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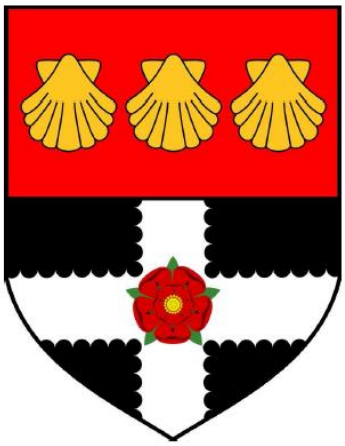

The cognitive responses to UK railway signals during train driving

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Thesis Submitted for the
Degree of Doctor of Philosophy

Cybernetics
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August 2017

Declaration

I confirm that this is my own work and the use of all material from other sources has been properly and fully acknowledged.

Paul Wright

Acknowledgements

The completion of this thesis was only possible with the support and cooperation of many people. My thesis advisors Professor Slawomir J.Nasuto and Professor Kevin Warwick have been a great source of wisdom, provided a broad range of knowledge and thoroughness of their thoughts. The countless hours that Slawek invested in reviewing and discussing my work.

Thanks to Dr. Ian Daly and Dr. AJ Portelli for training in the use of the EEG recording equipment and guidance on the application of artefact removal from the EEG data. Dr. Etienne Roesch for his guidance in the experiment design and introduction to cognitive psychology, and Dr. Mathew Spencer for passing on his Matlab code and knowledge of phase-locking functional-connectivity networks. And to all the staff in the School of Systems engineering who have help support this project in so many ways.

All the EEG recording volunteers without whom there would not be any data to analyse. My former colleagues at First Great Western and South West Trains for feedback about the initial experiment designs. My colleagues in the Brain Embodiment Laboratory who have provided vital knowledge. To all the people not already acknowledged who have influenced my journey to this point both positively and negatively.

Special thanks to goes to my lovely wife Azin.

The final word goes to those who could not be here at the project's completion.

Abstract

When a train driver's error results in a red, stop signal being passed without authority there is the potential for disaster. These events are termed a "SPAD", signal passed at danger without authority. Occasionally these incidents have led to tragedies such as the Ladbroke Grove accident in 1999. This accident led to 31 fatalities and over 523 injuries. Investigations of incidents have resulted in safety advancements that decreased the number of incidents and accidents. Despite all these efforts SPADs still occur and very little is known about the cognitive effects that the track-side signalling system has on the driver during normal operational conditions.

The motivation for understanding the cognitive and behavioural effects of the routine patterns of railway signalling is to identify potential high and low risk situations. The identification of neural correlates that predict the driver's state of readiness prior to a potentially dangerous situation. The combination of knowledge of these events and the insights into their causes could allow better systems, operational methods and logistics to be designed.

This is an Electroencephalograph, (EEG) study to identify neural correlates that are used to identify high and low risk response and perceptual accuracy situations. The behavioural data is recorded from the keyboard responses and used to guide the EEG analysis. The tools applied to solving the research problem are artefact detection and removal from the EEG data, followed by analysis for patterns and features.

The phase-locking functional-connectivity reveals repetition priming, antipriming, and neural precursors to correct and erroneous responses. The phase-locking for certain graph metrics are found to vary significantly prior to response errors.

The EEG analysis reveals that multiple cortical region coordinated cognitive activity is required to successfully perform multiple paradigm tasks. Certain channels and regions of the brain are important in creating a cognitive state that facilitated future correct responses. Different states are required to promote response accuracy for different forthcoming events.

Keywords

Electroencephalograph, EEG, train driving, railway signalling, phase-locking, functional-connectivity, repetition priming, antipriming, repetition suppression, negative priming and error prediction.

Glossary of terms

Artefact – A component of the recorded electroencephalograph data that originates from non-neurological sources. It contaminates the time-series data.

AP – Antipriming. The cognitive effect that occurs when repetition priming ends.

EEG – Electroencephalograph.

EMD – Empirical mode decomposition.

EMDPL - Empirical mode decomposition phase-locking.

ERP - Event related potentials.

IMF – Intrinsic mode function.

ISI - inter-stimulus interval. The time interval between stimulus onsets.

KSS – Karolinska Sleepiness Scale. This is a method of subjectively measuring the sleepiness or alertness.

Multi-SPAD – A signal passed at danger without authority more than 6 times in the last 5 years.

ND – Node degree. This is a network metric.

NNND – Node nearest neighbour degree. This is a network metric.

