This section culminates in Task-related/Dependent Frequency Modulation, which is the analysis method used in this current study. Task-related modulation of frequency bands assumes the controlling or influencing of, the amplitude of the frequency bands under scrutiny, from the stimulus the participants engages with. It has been used to see if pre-stimulus EEG theta activity also mirrors top-down cognitive preparation for a stimulus (Min & Park, 2010), also used over a wide range of frequencies, as a novel multisensory attention paradigm assessing attention modulated cortical oscillations (Friese et al., 2016), investigating multimodal operations in visual and auditory attention (Wang, Viswanathan, Lee, & Grafton, 2016) and identifying areas of the brain dealing with expressive language scrutinising theta modulated gamma band synchronisation (Doesburg, Vinette, Cheung, & Pang, 2012).
Chapter 7 Research Aims and Hypotheses

7.1 Study 1, Question 1.

Question 1 addresses whether within and across modalities participants’ performance on RC based cognitive, visual and auditory tasks are similar across binary, ternary and quaternary conditions.

7.2 Hypotheses

This study will operate with the baseline null hypothesis that $H^0$: (1) There will not be a statistically significant main effect for mode, i.e. cognitive mode, visual mode and auditory mode, on the dependent variable reaction time, as a result of task resolution. (2) There will not be a statistically significant main effect for arity, which has binary, ternary and quaternary levels, which reflect increasing levels of difficulty in task resolution, on reaction time. (3) There will not be a statistically significant main interaction between mode and arity, as in the effect of mode on reaction time will not change due to the different levels of arity.

$H1$: (1) (1) There will be a statistically significant main effect for mode, i.e. cognitive mode, visual mode and auditory mode, on the dependent variable reaction time, as a result of task resolution. (2) There will be a statistically significant main effect for arity, which has binary, ternary and quaternary levels, which reflect increasing levels of difficulty in task resolution, on reaction time. Moreover, it is expected as arity increases so too do reaction times, across all tasks, regardless of mode. (3) There will be a statistically significant main interaction between mode and arity, as in the effect of mode on reaction time will change due to the different levels of arity.
7.3 Study 2: Replication of study 1 with the inclusion of EEG

Study two will replicate study one, including the research aims and hypotheses already stated, with the addition of EEG. With the analysis of the EEG, the following research questions will be addressed, the research questions will be the same for each of the EEG experiments (visual, auditory & cognitive)

EEG research Questions: (1) Can neural oscillatory activity aid in separating the perceptual component(s) from the cognitive component, utilising Theta/Alpha task-dependent modulation, by comparing the mean difference of amplitude between the visual, auditory and cognitive region of interests (ROI’s) in the Relational Complexity visual/auditory/cognitive experiments (2), furthermore can the same Alpha/Theta frequency analysis display significant differences in amplitude across increasing levels of Working Memory (WM) load namely; binary, ternary and quaternary derived from the relational complexity theory.
8 methodology

8.1 Participants

Thirteen participants took part in the study (9 females, mean age of 27.5 years), from whom written consent to participate was obtained. Participants had normal hearing and vision or corrected to normal vision. The study protocol was approved by the institutional Research-Ethics Committee of the National University of Ireland, Galway.

8.2 Apparatus and materials

In the visual task all stimuli were created using Microsoft Word on Mac OSX (see Figure 17 (b). The stimulus was presented using Paradigm stimulus presentation software via a Dell OptiPlex 760 PC: Windows 7 operating system, 2.5GHz Pentium dual-core CPU, 4 GB of RAM, 64-bit operating system and a 16-inch LED monitor 1280 x 1024 resolution. The visual task consisted of target and probe stimuli which were rectangular. The search array consisted of either four, eight or sixteen probes see Figure 17 (a) and Figure 18 for an example trial.
Figure 17 (A) depicts set size, and (B) stimulus features for the visual RC task. Figure 17 (A) shows the different search sets in the visual task comprising of 4/8/16 probes. Figure 17 (B) shows the variations in visual stimulus form the binary comprised of a rectangular shape, which is kept constant and manipulated by colour: red, green, yellow and blue and orientation: 90/45/180/135 degrees. In the ternary condition by colour/orientation/feature dimension: 1/2/3/4. Finally, in the quaternary condition by colour/orientation/feature dimension and pattern: diamond/squares/brick effect/broken line effect.

In the auditory task, target and probe stimuli were manipulated in four ways to represent the varying levels of arity. Tones were created in Musescore 2.0 and manipulated in Audacity 2.1.2.0. Stock tones which had a set timbre, pitch and amplitude were chosen. The choices were based on piloting which sounds had roughly the same musical attributes, making sure these were not too different from each other to confer singular conspicuity. Sitar, acoustic guitar, piano and banjo were chosen for timbre. Pitch was manipulated by leaving the default of C (based on the western scale), and three other whole tones A, G, & E. Amplitude was manipulated four ways as well, the default was one; sitar 1.81 dB, acoustic guitar 0.169 dB,
piano .087db and banjo .087db, two was -10db, three was minus -20db and the fourth was -30db, from each of these defaults. Finally, noise quality was manipulated, firstly with no noise, then Brownian, pink and white noise was played with the tone, in a bid to disguise it. Figure 18 shows an example of one of the trials from the auditory experiment.

As in Figure 5 the cognitive task consisted of onscreen graphical representations of a modified version of the Halford Graphical Relational Complexity Task. Graphs were created in MS word on Mac OSX. See examples of each level of arity in Figure 5. See an example of a trial in Figure 18.

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Figure 18 Visual, Auditory and Cognitive Trial Schematics. In the visual experiment, participants were presented with a target stimulus in the middle of the screen for 1500 milliseconds (ms), followed by a fixation cross for 1500 ms (see Figure 17b). Following this, displays comprising either four, eight or sixteen stimuli were presented (see Figure 17b), and the participants were given 2500 ms to respond to the presence or absence of the target stimulus. The responses were made via a dedicated response box and feedback was given after each trial for a correct/incorrect response. The response time was calculated from
the onset of the search screen until the participant replied via the response box. In the auditory experiment, in each trial, a target sound was played accompanied by a graphic of a musical note, for approx 1000ms. Participants were then presented with a crosshair for 1500 ms followed by a sequence of four sounds (probes, approx. 1000ms each). Participants had to respond if the target was either absent or present within this sequence of these four sounds, as rapidly and accurately as possible using the dedicated response keypad. Participants had to listen to all four probes serially and were given 2500ms to respond. Response time was calculated from the onset of the timer after the fourth sound until a response was given via response keypad. In the cognitive task, participants were presented graphical representations of HGRCT. There was no time out, participants had to respond as rapidly and accurately as possible using the dedicated response keypad. Feedback was given after every trial.

8.3 Procedure and Design

All three experiments were deployed in a within subject’s design, consisting of the three separate tasks administered in random order. The independent variables were mode; which had three levels: visual, auditory and cognitive, and arity, with the three levels: binary, ternary and quaternary. The visual and auditory tasks included probe stimuli in which no target was presented, so these tasks included both target and target absent conditions. The dependent variables were reaction time measured in milliseconds and in visual and auditory tasks, performance accuracy.

The cognitive task was described on a whiteboard along with the perceptual tasks, and each level of arity across each level of mode was shown simultaneously, this made the understanding clearer, and a recap of this explanation was given on each of the three visits from the participants.

All stimuli were presented in an acoustically screened chamber. Participants engaged in practice trials followed by the experimental trials. The number of practice trials for the
visual/auditory tasks experiment was 12, with equal representation of conditions. Delivery of practice trials, experimental trials and allocation of which experiment to which participant was handled by the stimulus software. No threshold was required to be met in the practice trials, once the participant indicated they knew how to engage in the task, the experimental trials began. Practice trials was restarted/re-ran if need be. But all participants engaged in at least one block of practice trials for each experiment. Participants completed the experiment over three sessions with tasks kept session wise constant. The presentation order of tasks was counterbalanced between participants.

In the visual task, participants undertook the practice trials before the experiment proper. For the experimental trials, participants engaged in 9 blocks of 39 trials per block, with each level of arity represented by 13 trial per block cumulating in 117 trials per arity over the entire experiment of 351 trials. Participants were presented with a target stimulus in the middle of the screen for 1500 milliseconds (ms), followed by a fixation cross for 1500 ms (see figure 18). Following this, displays comprising either four, eight or sixteen stimuli were presented (see figure 17a), and the participants were given 2500 ms to respond to the presence or absence of the target stimulus. The responses were made via a dedicated response box and feedback was given after each trial for a correct/incorrect response. All trials were displayed randomly. An equal number of target present/absent trials were presented.

In the auditory task, participants undertook practice trials (12) followed by 12 blocks with each level of arity represented by 78 trials for each level of arity over the entire experiment of 234 trials. Stimuli were delivered via headphones with a default volume setting used for each participant above the hearing threshold. In each trial, a target sound was played accompanied by a graphic of a musical note. Participants were then presented with a crosshair
for 1500 ms followed by a sequence of four sounds (see Figure 18). Participants had to respond if the target was either absent or present within this sequence of sounds, as rapidly and accurately as possible using the dedicated response keypad.

Ahead of the cognitive task, participants practiced with laminated copies of graphs describing each of three levels of arity. The experimenter instructed participants on how to solve the graphs using a particular heuristic and asked that participants follow this method. Once the experimenter was satisfied the participant had a grasp of the calculations that were required, it was the turn of the participant to practice and once both the experimenter and participant were satisfied that the participant was able to solve each of the three types of graphs, the experiment proper was started. The experimental conditions were delivered via PC, and a keypad response was required. Participants were asked to solve the graphs as rapidly as possible (see figure 5), although no upper time limit was set. In total, participants sat three blocks each comprising of 39 trials, a total of 117 over the entire experiment, with trials (see figure 5) delivered randomly but with each level of arity represented equally within each block.
Chapter 9 Results Study 1

9.1. Study 1 Results

Figure 19, Figure 20 and Figure 21 are boxplots (the arity variable is categorical and not interval or continuous, scatterplots are not appropriate) showing the distribution of RT’s across the visual, auditory and cognitive trials respectively, before transformation and analyses. Thirteen per cent of the visual and auditory task trials were responded to incorrectly, while the error RTs tended to be slower overall than correct RTs. However, analysis of the probability correct by RT revealed no significant correlation between RT and accuracy, which argues against the correct data being contaminated by accuracy-speed trade-offs. Examination of the correct RTs (Figure 22) revealed non-normal distribution with a pronounced positive skew. A Kolmogorov ‘D’ test showed RT distributions to be approximately lognormal and, on this basis, subsequent analyses were conducted on the exponents of the means of log-transformed RT distributions for supporting ideas see (Box & Cox, 1964, 1982). Where Mauchly’s assumption of sphericity was violated, degrees of freedom were corrected using Greenhouse – Geisser estimates.
Figure 19 depicts the distribution of all RT's of visual data across binary ternary and quaternary levels of arity on the x-axis, with response time in milliseconds displayed on the y-axis.

Figure 20 depicts the distribution of all RT's of auditory data across binary ternary and quaternary levels of arity across binary ternary and quaternary levels of arity on the x-axis, with response time in milliseconds displayed on the y-axis.
Figure 21 depicts the distribution of all RT’s of cognitive data across binary, ternary and quaternary levels of arity on the x-axis, with response time in milliseconds displayed on the y-axis.

Figure 22. The top histogram shows correct RT data with a pronounced positive skew. The histogram depicts the same data following a log transform. Notice the shape of the distribution is more normal. NB: The plot is for illustrative purposes only.
The analysis was undertaken in four steps: First, visual and auditory tasks were analysed using repeated-measures analysis of variance (rANOVA) to establish differences between target present and absent RTs and to establish the effect of arity on RTs. Subsequently, a rANOVA was run on the target RTs in visual and auditory tasks along with the RTs in the cognitive task. This analysis was carried out to determine what, if any, were the differences between the perceptual and cognitive WM tasks in successful use of the to-be-remembered information. Third, analysis of the differences in RT slopes between cognitive and visual tasks was carried out to determine if there is a consistent range in process time over which the tasks differ. Finally, the transformed visual and auditory error data were examined for any effects of task difficulty. Transformed means are given in Table 1.

<table>
<thead>
<tr>
<th>Mode</th>
<th>N</th>
<th>M</th>
<th>SE</th>
<th>E%</th>
<th>M</th>
<th>SE</th>
<th>E%</th>
<th>M</th>
<th>SE</th>
<th>E%</th>
</tr>
</thead>
<tbody>
<tr>
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<td>6615.78</td>
<td>35.50</td>
<td>20.58</td>
<td>6661.76</td>
<td>44.11</td>
<td>17.30</td>
<td>6644.36</td>
<td>35.56</td>
<td>23.80</td>
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<tr>
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<td>6631.95</td>
<td>43.24</td>
<td>19.70</td>
<td>6610.84</td>
<td>36.93</td>
<td>31.13</td>
<td>6619.31</td>
<td>30.10</td>
<td>19.23</td>
</tr>
<tr>
<td>VTP</td>
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<td>888.11</td>
<td>33.37</td>
<td>7.51</td>
<td>1054.81</td>
<td>31.94</td>
<td>7.95</td>
<td>1136.67</td>
<td>48.43</td>
<td>14.40</td>
</tr>
<tr>
<td>VTA</td>
<td>13</td>
<td>1105.52</td>
<td>48.32</td>
<td>6.94</td>
<td>1277.46</td>
<td>35.81</td>
<td>6.63</td>
<td>1284.58</td>
<td>43.68</td>
<td>20.77</td>
</tr>
<tr>
<td>Cog</td>
<td>13</td>
<td>5686.34</td>
<td>403.69</td>
<td>4.33</td>
<td>12067.79</td>
<td>798.44</td>
<td>13.60</td>
<td>23501.45</td>
<td>1767.22</td>
<td>20.71</td>
</tr>
</tbody>
</table>

Table 1 Descriptive statistics for the log-transformed RT distribution including Binary, Ternary and Quaternary referring to binary, ternary and quaternary (respectively) conditions within the experiments. N = number of participants, M = average reaction time in milliseconds, SE = standard error of the mean and E% = percentage of error in all trials. ATP = auditory modality with target present. ATA = auditory modality with target absent. VTP = visual modality with target present. VTA = visual modality with target absent. Cog = cognitive modality.

Analysis of auditory task RTs revealed a main effect of target \([F(1,12) = 54831, p < .001, \text{e}^2=1]\), with a large and consistent RT difference likely due to participants waiting until presentation of the final sound before responding absent. There was no main effect of arity, and although the arity * target interaction was significant \([F(2,24) = 4.74, p < .05, \text{e}^2=.28]\) this
Cognitive Load and Working Memory Capacity; Within and Between Modality

was mainly due to non-significant differences between target and target-absent RTs modified by a non-significant difference between the binary and ternary conditions (binary RTs were 18 ms slower than ternary RTs, with 16 m standard error).

In the visual task both mains effects of target and arity were significant \( \left[ F(1,12) = 237.26, p < .001, \, e^2 = .95, \text{ and } F(1,12) = 90.75, p < .001, \, e^2 = .88, \right] \) for the target and arity RTs, respectively] as was the target * arity interaction \( \left[ F(2,24) = 6.68, p < .01, \, e^2 = .36 \right] \). As expected, the target-present RTs were faster than target-absent RTs due to the additional search carried out on target-absent displays. RTs increased with increasing arity suggesting that successful target search was influenced by a strategy of comparing items in the search matrix against the target representation in WM. The idea that this resulted in an increased time cost as a function of the number of required comparisons is examined below.

Comparison of the target RTs in the auditory and visual tasks alongside the cognitive task RTs revealed significant main effects for mode and arity \( \left[ F(1,12) = 144.94, p < .001, \, e^2 = .92, \text{ and } F(1.2,14) = 125.81, p < .001, \, e^2 = .91 \right] \) for the mode and arity RTs, respectively] as well as a significant mode * arity interaction \( \left[ F(1.19,14.3) = 121.82, p < .001, \, e^2 = .91 \right] \). Regarding mode, RTs were substantially slower, (see Figure 23) for the cognitive relative to the visual and auditory tasks [mean differences (and SE means) were 7,111 ms (921) and 12725 ms (913), between cognitive relative to auditory and visual, respectively]. In general, RTs increased with increasing arity [mean RTs (and SE means) were 4397 (141), 6595 (278) and 10428 (599) ms, for binary, ternary and quarternary conditions, respectively]). Although there was a tendency in visual and cognitive tasks for RTs to increase with increasing arity, this was not observed in the auditory task. The mode * arity interaction is due to a non-significant difference between binary RTs in the auditory and cognitive tasks (see Figure 23).
Figure 23 shows the untransformed RT means from the behavioural experiment in study two. Upon visual inspection, the overall trend an increase in arity is observed across all tasks apart from the auditory, and a more pronounced increase in the cognitive task.

In a third analysis, slopes were calculated for each participant for the visual and cognitive task RTs over arity. The mean Beta parameters indicated that all tasks were likely to be completed using quite different processes: For the visual RT’s there was an increase of 110 ms (Beta = 110) for each increase in arity, with the increased cost indicative of the time taken to match stimulus to target information by arity in working memory. By contrast, there is a negligible (1 ms, Beta = 0.6) increase in the auditory RTs indicating that the auditory task is probably completed at the end of stimulus presentation. This tends to suggest the auditory task measures a performance heuristic that is relatively unrelated to working memory, and for this reason, the auditory RTs are not considered further. By contrast to the visual RTs, in Halford’s task, there was a steeper slope with RTs increasing by 7,855 ms ($b = 7855$) with increasing arity. To examine for a deterministic relationship between cognitive and visual-task slopes, the cognitive-task slopes were regressed over the visual-task slopes. This analysis suggests the two
functions to be unrelated \[ F(1,11) = 0.31, \text{ns}, r^2 = .003 \], and thus supports the idea that cognitive load in Halford's task is relatively uninfluenced by the perceptual load.

The square root of the proportion of errors was arcsine-transformed to normality and analysed using the same rANOVAs as described above. For the auditory task, there were main effects of target and arity \[ F(1,12) = 12.43, p < .01, \text{e}^2 = .51, \text{and} F(1.7,20.9) = 15.82, p < .001, \text{e}^2 = .57, \text{for the target and arity conditions, respectively} \]. Errors were increased for trials in which no target was presented and was greater for ternary relative to either binary or quaternary conditions. The arity effect is consistent with the slightly slower RTs to ternary relative to the other arity conditions and may indicate that for ternary decisions a more specific relationship between the variables combining to form the target is of consideration. The target main effect was due to an increase in false alarms, although the latency of responses suggests against any interpretation regarding a speed-accuracy trade-off.

Analysis of errors in the visual task was broadly consistent with errors accompanying visual search: while there was no target main effect, the arity main effect and interaction were significant \[ F(1.7,20.5) = 59.1, p < .001, \text{e}^2 = .83, \text{and} F(2,24) = 3.59, p < .05, \text{e}^2 = .23, \text{for the arity and target * arity effects, respectively} \]. In a pattern, similar to the rise in RTs with increasing arity. Nevertheless, and as indicated by the significant interaction, errors were increased significantly between binary and quaternary and between ternary and quaternary conditions but not between binary and ternary conditions. This is nonetheless indicative of an increased difficulty to perform the task as processing load is increased.

Similar to the pattern of errors in the visual task, analysis of errors in the cognitive task revealed a significant increase in errors with increasing arity, again indicating that as processing load is increased, the task becomes more difficult to perform correctly \[ F(2,24) = 56.4, p < .001, \text{e}^2 = .83 \].
Analysis of all tasks together (errors collapsed over target for convenience in the auditory and visual tasks) was carried out with the factors task and arity. This showed significant differences between all tasks in the incidence of errors \[F(2,24) = 70.53, p < .001, \quad \varepsilon^2 = .855\], with errors in the auditory task highest, followed by a higher incidence of error in the visual as compared against the cognitive task.

9.2. Discussion Study 1

This study aimed to identify CL as independent of PL in the HGRCT, achieved by quantifying and controlling the perceptual components in visual and auditory tasks in a manner that ensured they were analogous to the CL manipulated in Halford’s task. In so doing it aimed to evaluate Halford et al.’s., (2005) claim that processing limits in humans have been at best estimated theoretically and that many of these estimates are estimates in visual WM. There has not in their view, been an effective empirical determination of processing capacity. This study aimed to show that visual WM operating on a PL is independent of the WM-process operating on a CL during the completion of Halford’s task.

The results of this study clearly show that in perceptual modes and across varying levels of arity, participants’ responses follow a similar trend. This trend can be described as follows: the visual tasks involve an increase in RT as arity increases, and so WM demands are increased. Quantified by a unit increase in arity visual RTs increase by 110 Ms, with no increase in the auditory RTs.

By contrast, the cognitive task requires overall longer RTs, with a steeper slope in performance as WM demands increase. Analysis of errors also showed significant differences between all tasks, with errors in the perceptual tasks higher than the cognitive task. Errors were not fast errors, the task was just slightly more difficult than the perceptual task, probably because of the time required to make the decision in the cognitive task allowing for check and
recheck to ensure accuracy (not possible in the perceptual task), which in turn offsets any potential speed-accuracy tradeoff (although evidence for a speed-accuracy relationship was not found). Otherwise, generally and as expected, errors tended to increase with increasing arity for all tasks.

Thus, and summarised, both RTs and errors were increased as RC increased; Perceptual tasks (visual and auditory) reveal similar trends in RT performance, but are substantially slower and with less pronounced RT over arity slopes, which do not appear to compare across participants with the corresponding RT over arity slope found in the cognitive task. On these bases, this study concludes that the CL described by Halford is not only substantively different, but it may be differentiated from the effects of PL measured in the analogous visual and auditory tasks.

Research using the RC metric and visual WM are few, especially outside developmental psychology which tends to use younger participants. One study found a significant main effect for arity on both RTs and response errors, based upon differences between the ternary, binary and unary conditions (Phillips, Takeda, & Singh, 2012). The error response trend in this study is the same between visual and cognitive tasks, these are distinguishable as an increase in error with increasing arity due to PL (visual task) and CL (cognitive task), this is reflected in the RT’s.

The primary aim of this study was to investigate if the RC metric could help disentangle PL from CL. The results from the current study show a significant increase in RTs with increasing WM load in the cognitive task that appears unrelated to an increase in RTs over arity in an analogous visual search task. This offers evidence that, while performance on the HGRCT may be influenced by PL and so by visuospatial WM capacity, it is primarily
dependent upon the performance of cognitive mechanisms that appear largely uninfluenced by the performance of perceptual processes.
Chapter 10 Study 2 Results

10.1. Results: Study two behavioral between subject’s ANOVA

Study 2’s behavioural experiment is a replication of study 1 apart from the between-subjects factor of mode (i.e. visual, auditory cognitive), and the extra trials in the perceptual experiments. Trials were increased to allow for artefact rejection, but not so much as to increase artefacts, especially eye blinks. The visual and auditory experiments kept the same number of experimental blocks as study 1, but ran the sequence twice, doubling the trials. Participants were recruited in a similar fashion, poster and email campaign circulated on a college campus mostly made up of undergraduate and postgraduate students from both NUI Galway and in the case of the visual experiment LMU Munich. The behavioural data gathered in study two has two purposes (1) it aids to replicate the findings in study 1, replication is a very powerful statistic (Luck, 2005) and it bolsters the overall current study if results follow a simple trend in study 1 and 2. And (2), the same trials and number of experiments are run in this behavioural experiment as with the upcoming EEG experiments, as behavioural data is gathered concurrently with the EEG recording by default (see 10.3 for details of participants).

Similar to study 1, error responses (12.%) were removed prior to analysis, data was not contaminated by a speed-accuracy trade-off, correct RT's revealed non-normal distribution and subsequently corrected for by log transformation. Violations of Sphericity was corrected for using Greenhouse-Gaissser estimates.

Mode (visual and auditory tasks) was examined as between-subjects factor using repeated-measures analysis of variance (rANOVA) with the within-subjects factors target (present, absent) and arity (binary, ternary, quaternary). Mauchly’s test of sphericity indicated
that the assumption of sphericity had not been violated for arity \(x^2(2)=1.427, p=.490\), and target x arity \(x^2(2) = 5.199\ p=.074\).

There was a significant main effect for target \([F(1, 36.)=23.53, p = < .001, \eta_p^2 = .395]\) due to the consistently faster target vs. target absent RTs irrespective to condition. The significant arity main effect \([F(1, 36.)=43.35, p = .008, \eta_p^2 = .546]\) was mainly attributable to an overall increase in RTs in the visual task with increasing arity, a slight trend in this direction was found for the auditory task, but these data were similar to those reported in Study 1. Mode was significant \([F(1, 36.) 261.63, p = < .001, \eta_p^2 = .879]\) due to overall, faster auditory relative to visual RTs. All interactions except the three-way interaction were non-significant. While the significant three-way interaction \([F(2,72,)=6.245, p = .003, \eta_p^2 = .148]\) was mainly due to an increase in the difference between target-present – absent RTs with increasing arity for the visual condition, the same effect was not found for the auditory condition.