NNNPLV – Node nearest neighbour phase locking value. This is a network metric.

NP - Negative priming. A cognitive effect that results from the active suppression selected stimulus targets.

PLV – Phase-locking value. An index synchronised between a pair time-series.

RP – Repetition priming. The cognitive response when exposed to same stimulus repeatedly.

SPAD – Signal passed at danger without authority. An official UK railway industry term.

TDSEP - Temporal decorrelation source separation. A non-zero time lagged method.

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Chapter

1. Introduction

1.1 Background

This thesis describes an investigation into the cognitive effects that railway signalling systems have on the train driver's performance. On rare occasions trains pass red, stop, signals without authority. Occasionally these incidents result in disaster. The Ladbroke Grove accident of 1999 resulted in 31 fatalities and over 523 injuries [25 and 33]. As a result a significant amount of investigative effort has been applied to understanding the causes of these events and reducing the number of signals passed at danger (SPAD). The cognitive effect that routinely encountered sequences of track side signals have on the driver preceding a SPAD is not clearly understood. Insights into the patterns of events that result in variation of the train driver's cognitive performance have obvious safety benefits. SPADs that are caused by driver error are considered to be the most serious type.

Accidents have prompted investigations and analysis of a range of potential contributory factors [26, 27, 29, 30 and 96-101]:

- Signalling system design.
- Train safety systems.
- Driving cab equipment design.
- Human factors.
- Psychological factors.
- Shift patterns.
- Behavioural analysis of the driver.
- The driver's daily work routine.

Procedural and technological improvements have led to an ongoing improvement in safety as measured by reducing reported SPAD's and fatalities [102 and 103]. However, history has shown that there is always the possibility of operational accidents, incidents caused by human error, and the design of the system. On rare occasions these errors result in a major accident with loss of life and significant equipment damage.

Throughout this technological evolution the key requirement for the train driver to correctly observe and react to the track side signals has remained unchanged. The capabilities of humans have remained the same throughout the development of the systems. The objective cognitive impact that the signalling information has on the driver's cognitive state during both correct and erroneous response situations is little understood.

1.2 Research objective

The research objectives in this thesis are to gain insight into the cognitive effects that normal railway signals have on the train driver: advancing the objective understanding of the cognitive factors associated with these operations. The application of Electroencephalograph (EEG) analysis, and signal identification accuracy will be used to measure the cognitive and behavioural effects of the following:

- The sequences of repeated signals.
- The changes of signal indication under normal operational conditions.
- Junction signals that prime for a change of visual target.
- Identifying precursors to correct and erroneous identification of the signals.

The transport industry has previously viewed the laboratory models as too simplistic. Conversely, many simplified models may be considered difficult to apply to complex real world situations. The objective is to bridge this gap by applying scientific methods to simulations of train driving.

1.3 Contribution to science

The contributions to science are the results of the investigation of the effect that the present day UK national railway signals have on the train driver's cognitive processes using electroencephalograph (EEG) analysis. The investigation is focused on normal operating

conditions with the purpose of aiding future safety improvements. The effects of repetition priming and antipriming are found to occur for the sequences of signals. Antipriming is associated with changes in the sequence of signals which are ordered by known “grammar” rules.

EEG features that are precursors to correct and erroneous responses to the task of identifying and responding to the current signal image are found. This analysis reveals features that preceded variations in response accuracy by one or two trials. The mixture of shared and unique features that preceded no change, change of stimulus and junction (changes of lateral position) trials are found.

The knowledge that short-term train driving perceptual or response accuracy variations can be identified in advance could be applied to railway safety related questions. The enhancements to the design ergonomics and understanding of their cognitive impact has the potential to avert future accidents or operational incidents.

Scientific laboratory based methods are successfully applied to the investigation of the complex real-world problems associated with train driving. The results demonstrate that laboratory based effects can be detected during the cognitive processing of computer simulations of track side signals. This indicates that relatively simple cognitive paradigms can yield important knowledge about human interactions with the real-world.

1.4 Layout

This is the layout of the following chapters:

Chapter 2 – Literature review. This contains a brief introduction to the operation of present day UK national railway signal systems and an overview of the task of train driving. The current extent of the behavioural, psychological and EEG analysis of train driver performance is reviewed. An introduction is provided to the operation of EEG recording. The existing methods of EEG analysis and phase-locking functional-connectivity analysis are discussed.

Chapter 3 – Experimental design. The details of the experiments and reasons for the design choices are stated here. Experiment one uses a sequence of single stimulus. Experiment two uses a pair of stimuli and is an extension of experiment one.

Chapter 4 – Methods. The analytical methods that are applied to the behavioural and EEG data are documented here.

Chapter 5 – Experiment one results. The behavioural and EEG data analysis. Experiment one contains a single stimulus per trial experiment. The analysis of the EEG data uses the methods described in chapter 4. The effects of the stimulus sequencing rules, repetition and changes-of-stimulus are assessed. The objective is to identify the statistically significant effects and correlations within the subject's responses. The emergent patterns of behaviour are tested to find which patterns of stimulus effect response accuracy. The phase-locking functional-connectivity analysis of the EEG data is documented here. Phase-locking functional-connectivity is used to investigate the changes to the overall patterns of cognitive activity associated with response accuracy.

Chapter 6 – Experiment two results. The behavioural and EEG data analysis for experiment two, which is a dual stimuli per trial experiment, and is an extension of experiment one. The analysis procedures and objectives are the same as those in chapter 5.

Chapter 7 – Discussion. The discussion of the behavioural data and EEG features detected in sequences of signals, changes in signal sequence, junction signals, and the precursors to correct and erroneous identification of the signals. The possible applications of the knowledge gained to the railway industry.

Chapter 8 – Conclusion. The contributions to science that this thesis makes are discussed. The connection between the EEG markers, behavioural responses and the research question are described. The cognitive effects that the railway signal sequences have upon the driver under normal operational conditions are identified. The application of laboratory based experiments to real-world questions, limitations and potential future developments are discussed.

Chapter

2. Literature review

2.1 Introduction

This thesis is an investigation of the effects that track side railway signalling systems have on the train driver's cognitive performance. On rare occasions trains pass red, stop signals. Occasionally, these incidents result in disaster. The Ladbroke Grove accident of 1999 is an example that resulted in 31 fatalities and over 523 injuries and was caused by a train passing a signal at danger without authority [25 and 33]. The industry term for these events is a "signal passed at danger" without authority (SPAD). The cognitive effect that routinely encountered sequences of track side signals have on the driver preceding a SPAD is not

clearly understood. Insights into the patterns of events that result in variation of the train driver's performance have potential safety benefits.

Section 2.2 is a summary of the aspects of train driving and UK national railway signalling related to the research question. This gives the reader an understanding of the key aspects of the train drivers working environment, critical factors and basic design of the systems related to this project. The current state of the art in train and car driving safety research that use EEG based approaches.

Section 2.3 reviews the cognitive and behavioural effects that relate to train driving and the experiments conducted. Section 2.3 discusses EEG analysis methods and related work on phase-locking and complex network analysis. Finally section 2.5 concludes the literature review.

2.2 Train driving and railway operations

2.2.1 Train driving

The task of the train driver includes a broad range of skills interacting with complex systems. There are numerous factors that could be considered to contribute to train driving safety:

- including shift patterns
- fatigue management
- trackside equipment design
- driving cab internal design
- timetable design

This thesis focuses on investigating the cognitive processes involved in the train driver's interaction with the track side signals under normal operational conditions.

The train driver is highly trained and is required to retain information from a detailed rulebook [7], understand the mechanical operation and handling characteristics of each type of train operated. Additionally, the driver needs to memorise each route's speed limits, station locations and platform capacities, signal and track layout and routing options and any operational information specific to it. The daily operational information and timetables/schedules are provided in printed format. There is a large amount of information to prioritise correctly and act upon throughout a journey. The daily routine requires good

levels of alertness and selective attention skills to correctly and safely apply the correct and right knowledge and actions. This may allow the design of systems and timetabling methods that are optimised to reduce human error rates.

Trains are heavy objects requiring significant braking distances that are often beyond the visual range of the driver. For example a suburban passenger train requires approximately 800m to stop smoothly from 60mph (100kph), and an express train 3,000m plus to stop smoothly from 125mph (200kph). Freight trains require longer braking distances for a given speed. This means that a system is required to give the driver advanced warning of any stop signals. The signalling communicates the advance information to the driver using lineside signals which are described in section 2.2.2.

2.2.2 Railway signalling

This section provides a brief description of the UK national railway signalling operation. The signalling system regulates the safe movements of trains on the railway network. The trains need to be kept a safe distance apart and conflicting movements prevented.