Comparison of the target RTs in the auditory and visual tasks alongside the cognitive task RTs (task being a between-subjects’ and arity a within-subjects’ factor) revealed significant main effect for arity \([F(1.102,59.5) = 71.33, p <.001, \eta_p^2 = .569]\), as well as a significant mode * arity interaction \([F(4,108) = 69.97, p <.001, \eta_p^2 = .722]\). As in Study 1, the significant two-way interaction was due to the tendency for cognitive and visual-task RTs to increase with arity, which was not found for the auditory task RTs: RTs were slower (see figure 24) for the cognitive relative to the visual and auditory tasks [mean differences (and SE means) were 16,105 ms (997) and 15,53 ms (997), between cognitive relative to auditory and visual, respectively]. In the cognitive mode RTs amplified with increasing arity [mean RTs (and SE means) were 2900 (167), 5471 (358) and 9651 (816) ms, for binary, ternary and quaternary conditions, respectively]. Similar to Study 1, there was a propensity in the cognitive \([M=7257.20, SE= 289.43, M=15010.9 ,SE=620.913, M=27,392.94, SE=1413.87]\) and visual
[(1001.08, SE=289.43, M=949.38 SE=620.913 , M=1114.47, SE= 1413.87)] tasks for RTs to increase overall with increasing arity, which was not observed in the auditory [(M=444.07,SE=289.43, M=452.82, SE=620.913 M=447.37, SE= 1413.87)] (means for binary, ternary and quaternary respectively). In spite of an overall increase in RTs with arity, the visual task produced a 52 ms decrease in RTs for ternary relative to binary conditions, although simple-effects analysis revealed this difference to be non-significant (p = .9). Regression analysis revealed RTs to increase with a unit increase in arity (β = 55 ms), although, contrary to Study 1, the slope for the visual task RTs over arity failed to achieve significance [F(1,54) = 2.372, p=.13].

Analysis of errors using the same analysis as carried out on the RTs revealed a significant difference between target and no target conditions [F(1,12) = 7.746, p=<.05, ηp² =.392]. This is in line with expectations and the outcome of study one, in that the target-absent displays produced more errors (false alarms: M=.280, SE=.009) than the target-present displays (M=.244, SE .014). Further, and as predicted based upon the outcome of study one, a significant main effect for arity was found [F(1,12)= 79.369, p<.001)]. A significant mean difference was found between the quaternary and binary levels of arity (M=201, SE=.23), the quaternary and ternary levels of arity (M=.066, SE=.018) and the ternary and binary levels of arity (M=135, SE=.017) indicating as arity increased so too did error production.

Finally, analysis of the mode by arity effect on error production (for target trials only), revealed both arity main effect and the arity * mode interaction to be significant [F(2,108) = 21.521, p=<.0001, ηp²=.285 and F(4,108) = 93.415, p=<.0001, ηp²=.776, respectively]. These effects were due to a general trend for errors to increase with arity, with significantly higher errors for the cognitive task compared against both auditory and visual tasks (but with no significant difference between auditory and visual tasks).
Figure 24 shows the untransformed RT means from the behavioural experiment in study two. Upon visual inspection, the overall trend was replicated from study one if figure 24 (study one’s means plotted) is compared to figure 24 (study two’s means plotted), in that, an increase in arity is observed across all tasks, with perceptual tasks sharing a similar trend and a more pronounced increase in the cognitive task. After the log transformation and subsequent analysis, however, the visual task displayed a non-significant decrease in RTs for ternary relative to binary conditions and contrary to Study 1, the slope for the visual task RTs over arity failed to achieve significance.

10.2. EEG experiments: Participants

EEG was recorded from 19 volunteers for each of the visual, auditory and cognitive experiments after receiving written informed consent. One subject was removed from the visual experiment analyses as due to high impedance values and the length of preparation of the electrodes. In the auditory experiment, 27 recordings were completed, in order to keep sample size across experiments constant, raw data of 19 participants out of 27 were selected based on visual inspection that showed a similar level of data quality (comparability in terms of noise level and artefacts) as the other experiments. Similarly, 19 recordings were done in
the cognitive experiment, to match the visual and auditory. The mean age of the visual, auditory and cognitive samples was; (n=19) (22.61) SD= (6.53), (n=19) (23.22) SD= (7.87) and (n=19) (24.42) SD= (7.77) respectively. 2, 9, 7 were male and 17,10, 12 were female respectively. All subjects had normal or corrected to normal vision and were not affected by a neurological or psychiatric disorder. Handedness was assessed by the Edinburgh Handedness Scale (Oldfield, 1971) which detected 17,13,14 amount righthanded, 1,4,2 amount left handed and 1,2,2 ambidextrous participants (visual, auditory & cognitive experiments respectively). Participants were financially compensated for their participation. The recording of the visual EEG took place in the Biological Psychology Research in LMU, Munich, Germany. Ethical approval was sought and granted from the National University of Ireland, Galway’s ethics committee and data were recorded on an Erasmus exchange program in which ethics to record the data were also granted by the established professor in Biological Psychology Research Unit.

10.3. Region of Interests (ROI’s)

Based on the previous literature discussed above, it is necessary for EEG analyses to split/isolate the 64 channel EEG recording into Region of Interests (ROI’s) that are associated with each of the modes under scrutiny. In this proposed study that is the Cognitive mode, which attempts to capture cognitive load (CL) based on the relational Complexity (RC) metric, and two perceptual modes visual and auditory, which will attempt to capture the perceptual component, or perceptual load (PL), under the RC metric. In the cognitive mode, the frontal midline (FM) ROI, which as stated earlier reflects neuronal assemblies best suited for focused attention and mental arithmetic, for example, is best suited for the resolution of the modified Halford graphs. The associated electrodes are AFz, F1, F2, FCz and Fz. The electrode
sites best suited for the auditory mode are C5, C6, FT7, FT8, T7, T8, TP7 and TP8. And for the visual mode: O1, O2, Oz, P03, P04, P07, P08 and POz. A graphic depicting the visual/auditory and FM ROI’s is below (figure 25). For justification of the chosen pooling of electrode sites into the relative ROI’s see Homan, Herman and Purdy, 1987; Lagerlund et al., 1993; Vitali et al., 2002 who used brain imagining techniques to justify the placement of electrodes according to the 10/20 system, the placement system used here (see appendix 9 for Brainvisions recommended electrode setting for the 10-20 system).

![Visual ROI, Auditory ROI, FM ROI](image)

*Figure 25 Visual/Auditory/FM Region of Interest visual graphic. The electrode sites best suited for the visual mode: O1, O2, Oz, P03, P04, P07, P08 and POz, the auditory mode C5, C6, FT7, FT8, T7, T8, TP7 and TP8 and the cognitive mode AFz, F1, F2, FCz and Fz.*

10.4 EEG Data Acquisition: Setup and Hardware

EEG was recorded using 64 scalp electrodes (Ag/AgCl ring electrodes; Easycap®) mounted the international 10-20 system against a nose reference. Signals were amplified with a 64-channel passive amplifier system (BrainAmp by Brain products, Girching, Germany). Two additional flat electrodes were placed superior too and next to the right eye to control for
horizontal and vertical eye movements. A sampling rate of 1000Hz was used. A low cut off rate of 0.5Hz and a high cut off rate of 80Hz and a notch filter was introduced offline. Impedance values were kept below 20 kΩ. The auditory and cognitive experiments were recorded at the EEG laboratory in NUI Galway, the same experimental setup was kept except that the amplifier (same manufacturer) was an active set up.

10.5 EEG Data Analysis of all Experiments.

EEG data were analyzed by using Brain Vision Analyzer 2.1 (BrainProducts®). Statistical analyses were carried out with SPSS. EEG channels were re-referenced to common average. For the active system used in the auditory and cognitive experiments, the AFz and FCz channels were interpolated and added into the new reference, this was done in a bid to match the passive setup, and the analyses tree was identical from this point on. Zero phase shift Butterworth IIR filter was implemented, the global filter settings were: Low cutoff: 0.5 Hz, time constant 0.3183099, order 8, high cutoff: 80 Hz, order 8 Notch filter: 50 Hz (to cancel out line noise) created using component Version 2.1.1.2516 via BrainVision Analyzer 2.1. Ocular correction was implemented using BrainVison Analyzer ICA, and data was then inspected manually to remove artefacts. This resulted in a loss of trials for the visual/auditory/cognitive experiments at the binary (35.83%, 24.96%, 10.12%), ternary (37.11%, 31.17%, 13.38%) and quaternary (30.47%, 25%, 28.76%) levels of arity respectively. Segmentation was carried out on the epoch labelled retention binary. This epoch captured the 1000ms before the participant responded to all of the binary trials at the binary level of arity (1000ms before keyboard response). The stimulus presentation and EEG acquisition were synchronised and event triggers marked the onset of the stimuli, probes and responses in the
EEG signal (recorded with Brain Products Brain vision recorder). Afterwards, Laplacian current source density (CSD) was calculated to attenuate the effects of volume conduction (smearing of signals across the scalp). A fast Fourier transformation (FFT) was carried out to break down the complex signal averaged over each epoch, for each electrode site (see appendix 10). The final step was to pool the channels into the ROI’s. The above steps were repeated for the ternary and quaternary levels of arity. This resulted in an exported file of the averaged millivolts per condition (binary, ternary and quaternary) at each ROI (FM, auditory and visual) and each frequency band (theta 4-8 Hz, alpha 8-12 Hz). This created the basis for the three levels of the ANOVA’s discussed in the result section. Incorrect and timed out trials were excluded in the analysis due to the fact that their number was rather small; and secondly, incorrect responses might also be caused by erroneous encoding or retrieval processes, whereas the current analysis exclusively focused on processes during the retention interval of successful trials.

10.6. EEG Analysis Results Section for the Visual Experiment.

**Within-subjects Analysis of Variance: 2x3x3 Design**

The following three-way ANOVA was carried out on the EEG data collected in the visual experiment. The ANOVA had three levels namely: frequency band (Theta and Alpha), region of interest (ROI) and arity. Region of interest (ROI) which has three levels (FM= frontal midline, vis = visual/occipital sites and aud = auditory/parietal sites) reports no violation of sphericity $\chi^2(2) = 2.914, p = .233$, arity which has three levels (binary, ternary & Quaternary) violates sphericity $\chi^2(2) = 19.68, p < .001$, as does the interaction between frequency band and arity $\chi^2(2) = 11.23, p = .004$, the interaction between ROI and arity $\chi^2(2) = .3367, p < .00$. The
interaction between frequency band, arity and ROI $x^2(2) = 23.52$, $p = .005$, and frequency band and ROI assumes sphericity $x^2(2) = .962$, $p = .618$.

As a result of Mauchly's test, the following corrections were put in place: for the main effect of ROI, sphericity assumed no correction. For the main effect of arity, the Greenhouse-Geisser correction $\varepsilon = .59$, for the interaction between frequency band and ROI sphericity assumed, no correction, between frequency band and arity the Greenhouse-Geisser $\varepsilon = .67$, for ROI and arity Greenhouse-Geisser $\varepsilon = .49$ and for frequency band, Arity and ROI sphericity assumed, no correction needed.

Main Effects:

The dependent variable for all of the EEG studies reported here is millivolts, a measure of amplitude in the EEG, which aids in the ability to distinguish whether or not there is a mean difference in amplitude from theta to alpha frequency bands, between different ROI's, over levels of arity (see Table 2 for ANOVA results and Figure 26 for means plotted). A non-significant main effect for frequency Band (theta versus alpha) was reported $[F(1, 18) = 2.475$, $p = .133$, $\eta^2_p = .121]$. A non-significant effect for region of interest (ROI) was also reported $[F(2, 36) = 1.674, p = .202, \eta^2_p = .085]$. Similarly, a non-significant effect was reported for arity $[F(1.186, 21.355) = 1.264, p = .282, \eta^2_p = .066]$. 

Table 2 EEG ANOVA Table for the Visual Experiment: Depicting the Frequency band * ROI * Arity Interaction, subsequent two-way interactions and main effects.

<table>
<thead>
<tr>
<th>Source</th>
<th>df</th>
<th>MS</th>
<th>F</th>
<th>p</th>
<th>( \eta_p^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>F Band</td>
<td>(1,18)</td>
<td>35.936</td>
<td>2.475</td>
<td>.133</td>
<td>.121</td>
</tr>
<tr>
<td>ROI</td>
<td>(2,36)</td>
<td>22.110</td>
<td>1.674</td>
<td>.202</td>
<td>.085</td>
</tr>
<tr>
<td>Arity</td>
<td>(1.186, 21.355)</td>
<td>1.699</td>
<td>1.264</td>
<td>.282</td>
<td>.066</td>
</tr>
<tr>
<td>F Band * ROI</td>
<td>(2,36)</td>
<td>31.728</td>
<td>8.976</td>
<td>.001*</td>
<td>.333</td>
</tr>
<tr>
<td>F Band * Arity</td>
<td>(1.348, 24.267)</td>
<td>1.265</td>
<td>9.226</td>
<td>.003*</td>
<td>.339</td>
</tr>
<tr>
<td>ROI * Arity</td>
<td>(1.972, 35.504)</td>
<td>.411</td>
<td>2.211</td>
<td>.125</td>
<td>.109</td>
</tr>
<tr>
<td>F Band * ROI * Arity</td>
<td>(2.315, 41.675)</td>
<td>.271</td>
<td>3.280</td>
<td>.041*</td>
<td>.154</td>
</tr>
</tbody>
</table>

Note. F Band = frequency Band, ROI = Region of Interest. MS = Mean squares, effect size = partial \( \eta_p^2 \). * Significant at the .05 alpha level.
Figure 26 shows the Visual EEG Profile Plots of the mean amplitudes for binary (Panel A), ternary (Panel B) and quaternary (Panel C) levels of arity, for all of the ROI’s (FM, visual and auditory) between the theta and alpha frequency bands. Alpha de-synchronisation is evident as arity increases from panel to panel, the inverse is also evident for the Aud (auditory) ROI, as expected as the auditory mode would not have been engaged.
Main Interactions: A significant interaction is reported between frequency band, ROI and arity \([F(4, 72)= 3.280, p= .016, \eta^2_p =.154]\). Contrasts report between the theta and alpha frequency bands, between the visual ROI and the auditory ROI significant differences in amplitude between the ternary versus quaternary level \([F(1, 18)=7.164, p=.015, \eta^2_p =.285]\), and the binary and quaternary level \([F(1, 18)=6.759, p=.018, \eta^2_p =.273]\). Visual inspection shows these interactions, suggesting that perceptual modes in the alpha band moderates this three-way interaction (Figure 27).

Table 3 displays significant simple effects for arity at the level of theta at the FM \((p=.007)\) and auditory \((p.022)\) ROI’s. As expected a significant simple main effect is reported for arity at alpha frequency band at the visual ROI \((p=<.001)\), this warrants the three-way ANOVA being broken down into 2 way ANOVA’s, each focussing on a different frequency band.
Figure 27 Depicts the Visual EEG's three-way interaction between the ROI's (visual, auditory & cognitive), levels of arity on the x-axis (binary, ternary & quaternary) and frequency band (panel (A) is the theta frequency Band, and panel (B) is the alpha frequency band). Panel (A) shows an increase in the dependent variable (MilliVolts) in theta from binary to ternary and a decrease from ternary to quaternary. The frequency band of interest is the alpha band, which is visual stimuli is expected to respond to alpha especially in the visual ROI. Panel B shows a pronounced decrease in alpha for the visual ROI as arity increases.
Table 3 shows post hoc comparisons for the simple main effects for Arity for the visual EEG experiment.

<table>
<thead>
<tr>
<th>Freq Band, ROI,</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theta</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fm</td>
<td>0.794</td>
<td>2</td>
<td>0.397</td>
<td>5.549</td>
<td>0.007*</td>
</tr>
<tr>
<td>vis</td>
<td>0.186</td>
<td>2</td>
<td>0.093</td>
<td>1.298</td>
<td>0.282</td>
</tr>
<tr>
<td>Aud</td>
<td>0.589</td>
<td>2</td>
<td>0.294</td>
<td>4.114</td>
<td>0.022*</td>
</tr>
<tr>
<td>Alpha</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fm</td>
<td>0.400</td>
<td>2</td>
<td>0.200</td>
<td>2.797</td>
<td>0.071</td>
</tr>
<tr>
<td>vis</td>
<td>3.084</td>
<td>2</td>
<td>1.542</td>
<td>21.539</td>
<td>&lt; .001*</td>
</tr>
<tr>
<td>Aud</td>
<td>0.106</td>
<td>2</td>
<td>0.053</td>
<td>0.741</td>
<td>0.482</td>
</tr>
</tbody>
</table>

Note. Freq Band = Frequency Band, ROI = Region of Interest. * Significant at the .05 alpha level.

A significant interaction between frequency band and arity is reported \[ F(1.348, 24.267)=9.226, \textit{p}=.003, \eta^2_p=.339 \]. To break this down contrasts reveal a significant difference in amplitude for the binary versus the quaternary level \[ F(1,18)=11.794, \textit{p}=.003, \eta^2_p=.396 \], and a significant difference for binary versus ternary level \[ F(1,18)=9.5001, \textit{p}=.006, \eta^2_p=.345 \], and similarly for the ternary versus quaternary level \[ F(1,18)=.174, \textit{p}=.682, \eta^2_p=.010 \]. Visual inspection of the plot (see Figure 28) associated with this interaction shows how each frequency band interacts with the levels of arity. Alpha shows a decrease in amplitude as arity increases from the binary level to the quaternary level. Inversely, theta shows an increase, albeit very slight from the binary level to the quaternary level of arity, and a marked increase at the ternary level of arity. In summary, alpha and theta respond differently to arity as depicted in Figure 28.
A significant interaction between frequency band and ROI was reported \([F(1.896, 34.12) = 8.976, p = .001, \eta^2_p = .333]\). Post hoc simple effect analysis reveal significance at the FM ROI \((p = < .001)\). Contrasts reveal a significant difference is reported between the visual ROI and the FM ROI \([F(1,18) = 8.149, p = < .011, \eta^2_p = .312]\). Similarly, a significant difference is reported from the FM ROI and the auditory ROI \([F(1,18) = 21.974, p = < .001, \eta^2_p = .548]\). Visual inspection of the associated profile plot (see Figure 29) suggests a decrease in amplitude at the visual ROI for alpha and a further decrease for alpha at the FM ROI. As predicted, the inverse is true at the auditory ROI (increase in alpha), as this experiment was targeted at the visual mode. This suggests that some of the ROI differences must be due to one or other of the frequency bands. Two-way ANOVA’s of alpha and theta separately should reveal this. A non-
significant interaction for ROI and arity was reported $[F(1.972, 35.504)=2.211, p= .125, \eta_p^2 = .109].$

Figure 29 shows the visual EEG experiment’s interaction with Freq Band x ROI. As this is the visual experiment it was expected to see a decrease in amplitude for alpha compared to theta at the vis (visual) ROI, and the inverse at the aud (auditory) ROI as the auditory modality would not be engaged, and a marked decrease in alpha is noted at the cognitive or FM ROI.

Within-subjects Analysis of Variance: 3x3 Design (Theta Visual):

Breaking down the three-way interaction above and looking at individual frequency bands namely; theta and alpha, separate two-way ANOVA’s were carried out to determine which frequency band drove the interaction. Region of Interest (ROI) which has three levels (FM= frontal midline, Vis = Visual/occipital sites and Aud = auditory/parietal sites) reports violation of sphericity $\chi^2(2) =6.187, p = .045.$ Arity which has three levels (Binary, ternary & Quaternary) violates sphericity $\chi^2(2) =9.278, p=.010.$ The interaction between ROI and Arity
also violates sphericity $x^2(2) = 18.658$, $p = .029$. As a result of Mauchly's test the following corrections were put in place: for the main effect of ROI, the Huynh-Feldt correction was used $\epsilon = .823$, the main effect of arity the Greenhouse Geisser correction $\epsilon = .704$ and for the interaction between ROI and Arity $\epsilon = .663$.

Main effects and interactions for Visual theta:

A non-significant main effect was found for ROI $[F(1.647, 29.641) = .820, p = .429, \eta_p^2 = .044]$, and similarly non-significant effect for arity $[F(1.408, 25.342) = 2.270, p = .137, \eta_p^2 = .112]$. A non-significant interaction was reported between ROI and arity $[F(2.651, 47.744) = 0.744, p = .516, \eta_p^2 = .040]$. This suggests that Theta did not respond to arity, and at this point can be excluded from any further analyses in relation to the visual EEG mean amplitudes.

Within-subjects Analysis of Variance: 3x3 Design (Alpha Visual):

Region of Interest (ROI) which has three levels (FM= frontal midline, Vis = Visual/occipital sites and Aud = auditory/parietal sites) does not violate sphericity $x^2(2) = 4.264, p = .119$. Arity which has three levels (Binary, ternary & Quaternary) violates sphericity $x^2(2) = 25.913, p < .001$. The interaction between ROI and arity also violates sphericity $x^2(2) = 35.551, p < .001$. As a result of Mauchly's test the following corrections were put in place: for the main effect of ROI’ sphericity assumed, no correction. For the main effect of arity, the Greenhouse Geisser correction $\epsilon = .561$ and for the interaction between ROI and arity $\epsilon = .462$.

Main Effects:

A significant main effect was found for ROI $F[(2,36) = 4.734, p = .015, \eta_p^2 = .208$, and when post hoc simple effects (see Table 5) were conducted results reveal significance for the binary ($p<.001$), ternary ($p=.02$) and quaterneary ($p=.01$) and similarly, for the interaction
between ROI and arity $F(1.847, 33.239) = 3.385, p = .049, \eta^2_p = .158]$, A non-significant main effect is reported for arity $[F(1.222, 20.199) = 1.992, p = .173, \eta^2_p = .1$ (see Table 4 & Figure 30).

Table 4 Visual EEG 2-way ANOVA Alpha: ROI * Arity. This table depicts the interaction between ROI and arity and the main effects of ROI and arity for the alpha frequency band.

**Visual EEG Alpha, ROI * Arity**

<table>
<thead>
<tr>
<th>Source</th>
<th>df</th>
<th>MS</th>
<th>$F$</th>
<th>$p$</th>
<th>$\eta^2_p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROI</td>
<td>(2,36)</td>
<td>48.514</td>
<td>4.734</td>
<td>.015*</td>
<td>.208</td>
</tr>
<tr>
<td>Arity</td>
<td>(1.222, 20.199)</td>
<td>2.030</td>
<td>1.992</td>
<td>.173</td>
<td>.1</td>
</tr>
<tr>
<td>ROI * Arity</td>
<td>(1.847, 33.239)</td>
<td>.711</td>
<td>3.385</td>
<td>.049*</td>
<td>.158</td>
</tr>
</tbody>
</table>

* Significant at the .05 alpha level.

**Note.** MS = Mean squares, effect size = partial $\eta^2_p$

Table 5 Post-hoc simple main effect ROI over the binary, ternary and quaternary levels of arity.

**Simple Main Effects - ROI**

<table>
<thead>
<tr>
<th>Level of Arity</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>$F$</th>
<th>$p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bin</td>
<td>37.79</td>
<td>2</td>
<td>18.90</td>
<td>5.340</td>
<td>.009</td>
</tr>
<tr>
<td>Tern</td>
<td>29.61</td>
<td>2</td>
<td>14.81</td>
<td>4.256</td>
<td>.022</td>
</tr>
<tr>
<td>Quat</td>
<td>30.93</td>
<td>2</td>
<td>15.47</td>
<td>4.518</td>
<td>.018</td>
</tr>
</tbody>
</table>

* Significant at the .05 alpha level.

**Note.** Type III Sum of Squares
Figure 30 depicts the Visual EEG experiment’s 2 way ANOVA interaction between ROI * Arity in the alpha band. The plot shows alpha desynchronisation occurs as arity increases from binary through to quaternary for the vis (visual) ROI, this response to alpha is as predicted.

Main Interaction & Contrasts ROI & Arity:

A significant interaction was reported between ROI and Arity \([F(1.847, 33.239) = 3.385, p = .049, \eta_p^2 = .158]\). Only one of the contrasts showed a significant difference in mean amplitude between the Vis ROI and the Aud ROI at the binary versus quaternary level \([f(1,18) = .4.679, p = .044, \eta_p^2 = .206]\). Visual inspection of the associated profile plot (see Figure 30) suggests that the interaction between the perceptual ROI’s bolster this interaction.

Paired Samples Dependent T-Tests for Alpha in the Visual EEG:

To test alpha band task-dependent modulation, paired sample t-tests were carried out between the region of interests (ROI’s) Frontal midline (FM), visual (Vis) and auditory (Aud), and each level of arity (Binary, ternary & Quaternary) within the visual mode.
For alpha frequency (see Table 6) band at the FM ROI significant differences are reported between the ternary and quaternary levels of arity (M= 7.19, SE =0.55) (M=7.00 , SE =0.54), t(18) = 2.94 , p<.05 d =.67), and between similar levels of arity at the visual ROI (M=8.69 , SE =0.67) (M=8.44 , SE =0.63), t(18) = 2.87 , p<.05 d =.66).

Table 6 Visual EEG Alpha dependent t-test. Following on from the significant two way interaction from the alpha frequency band paired sample t-tests were carried out.