Sufficient advanced warning is required prior to a red signal to ensure that the train can safely stop. This means that the trains have to be kept a safe distance apart, and the driver given advanced warning of the stop signals to ensure safe separation. The routing changes at the junctions are centrally controlled and beyond the immediate control of the train driver. Routing information is also communicated to the train driver via the signalling system. A detailed explanation of this is provided in experimental design chapter 3, sections 3.4 and 3.5.

The track side signals are normally positioned where they can be easily seen, subject to the limitations of the terrain and infrastructure, and in the driver's natural eye line. The standard four aspect system of signalling is used in the experiments. There are a minimum of two warning, cautionary signals before the red stop signal, see figure 2.1. The distance between the double yellow signal and the red is the braking distance suitable for the maximum line speed and train with the greatest braking distance. There is no direct transition from either green or double yellow to red under normal operational conditions. Given the significant braking distances it is important that the train driver identifies the cautionary signals and reacts correctly.

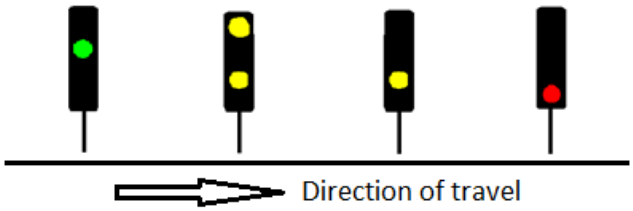

Figure 2. 1. This diagram illustrates the minimum sequence of cautionary signals that precede a red (stop) signal under the four-aspect signalling system on the UK's national railway network. A cautionary signal is one that displays a single or double-yellow light. The braking distance is between the double-yellow and red signals.

At junctions the routing information is communicated to the driver using a special type of signal. These are illustrated in figures 2.2 and 2.3. The illuminated bars above the coloured light indicate the pending route. This allows the driver to control the speed correctly in advance of the junction and verify that the route is correct.

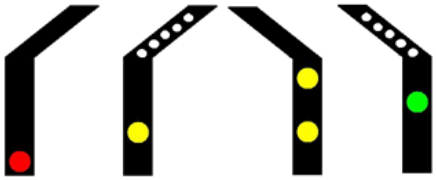

Figure 2. 2. These are examples of the junction signals. When the angled bar above the signal is illuminated it means there is a change of track at the next trial. The change is one step to the left or right.

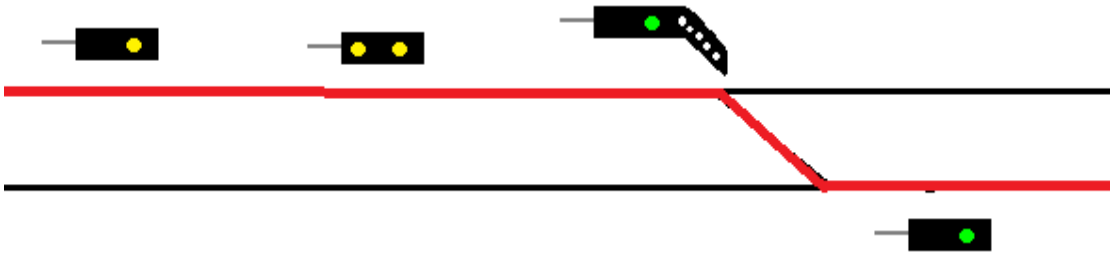

Figure 2. 3. This illustrates the routing of a train from one track to another using a junction signal. The signal incorporating the junction indicator is located prior to the junction. The junction indicator is only illuminated if the route is set to change to the adjacent track. A proceed aspect and a blank junction indicator means there is no change of track at the following junction. If a red aspect is displayed the junction indicator cannot be illuminated.

The systems have multiple levels of defence designed to prevent human error or mechanical failure causing an accident. The signalling systems allow the trains to operate safely at normal

speeds at day or night and in conditions of reduced visibility. This section is a summary of the operation of the signals selected for the experiments. A full explanation of the whole UK signalling system is provided in the Network Rail rulebook, modules S1 to S7, [7].

2.2.3 Signals passed at danger - SPAD

On rare occasions trains pass signals at stop (danger) without authority termed a SPAD. These can have serious consequences, especially when the cause is driver error. These create the risk for collisions with other trains or derailment [32].

In some incidents the nature of the driver's error is clear. Misjudgement of braking distance for the weather conditions, micro sleeping or distraction are known causes of SPADs. There are many other SPADs where the causes are not easily identifiable. The driver's physical reactions are correct until a critical moment when they fail to identify or respond to a signal correctly. The typical causes of signal reading errors that relate to this experiments are misidentification of signal meaning, failure to detect a change in repeated sequences, and "read-across" errors. A read-across error can occur when the driver is faced with multiple tracks and signals, then visually focuses on a signal associated with another track. The repetitive nature of the present day signals may also be a contributing factor. The differences in the cognitive processes that underpin correct and erroneous action during every day conditions is unknown.

A train driver working in the London suburban area can encounter up to 2,000 signals per week and at least 50,000 per year. Significant response or attentional errors are very rare. A train operating company with 1,000 train drivers may have approximately 20 SPADs in a year. This equates to a significant signalling related driver error rate of approximately 1 in 2,500,000.

Some signals repeatedly experience SPADs and are known as multi-SPAD signals. The underlying causes for these is not always clear, nor are simple solutions. Tables 2.1 and 2.2 list SPADs and the multi-SPAD signals respectively for one region of the national railway network during 2012. Table 2.2 lists multi-SPAD signals, those passed more than six times in the last five years. Signal SN63 has by far the highest SPAD rate incidence in the Western region with a count of 15. It is in a busy area of track near Paddington. There are a number of other adjacent signals on the same gantry for the same direction of travel with very similar

appearance. The adjacent signals do not have the same SPAD count. There are multi-SPAD signals in the vicinity of many major stations.

Table 2.1 lists the individual SPADs for 2012 for the Western region of the UK national railway network. The summaries of the reasons behind them frequently cite attention or selective attention related driver errors. Read across errors are referred to as selective attention mistakes when the driver actively focuses on the wrong visual target in an area where many are visible simultaneously. Once the driver has locked onto the wrong target attending, the correct one may have been inhibited. The incidents where a failure to react or remember a cautionary signal are attentional errors. An initial lack of vigilance or subsequent failure to attend the correct target are possible triggers for these types of errors. Once an erroneous perception or model of the world has been initiated further attentional errors may result. The initial location, cause and nature of the origin of the cognitive error is not clear.

The cognitive state of the drivers prior to the incidents is not known. However, the existence of multi-SPAD signals in the immediate vicinity of zero or low SPAD rate signals suggests that the incidents are not one-off individual failings. Advancing the understanding of how the normal operation of the track side signals effect the driver's cognitive processes has potential safety benefits.

The 2012 SPAD's

	Date	Signal	Location	Cause
1	31/1/12	SN28	Royal Oak	*Read across*
2	10/2/12	WM531	Blackwater	*Failed to obey Caution*
3	5/3/12	SN6109	Old Oak Common	*Unaware that signal applied*
4	14/3/12	R23	Penponds	*Failing to set the DRA*
5	15/4/12	W119	Bradford Junction	*Started previous platform on yellow signal*
6	28/5/12	SN36	Royal Oak	*Failed to obey Caution*
7	8/6/12	E72	Dawlish	*Distraction and failed to obey caution*
8	2/7/12	B106	Westerleigh Junction	*Braked late on final approach*
9	4/7/12	SN6081	Old Oak Common	*Unauthorised wrong direction movement*
10	6/7/12	S133	Iver	*Started previous platform on yellow signal*
11	22/7/12	B27	Bristol West	*Read across on gantry*
12	29/7/12	B26	Bristol East	*Read across on gantry*

Table 2. 1. This table shows the SPADs for the Western region for 2012, table from [74].

LINE OF ROUTE	LINE DESCRIPTION	SIGNAL	LOCATION	LAST SPAD	TOTAL NO. OF SPADS
GW103	Paddington to Uffington	SN63	Subway Jn Line 4 (Down)	07.07.2010	15
GW103	Paddington to Uffington	SN276	Southall West Up Relief	14.11.2010	5
GW103	Paddington to Uffington	SB6420	Foxhall Jn Bi-directional Relief	03.02.2010	3
GW105	Uffington to Fordgate via Box	SN232	Swindon Down Yard	08.04.2010	4
GW105	Uffington to Fordgate via Box	SN201	Thingley Jn Up Yard	17.01.2010	2
GW105	Uffington to Fordgate via Box	B55	Bristol East Jn Up/Down Relief	30.06.2008	3
GW108	Fordgate to Penzance	E118	Taunton East Jn Down Main	15.06.2010	7
GW108	Fordgate to Penzance	R23	Penponds (Cambourne) Down Main	14.03.2012	2
GW400	Barnt Green to Westerleigh Jn via Dunhampstead	B149	Yate Up Charfield	29.03.2011	5
GW450	Stoke Gifford East Jn to Bristol East Jn	B154	Bristol East Jn Down Filton Main	29.04.2010	2
GW500	Reading to Cogload Jn via Westbury & Frome A/LS	TR542	Reading Westbury Line Jn Up Westbury	19.10.2011	2
GW500	Reading to Cogload Jn via Westbury & Frome A/LS	TR865	Newbury Up Platform Loop	28.10.2012	4
GW700	Gloucester Barnwood to Severn Tunnel Jn	G37	Barnwood Jn Up Main	21.07.2009	4
GW870	Barry to Bridgend (Vale of Glamorgan line)	AW3	Aberthaw Down Main	02.06.2011	3
GW900	Pilning to Fishguard Harbour	C20	Leckwith Down Main	09.06.2009	3
SO560	Redhill to Guildford	GD907	Chilworth Down Reading	19.06.2011	3
SW105	Clapham Jn to Weymouth	E763	Millbrook Down Fast	04.11.2008	6
SW110	Woking Junction to Portsmouth Harbour	HT59	Portsmouth & S'sea Down Main	03.06.2011	2