<table>
<thead>
<tr>
<th>Paired Samples T-Test Alpha Frequency Band</th>
<th>t</th>
<th>df</th>
<th>p</th>
<th>Cohen's d</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alpha FM Bin - Alpha FM Tern</td>
<td>-0.106</td>
<td>18</td>
<td>0.916</td>
<td>-0.024</td>
</tr>
<tr>
<td>Alpha FM Tern - Alpha FM Quat</td>
<td>2.935</td>
<td>18</td>
<td>0.009</td>
<td>0.673</td>
</tr>
<tr>
<td>Alpha FM Bin - Alpha FM Quat</td>
<td>1.397</td>
<td>18</td>
<td>0.179</td>
<td>0.321</td>
</tr>
<tr>
<td>Alpha Vis Bin - Alpha Vis Tern</td>
<td>1.252</td>
<td>18</td>
<td>0.227</td>
<td>0.287</td>
</tr>
<tr>
<td>Alpha Vis Tern - Alpha Vis Quat</td>
<td>2.872</td>
<td>18</td>
<td>0.010</td>
<td>0.659</td>
</tr>
<tr>
<td>Alpha Vis Bin - Alpha Vis Quat</td>
<td>1.881</td>
<td>18</td>
<td>0.076</td>
<td>0.431</td>
</tr>
<tr>
<td>Alpha Aud Bin - Alpha Aud Tern</td>
<td>0.264</td>
<td>18</td>
<td>0.795</td>
<td>0.061</td>
</tr>
<tr>
<td>Alpha Aud Tern - Alpha Aud Quat</td>
<td>0.844</td>
<td>18</td>
<td>0.410</td>
<td>0.194</td>
</tr>
<tr>
<td>Alpha Aud Bin - Alpha Aud Quat</td>
<td>0.712</td>
<td>18</td>
<td>0.485</td>
<td>0.163</td>
</tr>
</tbody>
</table>

*Note.* Student's t-test.

10.7. Overall/summary results for the Visual EEG experiment

Based on alpha/theta frequency band modulation, theta did not respond to arity in the visual experiment, instead responded to alpha displaying an arity dependent decrease in amplitude, especially in the visual ROI (see figure 8 for ROI’s). This suggests the task is affected by perceptual load rather than cognitive load. Initial significant 3-way interaction between frequency band * ROI * arity (see figure 26) warranted a closer look at the individual
frequency bands namely theta and alpha. In these 2-way ANOVA’s theta displayed non-
statistical significance and was deemed unresponsive, alpha, however, seems to underpin the
original interaction (see appendix 1,2,3 for sample EEG topography).

10.8 Auditory EEG Experiment Results

EEG Analysis Results Section for the Auditory Experiment.

Within-subjects Analysis of Variance: 2x3x3 Design:

Mauchly's test for sphericity doesn’t report for the main effect of frequency band
(Theta, Alpha) as it has only two levels. Region of Interest (ROI) which has three levels (FM=
frontal midline, Vis = Visual/occipital sites and Aud = auditory/parietal sites) violates the
assumption of sphericity $\chi^2(2) = 13.957, p=.001$. Arity which has three levels (Binary, ternary
& Quaternary) assumes sphericity $\chi^2(2) = 4.087, p=.132$. Frequency band and ROI $\chi^2(2) =
.10.182, p=.006$ violates sphericity. Frequency band and arity $\chi^2(2) = 5.208, p=.074$ assumes
sphericity. The interaction between ROI and arity $\chi^2(9) = 23.713, p=.005$ violates sphericity,
as does the interaction between frequency band, arity and ROI $\chi^2(9) = 18.94, p=.026$.

As a result of Mauchly's test, the following corrections were put in place: for the main
effect of ROI the Greenhouse-Geisser $\varepsilon = .641$, the main effect of arity no correction assumes
sphericity, the main interaction between frequency band and ROI the Greenhouse-Geisser $\varepsilon =.
689$, the main interaction between frequency band and arity no correction assumes sphericity,
the main interaction between ROI and arity the Green-house Geisser $\varepsilon = .668$, and the
interaction between frequency band, arity and ROI Green-house Geisser $\varepsilon = .662$. The
dependent variable for this study is millivolts, a measure of amplitude in the EEG, which aids
in the ability to distinguish whether or not there is a mean difference in amplitude from theta to alpha frequency bands, between difference ROI's, over levels of arity.

Main effects:

A significant main effect for region of interest (ROI) was also reported \([F(1.282, 23.077)=11.357, p=<.001, \eta_p^2 =.387]\). A non-significant effect for frequency band (theta versus Alpha) was reported \([F(1,18)= .903, p= .355, \eta_p^2 =.048]\). A non-significant effect was reported for arity \([F(2,36 )=.873, p=.426, \eta_p^2 =.046, \text{ (see Table 7 and Figure 31) }\].

*Table 7 EEG Auditory, Frequency Band *ROI * Arity. Depicting the frequency band, arity and ROI three-way interaction, followed by the two-way interactions and the main effects for each independent variable.*

<table>
<thead>
<tr>
<th>Source</th>
<th>df</th>
<th>MS</th>
<th>F</th>
<th>p</th>
<th>(\eta_p^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F Band</td>
<td>(1,18)</td>
<td>23.732</td>
<td>.903</td>
<td>.355</td>
<td>.048</td>
</tr>
<tr>
<td>ROI</td>
<td>(1.282, 23.077)</td>
<td>357.577</td>
<td>11.357</td>
<td>.001*</td>
<td>.387</td>
</tr>
<tr>
<td>Arity</td>
<td>(2,36)</td>
<td>.155</td>
<td>.873</td>
<td>.426</td>
<td>.046</td>
</tr>
<tr>
<td>F Band * ROI</td>
<td>(1.379, 24.817)</td>
<td>81.185</td>
<td>11.624</td>
<td>.001*</td>
<td>.392</td>
</tr>
<tr>
<td>F Band * Arity</td>
<td>(2,36)</td>
<td>.103</td>
<td>1.016</td>
<td>.392</td>
<td>.053</td>
</tr>
<tr>
<td>ROI * Arity</td>
<td>(2.672, 48.095)</td>
<td>.310</td>
<td>1.633</td>
<td>.198</td>
<td>.083</td>
</tr>
<tr>
<td>F Band * ROI *</td>
<td>(2.647, 47.651)</td>
<td>.106</td>
<td>.436</td>
<td>.704</td>
<td>.024</td>
</tr>
<tr>
<td>Arity</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Note. F Band= frequency Band, ROI = Region of Interest. MS = Mean squares, effect size = partial \(\eta_p^2\). * Significant at the .05 alpha level.
Figure 31 Mean amplitudes for (a) binary level of arity, (b) ternary level of arity and (c) quaternary level of arity for the auditory EEG experiment on the x-axis and the dependent variable millivolts on the y-axis.
Main Interactions:

A significant main interaction between frequency band and ROI was reported \( [F(1.379, 24.817) = 11.634, \ p = .001, \ \eta^2_p = .392] \). A non-significant main interaction between frequency band and arity is reported \( [F(2, 36) = 1.016, \ p = .372, \ \eta^2_p = .053] \). A non-significant main interaction for ROI and arity was reported \( [F(2.672, 48.095) = 1.633, \ p = .175, \ \eta^2_p = .083] \). A non-significant main interaction is reported between frequency band, ROI and arity \( [F(4, 72) = .436, \ p = .704, \ \eta^2_p = .024] \).

**Figure 32** Shows mean amplitudes (y-axis) for the Auditory EEG (A) theta (B) Alpha frequency band, over levels of arity on the x-axis. As auditory is a perceptual mode, response to alpha is of interest. Panel (B) response to alpha for the auditory ROI shows a slight increase from binary to ternary and decrease from ternary to quaternary levels of arity.
10.9 Summary Auditory EEG results
None of the interactions involving arity was significant, this warranted an end and exclusion of the auditory EEG data from further analyses. Upon visual inspection of the associated profile plots (see figure 32), theta/alpha modulation evidence (NB reported as non-significant in this study) is seen with a decrease in amplitude in alpha and corresponding increase in theta for the FM ROI and the Aud ROI, expected as is was a task targeted at the auditory mode, and the inverse in the vis ROI, a decrease in theta and increase in alpha (see appendix 1,2,3 for sample EEG Topography).

10.10 EEG Analysis Results Section for the Cognitive Experiment.
Within-subjects Analysis of Variance: 2x3x3 Design:

Mauchly's test for sphericity doesn’t report for the main effect of frequency band (Theta, Alpha) as it has only two levels. Region of Interest (ROI) which has three levels (FM=frontal midline, Vis = Visual/occipital sites and Aud = auditory/parietal sites) violates the assumption of sphericity $\chi^2(2) = 6.583, p = .037$. Arity which has three levels (binary, ternary & quaternary) does not violate sphericity $\chi^2(2) = 0.164, p = .921$, As does frequency band and ROI, it assumes sphericity $\chi^2(2) = 4.932, p = .085$. The interaction between frequency band and arity $\chi^2(2) = 2.341, p = .310$ assumes sphericity. The interaction between ROI and arity $\chi^2(2) = 24.151, p = .004$ violates sphericity. The interaction between frequency band, arity and ROI $\chi^2(2) = 12.686, p = .179$ assumes sphericity

As a result of Mauchly's test the following corrections were put in place: for the main effect of ROI; the Huynd-Feldt correction $\epsilon = .812$. For the main effect of arity; sphericity assumed. For the interaction between frequency band and ROI and, between frequency band
Cognitive Load and Working Memory Capacity; Within and Between Modality

and arity; sphericity assumed, no correction. For ROI and arity, the Greenhouse-Geisser \( \varepsilon = .585 \), and for frequency band, arity and ROI sphericity assumed, no correction needed.

Main Effects:

The dependent variable for this study, as with both perceptual studies, is millivolts. A significant main effect for frequency band (theta versus Alpha) on the dependent variable millivolts was reported [\( F(1, 18)= 90.273, p= <.001, \eta^2_p = .824 \)]. A significant main effect for region of interest (ROI) was also reported [\( F(1.623,29.222)=21.378, p=.<.001, \eta^2_p = .543 \)]. A non-significant effect was reported for arity [\( F(2,36)= .620, p=.544, \eta^2_p = .033 \), (see Table 8 and Figure 33)]

Table 8 cognitive EEG Frequency band *ROI* Arity three-way interaction. Depicting the three-way interaction between frequency band, arity and ROI, with subsequent two interactions and main effects for each of the independent variables.

<table>
<thead>
<tr>
<th>Source</th>
<th>df</th>
<th>MS</th>
<th>F</th>
<th>p</th>
<th>( \eta^2_p )</th>
</tr>
</thead>
<tbody>
<tr>
<td>F Band</td>
<td>(1,18)</td>
<td>149.144</td>
<td>90.273</td>
<td>&lt;.001*</td>
<td>.834</td>
</tr>
<tr>
<td>ROI</td>
<td>(1.623, 29.222)</td>
<td>179.492</td>
<td>21.373</td>
<td>&lt;.001*</td>
<td>.534</td>
</tr>
<tr>
<td>Arity</td>
<td>(2, 36)</td>
<td>.078</td>
<td>.620</td>
<td>&lt;.001*</td>
<td>.033</td>
</tr>
<tr>
<td>F Band * ROI</td>
<td>(2, 36)</td>
<td>10.194</td>
<td>7.588</td>
<td>&lt;.002*</td>
<td>.297</td>
</tr>
<tr>
<td>F Band * Arity</td>
<td>(2, 36)</td>
<td>.022</td>
<td>.237</td>
<td>&lt;.001*</td>
<td>.013</td>
</tr>
<tr>
<td>ROI * Arity</td>
<td>(2.338, 42.089)</td>
<td>1.319</td>
<td>5.583</td>
<td>&lt;.005*</td>
<td>.237</td>
</tr>
<tr>
<td>F Band * ROI * Arity</td>
<td>(4, 72)</td>
<td>.107</td>
<td>1.353</td>
<td>&lt;.259</td>
<td>.070</td>
</tr>
</tbody>
</table>

Note. F Band= frequency Band, ROI = Region of Interest. MS = Mean squares, effect size = partial \( \eta^2_p \). * Significant at the .05 alpha level
Figure 33 Plot of average means in Millivolts (y-axis) for the cognitive EEG experiment. Mean amplitudes for (a) binary level of arity, (b) ternary level of arity and (c) quaternary level of arity, for the auditory EEG experiment on the x-axis.
Main Interactions

A significant main interaction for ROI and arity (see Figure 34) was reported \[ F(2.338, 42.089) = 5.583, \ p = .005, \ \eta^2_p = .237 \], with significant simple main effects for ROI moderated by arity (binary, ternary & quaternary, \( p < .001 \), see Table 9). A significant difference in amplitude is reported between the visual ROI and the FM ROI at the binary versus the ternary level \[ F(1,18) = 8.033, \ p = .011, \ \eta^2_p = .309 \], and a significant difference between the binary and quaternary level \[ F(1,18) = 9.448, \ p = .007, \ \eta^2_p = .344 \]. A significant difference is reported between the visual ROI compared to the auditory ROI at the binary level versus the ternary level \[ F(1,18) = 8.358, \ p = .010, \ \eta^2_p = .317 \], and significant difference at the binary versus quaternary level \[ F(1, 18) = 11.951, \ p = .003, \ \eta^2_p = .399 \]. A significant main interaction between frequency band and ROI (see Figure 35) was reported \[ F(2,36) = 7.588, \ p = .002, \ \eta^2_p = .297 \], with significant simple main effects for frequency band moderated by ROI \( p < .001 \), \( p = .003 \) & \( p < .001 \) for the FM, Vis and aud ROI’s respectively (Table 10).

Contrasts reveal a significant difference is reported between the visual ROI and the FM ROI \[ F(1,18) = 8.278, \ p = .010, \ \eta^2_p = .315 \]. Similarly, a significant difference is reported from the FM ROI and the auditory ROI \[ F(1,18) = 15.047, \ p = .001, \ \eta^2_p = .455 \]. A non-significant difference in amplitude is shown between the visual ROI and the auditory ROI \[ F(1,18) = 118, \ p = .735, \ \eta^2_p = .007 \]. A non-significant main interaction between frequency band and arity is reported \[ F(2,36) = .236, \ p = .790, \ \eta^2_p = .013 \].
Table 9 simple main effects of ROI moderated by Arity.

Simple Main Effects - ROI

<table>
<thead>
<tr>
<th>Level of Arity</th>
<th>Sum of Squares df</th>
<th>Mean Square</th>
<th>F</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bin</td>
<td>78.33 2</td>
<td>39.17</td>
<td>16.30</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Tern</td>
<td>99.72 2</td>
<td>49.86</td>
<td>21.44</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Quat</td>
<td>116.43 2</td>
<td>58.21</td>
<td>24.64</td>
<td>&lt;.001</td>
</tr>
</tbody>
</table>

Note. Type III Sum of Squares

Table 10 simple main effects of frequency Band moderated by ROI.

Simple Main Effects - Freq band

<table>
<thead>
<tr>
<th>Level of ROI</th>
<th>Sum of Squares df</th>
<th>Mean Square</th>
<th>F</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>FM</td>
<td>115.04 1</td>
<td>115.04</td>
<td>129.82</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Vis</td>
<td>24.59 1</td>
<td>24.59</td>
<td>12.16</td>
<td>0.003</td>
</tr>
<tr>
<td>Aud</td>
<td>29.90 1</td>
<td>29.90</td>
<td>20.91</td>
<td>&lt;.001</td>
</tr>
</tbody>
</table>

Note. Type III Sum of Squares

Figure 34 shows the interaction between ROI & Arity for the Cognitive EEG experiment. The visual ROI would appear to driving the interaction with a steady increase over arity, without a significant three-way interaction which includes the theta and alpha frequency bands, further analyses of the bands is not warranted.
Figure 35 shows a significant interaction between frequency band over arity. Panel A depicts Theta band and Panel B depicts the Alpha. As the initial three-way interaction is not significant, a follow-up breakdown of 2 way ANOVA’s for each band is not justified.

10.11 Overall summary cognitive EEG

The cognitive experiment did not respond as expected to alpha or theta, especially the later as it was predicted as a cognitively only task, increased amplitude over arity in the theta band, at the FM ROI was predicted. Main effects are reported for frequency band and ROI. Interactions show significance for ROI * arity, and frequency band * arity (see appendix 1,2,3 for sample EEG Topography).
Chapter 11 Study 2 Behavioural & EEG Results with Discussion

The overall aim of study 2 was to replicate the behavioural findings in study 1, with the addition of a concurrent EEG recording. The purpose of utilising the EEG was to determine if (A): subsequent analysis of neural oscillatory activity could aid in separating the perceptual component(s) from the cognitive component(s), utilising theta/alpha task-dependent modulation, by comparing the mean difference of amplitude between the visual, auditory and cognitive region of interests (ROI’s) in the RC visual, auditory and cognitive experiments (B), furthermore if the same alpha/theta frequency analysis could display significant differences in amplitude across increasing levels of WM load namely; binary, ternary and quaternary derived from the RC theory.

As a result of the current study, in relation to the visual experiment, it has been shown that alpha amplitude was selectively modulated by arity over occipital lobes (see appendix 3 for EEG topographies, Visual Experiment, Visual ROI, Binary Condition, Visual Experiment, Visual ROI, Ternary Condition Visual Experiment, Visual ROI, Quaternary Condition). Demonstrating that the visual task responded well to PL. The visual task did not respond to FM theta modulation, as expected. In the analogous auditory perceptual task, modulation in either frequency band did not present. The cognitive task did not respond to alpha (expected) the EEG parameters associated with PL, however, it did not as a supposed cognitive task only, respond to FM theta.

The findings in this current study clearly show that as hypothesised in the visual experiment, an incessant strongly modulated alpha was presented as PL increased, in this case as the level of arity increased. Importantly this alpha de-synchronisation modulation occurred over occipitals electrode sites, as opposed to the frontal or temporal sites, this bolstered the
overall aim of the thesis in a bid to disentangle perceptual from the cognitive load, utilising EEG.

No significant findings were found in relation to frequency modulation for either alpha; PL, or theta; sustained attention components of the auditory experiment. Inspection of the associated plot of means suggests that the overall direction of the experiment was in line with was hypothesised. Namely, that alpha desynchronisation was displayed inversely to the visual experiment, in that alpha was suppressed at temporal recordings sites, temporal sites being associated with auditory processing (Zoefel & VanRullen, 2017). Reasons for this could include: Perhaps the visual system is deactivated during the auditory task (Regenbogen et al., 2012) which in turn could represent a task-irrelevant visual alpha increase. Or perhaps, based on these observed oscillations, a modified updated version of the task is warranted. Suggestions for these modifications will be discussed in the limitation’s sections.

Notable findings from the current study about the cognitive experiment were that it did not respond to alpha or theta as expected. However, it did respond to load, operationalised by arity. The cognitive experiment was expected to display FM theta synchronisation, especially at the FM ROI. Concurrently, alpha de-synchronisation was expected at the visual and auditory ROI’s, as these modes, in theory, should have been made redundant during cognitive only processing.

According to Sauseng, Conci, Wild and Geyer (2015) if two detached areas of the brain are functionally coupled (frequency bands from different areas correlate) it is presumed that a higher level of clear, synchronous neuronal activity can be seen between these detached areas than one would expect from chance. The current visual experiment cannot align with this statement, as in FMT synchronisation modulation was not present, so did not reflect participants sustained attention, coupled with the current alpha suppression over occipital sites.
However, the visual experiment is in line with literature relating to alpha suppression over occipital EEG recording sites and PL, discussed next.

According to Klimesch (1997), investigators claim the EEG frequency within the alpha band; 8 -13 Hz approximately, originates from the thalamus and encourages synchronised neural activity in the cortex. Jensen, (2002) sets out from the viewpoint that memory codes are retrieved via longitudinal paths connecting thalamic nuclei with the cortex, and that alpha is the principal rhythm mirroring the motion of these paths: alpha frequency must be linked to memory performance. The current visual experiment results bolster this ideology with increased modulation of alpha with increased memory load, as represented by the EEG. Additionally, in opposition to other studies in which alpha was seen to reflect idling, alpha peaks were seen to increase with WM load (Jensen, 2002).

Again, alpha increased when participants had to remember one (load 1) or three (load 3) letters (memory set) and perform a search for these letters amid a recognition set containing four letters provided (Gomarus, Althaus, Wijers, & Minderaa, 2006). Sauseng et al., (2005) show that throughout the retention period in WM, an increase in power of alpha oscillations at prefrontal sites and decrease at occipital can be observed from electrode sites when participants engage in top-down processing. The current visual experiment reflects the same alpha power pattern, at the relevant occipital ROI, moreover as arity increases.

In relation to the cognitive experiment, the expectation was for FMT modulation of increased theta and suppression of alpha over visual and auditory ROI’s (see Klimesch (1999). The only statistically significant interaction to report from the current study is between ROI (visual, auditory and frontal midline) and the level of WM load or arity (binary, ternary and Quaternary), but lacks the frequency band interaction for the underlying three-way interaction.
Studies (Gärtner et al., 2015; Katahira et al., 2018) focusing on theta and mental arthritic (which could be said the HGRCT focuses on/taxes exclusively) show as theta power increases load increases. Moreover, one study (Sammer et al., 2007) attempts to track theta activation across the cortex with combined EEG/fMRI, displaying theta activation in the insular cortex, hippocampus, superior temporal areas, cingulate cortex, superior parietal, and frontal areas. Temporal and insular activation is in harmony that theta precisely reflects encoding processes employment of multiple regions of the brain, and their contributions, implying that surface-recorded theta signifies inclusive functional brain states, rather than definite processes in the brain, this binding of widely distributed cortical assemblies, is what cognitive processes are said to rely on (Sammer et al., 2007). This widely distributed theta cortical activity may start to show the difficulty in why any cognitive task, including the current one, fails to capture theta modulation across ROI’s.

A study focused on the processing of numerical information, again which the HGRCT claims to do, showed increased theta and alpha modulation looking at the mental arithmetic ability and the eating habits of children, in fasting and non-fasting participants. Comparative to the non-fasting group, those who sustained fasting presented with greater power increases across sites in upper theta (6–8 Hz) and both alpha bands (8–10 Hz; 10–12 Hz). Increased modulation in theta implies larger strains on WM. Amplified alpha may aid task-essential activity by subduing non-task-essential activity. The current study did not present with alpha synchronisation (an increase of) across arity, so the role of alpha in the processing of RC based cognitive task is inconclusive, based on the result of this study.

In the current study, the visual experiment showed task dependent frequency modulation over visual sites across arity, at the associated occipital or visual ROI. It can be said the visual experiment responded well to the visual RC paradigm. The same cannot be said
for the auditory RC based experiment, which was to act as a control for the perceptual component of the study. The expectations being that significant task-dependent alpha desynchronisation modulation would present at the auditory ROI and synchronisation at the visual ROI, with FMT synchronisation. One possible reason for this is the serial presentation of the stimuli, perhaps within a trial, the participant nominates the first of the four probe stimuli as a match, then focused attention stops, theta decreases, and the response made after the three successive tones (the experiment did not allow a response until all tones were played) does not reflect the moment of task resolution. This limitation in task design is acknowledged here. Although at the piloting stage, auditory experiments were run in which the probes were presented at the same time, which lead to a ‘cocktail party’ type of effect (see Stifelman & Stifelman, 1994), participants found the task too difficult.

The limitations of the RC auditory experiment may also be associated with the apparatus used to collect the data, the EEG. For instance, it has been suggested that the combination of EEG and MEG (magnetoencephalography) provide complementary information. The MEG is less affected by volume conduction, the smearing of signals across the scalp, which contributes to a less noisy signal, and the source of that signal. There is gathering evidence that several auditory activities originate from the superior temporal plane and the lateral surface of the superior temporal gyrus (Shahin, Roberts, Miller, McDonald, & Alain, 2007). Furthermore, it is suggested can only be modelled with tangential sources and radial sources. Radial sources (from gyri) it can be said do not contribute much MEG, but add to the EEG signal, and inversely tangential sources (from sulci). The worry being the MEG would miss contributions from gyri, so concurrent EEG is run (Shahin et al., 2007). The current RC based auditory experiment could benefit from concurrent EEG/MEG to aid source
localisation. Also, a priori sample size calculation using g power (Faul, Erdfelder, & Buchner, 2012) suggest a larger sample size \(n=43\) is required for a \(0.2\) effect size and \(0.05\) confidence interval, this is larger than the observed power of \(0.154\) in this study. This study acknowledges the benefits of a larger sample size and the limitations of the EEG.

In the cognitive experiment, the current study does not result in modulation of alpha, so no response to perceptual load, which is in line with what was hypothesized. The absence of modulation in theta undermines the current effort. Again, it could be an issue of statistical power, as with the previous auditory experiment, considering the experiment was mapped onto the perceptual for the number of IV’s and levels of IV, \(n=43\) would also be required for EEG recording.

There is a concept that alpha suppression could also reflect CL, and that perhaps current approach of FMT synchronisation and alpha visual/auditory ROI de-synchronisation was incorrectly formulated. Palva and Palva (2007) suggest EEG alpha signatures reflect globally coordinated WM processes achieved by cross-frequency phase dependencies. Jensen (2002) contends that alpha synchronisation with increasing WM demands is evident, and this conflicts with previous studies. This was revealed during a time-frequency analysis, that alpha diminished during the last 2.5 seconds of a 2.8 second of retention interval following the probe. Perhaps the current cognitive study would benefit from time-frequency analysis, especially since the participants spend quite a lot of time solving the graphs.