Table 2. 2. This is a list of multi-SPAD signals for the Western region of the national railway network from 2012. A multi SPAD signal is a signal that has been passed without authority six or more times in the last five years, table from [150].

2.3 Driving performance research

This section focuses on train and car driving research that uses EEG. The research methods that use objective measures of cognition to assess performance, EEG and behavioural statistics are of particular interest. Research into driver safety for both railway and road transport is a popular and relevant field of research. The knowledge gained has the potential to save lives.

Investigations of various aspects of train driving have been conducted. These include psychological and behavioural studies using self-rated fatigue, reaction time, blink rate, heart rate and eye tracker investigations provide limited objective information about the state of the subjects [8, 36, 38, 81, 89, 104 and 105]. Self-assessed fatigue rates can lag behind the subject's actual fatigue level if it is changing. It is subject to unknown variation between individuals. Blink rates and duration give an objective fatigue measure, but fail to provide any

information of the detailed cognitive state of the participant [8 and 76]. The Karolinska sleepiness scale (KSS), has been verified as an accurate method of self-rated sleepiness and alertness rating. It has been shown to be consistent with EEG measures of fatigue [4, 5 and 92]. This scale has equal positive and negative weighting and a neutral response option. The KSS system of alertness rating is used for gathering the participants' pre-experiment statistical information.

It is important to define what is meant by the terms fatigue, attention, vigilance and alertness. Vigilance was defined as a "state of readiness" by Mackworth in 1957 [85]. These terms are commonly used when referring to human performance and human factors. The meaning associated with the terms can vary between authors and paradigms. In this project the term fatigue refers to the level of sleepiness. Attention is used in the context of maintaining mental focus on the correct stimulus and primary task. Vigilance and alertness are different to attention, they refer to the subject's ability to adapt their cognitive state to new events as they arise.

The question being asked is how do the sequences of track side signals affect the driver's cognitive state? The variations in response accuracy may have multiple causes. The role that the levels of fatigue, behavioural factors, repetition of the signals, or the particular sequence of the signals have is investigated.

2.3.1 Train driving

There are a range of potential issues hampering the application of EEG recording equipment in the real train driving environment. If the wearing or presence of the equipment is thought to be a distraction, and therefore a safety issue, the safety and regulatory authorities will not permit its use. The present day railway environment has many sources of electrical interference from high voltage power systems. These operate at between 750 and 25,000 volts and hundreds or thousands of amperes. Many of them are not shielded fully against electro-magnetic emissions.

Simulators offer a practical alternative that resolves most of the safety, technological and bureaucratic issues. Current simulators provide a full range of controls and realistic rich audio visual virtual environments. The high fidelity simulators present multiple stimuli and paradigms in parallel. The question of which types of cognitive information can be reliably extracted from the EEG data in these situations is open. When using a commercial simulator

synchronising the EEG recording accurately to the stimulus presentation and responses may be difficult if that facility is not present in the software. Multiple stimuli and response combinations can occur in parallel. Bespoke simplified simulated 2D or 3D environments are an effective solution.