Following on from time-frequency analysis it may be more appropriate if one is to consider that participants engage in sequential processing. This could explain why they show the observed behavioural effect (substantial deflection in slopes over arity for the cognitive task); but it would also mean that the CL at a particular point in time would always be the same, independent of arity. This could explain the absence of EEG effects of arity. Perhaps time-
frequency analysis of several epochs, in a bid to track over time cognitive state; before button response by the participant, could shed light on frequency modulation. In addition to these epochs, splitting of alpha into upper and lower frequency bands may also refine cortical activation representation of RC.

FMT synchronisation and alpha desynchronisation were not present as expected in each of the studies presented currently. Where alpha was significantly modulated in the visual experiment theta was not, neither modulated in the auditory or cognitive experiments. It has for example been posited looking at alpha and theta oscillations in isolation may not advance or help WMC investigation, many conclusory remarks in contemporary studies point towards coupling of frequency bands i.e. (Canolty & Knight, 2010; Sotero, 2016)

Moreover, Colgin (2013) asks if and how theta coupling can bolster communication across brain areas. Colgin suggests that in a given or relevant brain region, theta synchronisation may encourage or lead to a more relevant activation of neurons that will be required ‘downstream’, making sure that the downstream neurons are excitable when the time arrives to play their role in task completion. United with theta’s relatively slow timing, which allows for synaptic delays, meaning it has the temporal characteristics to maintain coupling in spatially segregated cortical areas, as opposed to higher oscillating frequency bands, so is better suited to serve as a neuronal communicator. Future RC based experiments could benefit from frequency band coupling analysis.

A review of the statistical analysis carried out in the present study is warranted, especially when one considers the absence of alpha or theta after revision of the relevant literature indicated a strong probability of their presence. According to Leppink, O’Sullivan and Winston (2017), there is a prevalent practice apparent in academic settings of the interpretation of non-significant findings as support of the null hypothesis, no effect, no
difference or no relation. “Absence of evidence is not the same as evidence of absence” (p.117), p-values and confidence intervals may offer some indication against a null hypothesis, but cannot provide evidence in favour of a null hypothesis.

A two-pronged approach is posited by Leppink et al.,(2017), (1) sample size, power replication research and meta-analyses could oppose the practice of construing non-significant results as indications in favour of the null hypothesis, and that (2) Bayesian hypothesis testing, could aid researchers to assess the strength of evidence in favour of the null hypothesis or against it. In relation to the latter, quite simply this is done by testing one model (null) against another model (alternative).

The testing of the null hypotheses can be thought of as one side of Bayesian statistics. A p-value echoes the probability of the data (or data that is more extreme) given H0. Though, the probability of the data given HA is not considered with the p-value, whereas it is considered in the Bayes Factor ( see Biel & Friedrich, 2018 for an example). According to Dienes (2014) the Bayesian approach allows for the accepting and rejecting of the null hypothesis, to be placed an equal footing, it could be argued the current study using inferential analysis does not allow this, and a Bayesian approach may reflect oscillatory activity across WM load and ROI’s more accurately, as depicted in the profile plots in this current study.
12. Limitations, Future Directions & Conclusion.

12.1 Restatement of Thesis.

The primary aim of this thesis was to investigate if the RC metric could help disentangle PL from CL, achieved by (1) creating analogous perceptual tasks both auditory and visual and pitching them against the HGRCT, a cognitive task. WM was manipulated using binary, ternary and quaternary interactions across all experiments, allowing for analysis of an interaction between WM load and mode (perceptual versus cognitive). An ancillary aim (2) was to investigate if perceptual processing affected cognitive processing in the HGRCT, acknowledging it’s authors claim it was controlled for in the task design.

12.2 Summary of Major Findings

Behavioural results

The behavioural results from study 1 & 2 study, which looked at the RT’s from the RC based visual, auditory and cognitive-based stimuli, underpinned the further EEG investigation based upon the significant differences in RT slopes over arity. Mutually, RTs and errors were increased as RC increased; Perceptual tasks (visual and auditory) divulge similar trends in RT performance, but are considerably slower and with less pronounced RT over arity slopes. This does not seem to be constant with the equivalent RT over arity slope found in the cognitive task. On these foundations, it can be concluded that the CL defined by Halford is not only fundamentally different, but it may be differentiated from the effects of PL measured in the analogous visual and auditory tasks.
EEG results: tasks response to alpha.

Results of the EEG experiments in relation to the visual experiment shows an alpha response with an arity dependent decrease in amplitude, especially in the visual ROI. This suggests the visual task is affected by PL rather than CL, consistent with expectations. The auditory EEG did not reveal a specific alpha response as expected, with no arity task dependent decrease similar to the visual EEG experiment in the corresponding auditory ROI. In the HGRCT task, there was also no specific alpha response. Taken together and with the differences between auditory and visual task data in mind, this suggests the EEG alpha band, in relation to the results of this current study, demonstrates an association with PL, consistent with expectations. See chapter 11 for how alpha is related to other studies.

EEG results: tasks response to Theta

While a Frontal Midline Theta (FMT) response was expected, this was not revealed in these analyses. However, evidence of FMT is not entirely absent: inspection of associated profile plots, and also EEG topographies (Appendix 1) shows theta modulation change over varying levels of arity. In the visual experiment, for example, evidence of FMT activity is shown, not reported in this study as significant, however not absent (as argued in the Bayesian approach). The analogous auditory RC based experiment did not respond to either alpha or theta; contrary to expectation. In the auditory task (see appendix 1) the EEG topographies display theta modulation over varying levels of artiy, suggesting varying levels of sustained attention, not reported as significant here, but evident nonetheless, similarly the Bayesian approach (described in future directions section) may be useful here. The cognitive RC based experiment did not respond to alpha or theta, especially the latter, as synchronised FM theta over arity was expected, mainly as it was claimed to be a ‘purely’ cognitive task.
EEG results: task response to theta and relation to other studies

The current EEG results are not aligned with findings in relation to FMT and sustained attention in that, for example, FMT oscillations were seen to be related to digit span scores and increased memory load (Zakrzewska & Brzezicka 2014). FMT has been found to increase over visual working-memory load and also it is suggested that is not only due to the visual load, but also mental effort related to for example; towards the end of a task of which a participant may have been engaging in for quite some time (Onton, Delorme, & Makeig, 2005b). It has been suggested that when operating under a WM capacity of four, FMT power peaked at load four, and then levelled off from load four to six, suggesting theta activity was load dependent (Zhang, Zhao, Bai, & Tian, 2016). The current HGRCT task did not produce task dependent theta when the interaction of frequency band, mode and arity is accounted for.

Perceptual processing affected cognitive processing in the HGRCT

To assess the effect of perceptual processing on the HGRCT cognitive task one must start by comparing the visual task to the cognitive task in this study, this asks what kind of processes are involved in the visual search task and what processes are involved in the cognitive task. One can start by stating that the visual search task involves a conjunction search, A conjunction search is a visual search procedure, which in this case requires a presence/absence decision to a (trial-wise) previously presented target, presented within a display of distractors, possessing one or more features in common with the target. This design was implemented in order to manipulate levels of visual arity. Similarly, to the auditory task, the cognitive task does not involve a search per se, but the cognitive task does have a perceptual component, and this component does involve analysis of a visually presented display and requires assigning a value to spaces on the graph, or rather the number of spaces, which infer the difference in values
between the bar heights on the graphs. One could argue that after this point this is where the similarity ends, as regards the visual perceptual task, and the perceptual component of the cognitive task. As described earlier the visual task may take upon a memory based or neural map/template-based search, which requires tagging and filtering of relevant and distracting information, until the response is given. This tagging and filtering process is not required in the cognitive task.

Discussed already is the possibility that the binary task could, depending on the trial on occasion be solved without arithmetic and using perceptual processing only (some binary trials might have a more pronounced “pop out” element than others, when one bar height is compared to ten for example as opposed to one bar height compared to two). Evidence for the role of WM in arithmetic claims there are there stages involved namely: the participant must (1) encode (encoding said to be the first process, see Melton, 1963) the presented information, (2) perform the calculation, which may require retrieval from certain memory stores and provide a response (DeStefano & LeFevre, 2004). Compared to visual search the cognitive task shares processing steps up until the encoding stage, then the remaining processing steps of calculation and retrieval makes the resolution of the cognitive task, a lengthier process.

The next part of the cognitive task, after encoding is arithmetic or mental calculation, which according to the Halford et al., (2205) is where CL is manipulated and houses the different processes from the visual search task (no arithmetic or mental calculation required for the visual task), and it is here where the processing requirements and strategies diverge, which in turn explains the longer RT for HGRCT tasks.
12.3 Limitations

Visual search

Participants seeking targets among distractor items, guide their attention with (1) top-down information (based on participants knowledge) and bottom-up information (based on the stimulus independent of previous experience & knowledge). Top-down guidance can be broken down further: explicit information (e.g., verbal description, not used in this current study) and implicit priming by preceding targets (top-down because it implies knowledge of previous searches, arguably used in this current study) (Jeremy M Wolfe, Butcher, Lee, & Hyle, 2003)

Because a visual search paradigm was employed, in an attempt to tax WM one must consider the question of whether visual search requires working memory at all? One theory is that visual search requires no memory (Horowitz & Wolfe, 1998): this theory claims typical visual search practices to be amnesiac, with representations maintained only as long as search is ongoing and the target is not yet located. This model works under the assumption that participants know in advance what targets will look like and rank salient visual information such as size and colour pre-attentively across the search matrix, thereby allowing search to be guided quickly to likely target locations by effectively filtering out distractors that are less probably the target. In another theory, memory is considered unnecessary for search given that change detection and pop out may direct attention, regardless of the number of distractor items, (Liesefeld, Liesefeld, Müller, & Rangelov, 2017).
Visual Vs Cognitive

One limitation in relation to the shared processing steps between the perceptual processes shared by the visual task and the HGRCT is the 'pop out' issue (Horowitz & Wolfe, 1998). Some binary trials might have a more pronounced “pop out” element than others, which is when one bar height is compared to ten for example as opposed to one bar height compared to two, the larger gap pops out. Anecdotal evidence suggests that participants were able to solve the binary version of the cognitive task using perceptual processing alone: the binary HGRCT trials, being the easier of the WM manipulations, could be solved by visual inspection, as it involved only four bars to process. It is possible for significant differences in bar height to pop out without the need to calculate the difference in bar heights, which is essential to task resolution in the ternary and quaternary trials in the cognitive task. This could explain the magnitude of the deflection in the slope relative to the cognitive task over arity which started to increase exponentially from the ternary trials on. It has not been possible in this current study to measure the magnitude of the effect of pop out on trials, regardless of arity.

Auditory experiment limitations: serial vs parallel

Horowitz and Wolfe, (1998) claim memory-driven searches include both serial and parallel target searches. Serial search models assume the mechanism in charge of attention can process the identity of a single item at any one time, once the item has been tagged as a distractor, an inhibitory mechanism excludes it from a revisit. Parallel based search theories assume that identity is ascertained over the length of the trial, in a parallel fashion. When enough information confirms identity, or when all items are tagged as distractors, a response is given. A shared assumption between serial and parallel search is they both operate on
accumulating information about the scene over the length of the trial (Horowitz & Wolfe, 1998).

Reported is a small increase in the auditory RTs representative that the auditory task is possibly accomplished at the end of stimulus presentation. The RTs would suggest information is processed serially by virtue of the serial presentation of the stimuli (they are not presented at the same time as in visual and cognitive modes). The flat RT slopes suggest this information is accumulated and stored (presumably in WM) and RT’s are made simply on the basis of testing the accumulated items in WM against the test sound presented before the task begins. This suggests very efficient chunking, but because there is a perfectly flat search function over parity, it isn’t particularly helpful for comparison against the other condition. This leans towards suggesting the auditory task measures a performance heuristic that is comparatively unconnected to WM, and for this reason, the auditory RTs were not considered any further, and presentation of probes simultaneously were ruled out at the piloting stage as outlined in Chapter 11. No current viable solution is offered to remedy parallel/simultaneous presentation of auditory probes.

12.4 Future Directions

Subtler approach to analysis.