To date the application of EEG analysis to investigate train driving performance has focused primarily on fatigue detection. The methods used either alpha band power, alpha and theta band power, or alpha, beta and theta band power ratios as a simple numerical fatigue indices [36, 37, 52, 77, 78, 80, 85 and 86]. However, there are many causes for variation in frequency band power within the brain. Each frequency band has multiple roles depending on the location of the electrode and the subject's primary cognitive task. The benefits and reliability of these methods of fatigue detection in real-world working environments have yet to be confirmed. A combination of measures may provide a reliable solution. If systems of this type show that human cognitive performance is consistently poor at certain times of day or during particular work patterns the implications for the railway industry are significant. It would confirm many common observations that are currently ignored. The negative effects of directly switching from a shift ending at 02.00 and one that begins at 04.00 26 hours later. Or repeatedly switching between morning and evening shift patterns with a minimum 12 hour break during a number of consecutive days. This could have significant logistical and financial impact.

An eye tracker study of train drivers of trains in service by the Rail Safety Standards Board, RSSB investigated the visual strategies employed by drivers [89]. A limitation of the study is that it could not verify if the drivers are cognitively attending the object of visual focus. A possible interpretation of their results is that the driver's eyes tend to look straight ahead for most of the time. This is also the position of least effort for the eye muscles. The driver's in-depth prior knowledge of the route and the constancy of the railway environment would enable them to respond to many stimulus without having to centre their vision on them.

A psychomotor vigilance test, self-rated fatigue study of simulated train driving found that self-rated fatigue correlated with more train handling errors and later responses [28]. The results of this study is that self-rated fatigue using their method is a good detector of the conditions of increased potential for accident. If the same situation where transferred from the simulator to the real world, the drivers would have to continue working when fatigued. There is normally no one else there to take over their duties.

The current techniques do not provide a detailed understanding of the cognitive processes that affect driver performance. If a response error is not due primarily to excessive fatigue, then what caused it? The repetition of stimulus, changes-of-stimulus or sequencing may play a critical role, alternatively errors may simply occur at random. The difference between EEG features that precede, correct and response errors are of interest. These could provide insight into why the errors occur.

2.3.2 Car driving

Car driving in both real and simulated environments is more accessible to researchers than the railway environment. EEG analysis during car driving has focused primarily on fatigue detection. The methods use either alpha band power, or alpha and theta band power based indexing methods [91, 92 and 93]. A study into the effects of long monotonous car driving reported a progressive increase in fatigue during the journey [86]. The effects of distraction were investigated using EEG analysis. The findings were that the right frontal cortex region is most effected by distraction [94]. While offering a simple method of objectively gauging participant alertness, the analysis does not provide detailed fine time resolution information of the cognitive processes involved in the variations in performance.

The effect of anticipation as measured by EEG and its effect on response time is analysed showing that the EEG amplitude at the Cz electrode decreases significantly immediately before braking [107]. Many studies use EEG signal amplitude to measure attention or alertness. A combination of frequency band power spectra are shown to measure the adverse effects of monotonous driving in [93]. An investigation of general levels of cognitive engagement with the driving task show that the right frontal cortical region is important for spatial tasks [94]. Anticipatory braking EEG features are identified using event related potentials, (ERPs), and power spectra based methods to detect these features in [106 to 109]. Blink rates, heart rates and power spectra are used to provide indexes of alertness during monotonous driving. Heart rates decrease and blink rates increase combined with bursts of alpha frequency as the monotony increases [76]. These investigations illustrate that EEG analysis is useful for investigating cognitive performance during car driving.

2.3.3 Summary of driving analysis

Self-rated subjective fatigue measures have been found to provide accurate long-term measures of driver fatigue. They lack high time resolution, and are prone to human subjective judgement. The EEG frequency band power offer an objective higher time resolution method of fatigue detection. However, the methods may give rise to false positives or negatives due to the multiple cognitive roles of the frequencies involved and variation between individuals. When driver response related errors occur the underlying precursors are not fully understood.

2.4 EEG methods of analysis

The extraction of patterns from EEG data require pre-processing of the time-series. Any artefacts caused by unwanted external sources need to be removed leaving cleaned EEG data. Chapter 4, section 4.3 describes the procedure in detail. The cleaned channels can be decomposed into frequency-power spectra and phase information. The features of these can be used to compare the cognitive states of different experimental conditions or their evolution over time. These measures offer an insight into the cognitive states of the brain in high time, low spatial resolution.

The differences between the cognitive states of significantly low and high response error rate situations indicate the differences in brain activity associated with them. This knowledge helps to develop an understanding of when and why success and error occurs. Electroencephalograph, EEG, analysis provides ways of objectively measuring, and of contrasting patterns of cognitive activity that are associated with significantly high and low levels of human performance.