To recap, Alpha and Theta are reported as sensitive to task difficulty (Klimesch 1999; Klimesch, Schack & Sauseng 2005). In Klimesch et al's., (2005) review it is suggested that when attention is focused on a stimulus, whether this is visual, auditory, tactile, or cognitive, the alpha waves routinely disappear or are significantly reduced in amplitude. This occurrence
is commonly called alpha blocking but is also denoted as arousal, activation, and desynchronization, as first described by Berger (Salamon & Post 1965). By contrast, theta activity increases, as reported in the visual experiment here in magnitude as tasks become more difficult (Kropotov & Kropotov, 2016). Similar results were reported by Gevins and Smith (2000) who found that the difficult version of a spatial WM task elicited lower alpha but higher theta activity than the easier task. These results suggest that alpha and theta oscillations are differentially related to task difficulty but interact. As task difficulty increases, alpha activity decreases (desynchronises), whereas theta activity increases (synchronises). The current study used task dependent frequency modulation as a method of analysis, as no baseline, a prerequisite for ERS/EDRS (see chapter 6.2), was used to compare. This study acknowledges that ERS/ERDS may be a subtler approach.

Revaluating the ROI's associated with this current study may also be warranted. Another method of pooling together electrode sites to create ROI's is utilising the ICA method (see chapter 4.2). The idea being, as already mentioned earlier, research has backed up the use of the predetermined ROI's in the current study (see chapter 10.3), based on imaging techniques with a high spatial resolution to bolster correlations between electrode sites and cortical assemblies (see chapter 10.3). The end result would be electrodes pooled into ROI's based on the ICA's ability to disentangle spatial patterns mixed up in the EEG single, using linear composition of the 64 EEG channels to reveal underlying statistical sources (Stropahl, Bauer, Debener, & Bleichner, 2018). Moreover, concurrent use of high spatial resolution imagining techniques with EEG; result in the brain areas, from which the EEG signatures originating from being identified as locales of activation patterns from the analysis of fMRI data. Arguably resulting in ROI's that are more accurately matched from EEG electrode to brain structure (Ullsperger & Debener, 2010).
Comparing electrodes between ROI's

As shown in chapter 10.3, electrodes are pooled together to form ROI's, and as discussed in chapter 3.2 the PFC, for example, has distant spatial regions. One possibility is to explore these spatially segregated regions by statistically analysing theta modulation between electrodes. This proves problematic with the EEG (see chapter 11) as it has a poor spatial resolution, and the, of course, it does not really make sense since the EEG sometimes record a signal very far from the cortical site, known as the inverse problem (Mahjoory et al., 2017), while others claim to have mathematical solutions for this (Maksymenko, Clerc, & Papadopoulo, 2018).

12.5 Conclusion

It can be concluded that as arity increases, it becomes harder to operate on the perceptual information. In the current paradigm, this difficulty is measured in the different RT's between cognitive and visual modes and this difficulty can only be explained in terms of processes acting to solve the HGRCT, in addition to the processes involved in visual-processing and visual-WM encoding. It also seems that the cognitive task apart from the occasional binary trial may share the same perceptual processing steps (encoding) up until the stage at which calculations are required to resolve the HGRCT. At this stage, after initial encoding processing involving WM operations and mental calculation is required, (see DeStefano & LeFevre, 2004), which are not required for the visual task. Later processing explains the exponential cost in RT for cognitive relative to either visual or auditory tasks,
especially at the ternary and quaternary levels. The explanation advanced above may also explain why at the binary level of arity RT differences between modes are small.

In relation to memory formation and maintenance which are mental operations that Halford et al.,(2005) claim are necessary for their HGRCT task, the issue that the task still only taxes visual WM remains. Although the RT slows would indicate the processes to be quantitatively different, it is not easy to parcel out visual encoding from mental operations and by extension to the latter, the processes concerned with the formation and maintenance of visual WM. The question is how to differentiate between perceptual and cognitive loads accurately and thereby correctly evaluate the fundamental tenet of RCT, that the WM load in Halford’s tasks is cognitive. The two loads are related, and significance of relational integration (the main process involved in the HGRCT) has emerged in the literature, for example, Oberauer (2005a) who claims that the primary function of WM can be best explained as a system of temporary relational systems with a finite capacity for binding together component representations. The problem is compounded by the idea that the relational systems concerned are best conceptualised as ‘bindings’, a topic which has a large literature base examining the physiological response to perceptual tasks (Robertson, 2005; Treisman, 1999; Treisman, 1996; Whitney, 2009; Wolfe & Cave, 1999). This current study was unable to add to this binding debate.

Limitations of the current study have been discussed ranging from: issues of serially presented stimuli (auditory experiment), how the cognitive experiment may benefit from time-frequency analysis, similarly splitting up of frequency bands in lower and higher based Hz would add an extra layer of analyses. The use of other imaging techniques namely: MEG and the revaluation of the role of alpha in cognition. Suggestions for future research include the
coupling of frequency bands built into experimental design, using ICA to create new ROI's, the Bayesian approach to statistical analyses, the latter to put the acceptance and rejection of the null hypothesis on an equal footing, thus allowing more scope to assess neural oscillations and the ability to attempt the disentanglement of perceptual and cognitive load in future experimental work.
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Appendix 1

Below are representative EEG topographies in the Visual, Auditory and Cognitive experiments, over each level of arity between the Theta and Alpha frequency bands.

Auditory Binary Condition
Auditory Experiment Ternary Condition
Auditory Experiment Quaternary Condition
Visual Experiment Binary Condition
Visual experiment Ternary Condition
Visual Experiment Quaternary Condition
Cognitive Load and Working Memory Capacity; Within and Between Modality

Cognitive Experiment Binary Condition
Cognitive Load and Working Memory Capacity; Within and Between Modality

Cognitive Experiment Ternary Condition
Cognitive Load and Working Memory Capacity; Within and Between Modality

Visual Experiment Quaternary Condition
Appendix 2

Representative EEG Topographies Mode matched to ROI

**Auditory Experiment, Auditory ROI, Binary Condition**
Cognitive Load and Working Memory Capacity; Within and Between Modality

Auditory Experiment, Auditory ROI, Ternary Condition

[Diagrams showing brain activity with labeled regions: Theta and Alpha]
Auditory Experiment, Auditory ROI, Quaternary Condition

Theta

4.81 μV 0 μV 6.81 μV

Alpha
Visual Experiment, Visual ROI, Binary Condition
Visual Experiment, Visual ROI, Ternary Condition
Visual Experiment, Visual ROI, Quaternary Condition
Cognitive Load and Working Memory Capacity; Within and Between Modality

Cognitive Experiment, Cognitive ROI, Binary Condition
Cognitive Experiment, Cognitive ROI, Ternary Condition
Cognitive Load and Working Memory Capacity; Within and Between Modality

Cognitive Experiment, Cognitive ROI, Quaternary Condition
Appendix 3
Representative EEG Topographies all modes (visual, auditory & cognitive), ROI’s (visual, auditory & cognitive) and Levels of Arity (binary, ternary & quaternary) for Theta and Alpha.

Auditory Experiment, Auditory ROI, Binary Condition
Cognitive Load and Working Memory Capacity; Within and Between Modality

Auditory Experiment, Auditory ROI, Ternary Condition
Auditory Experiment, Auditory ROI, Quaternary Condition
Auditory Experiment, Visual ROI, Binary Condition
Auditory Experiment, Visual ROI, Ternary Condition
Auditory Experiment, Visual ROI, Quaternary Condition
Auditory Experiment, FM ROI, Binary Condition
Auditory Experiment, FM ROI, Ternary Condition
Auditory Experiment, FM ROI, Quaternary Condition
Visual Experiment, Auditory ROI, Binary Condition
Visual Experiment, Auditory ROI, Ternary Condition
Visual Experiment, Auditory ROI, Quaternary Condition
Visual Experiment, Visual ROI, Binary Condition
Visual Experiment, Visual ROI, Ternary Condition
Visual Experiment, Visual ROI, Quaternary Condition
Cognitive Load and Working Memory Capacity: Within and Between Modality

Visual Experiment, FM ROI, Binary Condition
Cognitive Load and Working Memory Capacity; Within and Between Modality

Visual Experiment, FM ROI, Ternary Condition
Visual Experiment, FM ROI, Quaternary Condition
Cognitive Load and Working Memory Capacity; Within and Between Modality

Cognitive Experiment, Auditory ROI, Binary Condition
Cognitive Experiment, Auditory ROI, Ternary Condition
Cognitive Load and Working Memory Capacity; Within and Between Modality

Cognitive Experiment, Auditory ROI, Quaternary Condition
Cognitive Load and Working Memory Capacity; Within and Between Modality

Cognitive Experiment, Visual ROI, Binary Condition

![Diagram of cognitive experiment results showing brain activity in Theta and Alpha bands.](image-url)
Cognitive Load and Working Memory Capacity; Within and Between Modality

Cognitive Experiment, Visual ROI, Ternary Condition
Cognitive Load and Working Memory Capacity; Within and Between Modality

**Cognitive Experiment, Visual ROI, Quaternary Condition**
Cognitive Load and Working Memory Capacity; Within and Between Modality

Cognitive Experiment, FM ROI, Binary Condition
Cognitive Load and Working Memory Capacity; Within and Between Modality

Cognitive Experiment, FM ROI, Ternary Condition
Cognitive Experiment, FM ROI, Quaternary Condition
Appendix 4

Reaction time means for Study 1, within subjects’ behavioural experiment.

Reaction times in Milliseconds study one

<table>
<thead>
<tr>
<th>Mode</th>
<th>Arity</th>
<th>Mean</th>
<th>SD</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Auditory</td>
<td>Binary</td>
<td>366.0</td>
<td>128.7</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>Ternary</td>
<td>366.3</td>
<td>117.2</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>Quaternary</td>
<td>367.2</td>
<td>102.2</td>
<td>13</td>
</tr>
<tr>
<td>Visual</td>
<td>Binary</td>
<td>946.3</td>
<td>134.2</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>Ternary</td>
<td>1104.6</td>
<td>118.7</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>Quaternary</td>
<td>1165.8</td>
<td>160.0</td>
<td>13</td>
</tr>
<tr>
<td>Cognitive</td>
<td>Binary</td>
<td>4512.5</td>
<td>1185.5</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>Ternary</td>
<td>10810.2</td>
<td>3055.9</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>Quaternary</td>
<td>20222.4</td>
<td>6202.4</td>
<td>13</td>
</tr>
</tbody>
</table>
Appendix 5

Reaction times for study 2, behavioural between subjects

Reaction time in Milliseconds for study two

<table>
<thead>
<tr>
<th>Mode</th>
<th>Arity</th>
<th>Mean</th>
<th>SD</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Auditory</td>
<td>Binary</td>
<td>441.3</td>
<td>124.96</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>Ternary</td>
<td>443.0</td>
<td>151.69</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>Quaternary</td>
<td>441.9</td>
<td>109.41</td>
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Appendix 6

Cognitive EEG Experiment, amplitude measured in Millivolts for each Frequency Band (Theta, Alpha), ROI (FM, Visual, Auditory) and level of Arity (Binary, ternary, Quaternary).

<table>
<thead>
<tr>
<th></th>
<th>N</th>
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<th>SD</th>
<th>SE</th>
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<tbody>
<tr>
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Appendix 7

Visual EEG Experiment, amplitude measured in Millivolts for each Frequency Band (Theta, Alpha), ROI (FM, Visual, Auditory) and level of Arity (Binary, Ternary, Quaternary).

<table>
<thead>
<tr>
<th>Descriptives: Mean Amplitudes in Millivolts</th>
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<th>SD</th>
<th>SE</th>
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<tbody>
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Appendix 8

Auditory EEG Experiment, amplitude measured in Millivolts for each Frequency Band (Theta, Alpha), ROI (FM, Visual, Auditory) and level of Arity (Binary, ternary, Quaternary).

<table>
<thead>
<tr>
<th>Descriptives: Mean Amplitudes in Millivolts</th>
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<td></td>
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<td>N</td>
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Appendix 9

Appendix 10

Grand averaged power spectra for the visual EEG experiment at the binary level

Of arity across the FM, Visual and Auditory ROI’s.
Grand averaged power spectra for the visual EEG experiment at the ternary level

Of arity across the FM, Visual and Auditory ROI’s.
Grand averaged power spectra for the visual EEG experiment at the quaternary level of arity across the FM, Visual and Auditory ROI’s.
Grand averaged power spectra for the Auditory EEG experiment at the binary level of arity across the FM, Visual and Auditory ROI’s.
Grand averaged power spectra for the Auditory EEG experiment at the ternary level of arity across the FM, Visual and Auditory ROI’s.
Grand averaged power spectra for the Auditory EEG experiment at the quaternary level of arity across the FM, Visual and Auditory ROI’s.
Grand averaged power spectra for the Cognitive EEG experiment at the binary level of arity across the FM, Visual and Auditory ROI’s.
Grand averaged power spectra for the cognitive EEG experiment at the ternary level of arity across the FM, Visual and Auditory ROI’s.
Grand averaged power spectra for the Cognitive EEG experiment at the Quaternary level of arity across the FM, Visual and Auditory ROI’s.