2.4.1 Why use EEG?

When humans provide subjective information in response to questions there are likely to be variations within a subjects reporting accuracy, and across subjects. Humans are not fully aware of the details of their cognitive activity. The inputs and resulting behaviour are the only level of detailed awareness. The perceptions that the senses produce can vary, and are prone to inaccuracies caused by sensory illusions. Objective measurement of the brains

patterns of activity and matching them to behaviour can be achieved using the analysis of electroencephalogram EEG recordings.

EEG technology is a non-invasive and painless method of objectively recording the brains activity [63 and 110]. The EEG records some of the human brains activity in high time and low spatial resolution. The system can detect events that happen in tens of milliseconds at a low spatial resolution. The standard 10-20 layout with 19 electrodes is used in this project as illustrated in figure 2.4 [73]. Each single electrode records activity of large populations of cortical neurons. The EEG recording provides objective data about the cognitive responses of some of the cortices to stimuli. It can be co-registered with behavioural and stimulus presentation data so that the EEG responses can be correlated with the significant patterns within behavioural data. Consistent EEG data features can be found by investigating subsets of the recording using the behavioural data to meaningfully group the data.

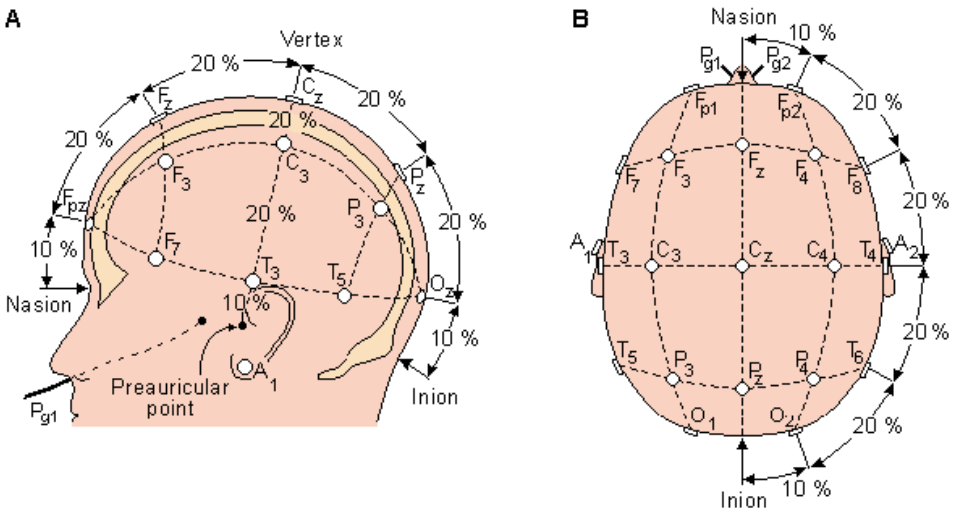

Figure 2. 4. The standard 10-20 EEG electrode cap layout. Image from http://www.bci2000.org/wiki, October 2015.

The recording of EEG data during driving tasks in both real vehicles and in simulators is possible because the equipment is light, portable, and operates with standard computer technology. The cost of the equipment and its operation is relatively low. The details of how EEG recordings work and the history of the technology are provided in section 2.4.2. The processes of artefacts removal which is required to make the EEG data usable is discussed in section 2.4.3. The methods of analysing the cleaned EEG data are described in section 2.4.4.

2.4.2 History of EEG and recording the data

Recording human brain signals using EEG technology was first documented by Hans Berger in 1929 [35]. The first recordings compared waking and sleeping states, and are used to investigate neurological ailments such as epilepsy.

Advances in EEG recording technology have enabled the investigation of a broad variety of cognitive phenomena. The sensitivity of the electrodes applied to the scalp and amplifier performance allow increasing numbers of electrodes to be used, increasing spatial resolution. The sensitivity and noise profile of the amplifier has improved producing better signal to noise ratios and higher sampling rates. The higher sampling rates allow examination of the EEG time series in smaller time intervals.

The EEG electrodes capture the cortical electrical activity immediately in their vicinity. The recorded signals originate from the pyramidal neurons that have parallel alignment in groups in the cortical regions on the surface of the brain [35], see figure 2.5. The alignment of the pyramidal neurons combined with their mass activation produce a signal that can be detected at the scalp, see figure 2.6. The recorded signal at an electrode is the voltage difference between it and a reference electrode. When many electrodes, channels of data are recorded in parallel a common reference electrode(s) is used. This results in a set of signals that are directly comparable.

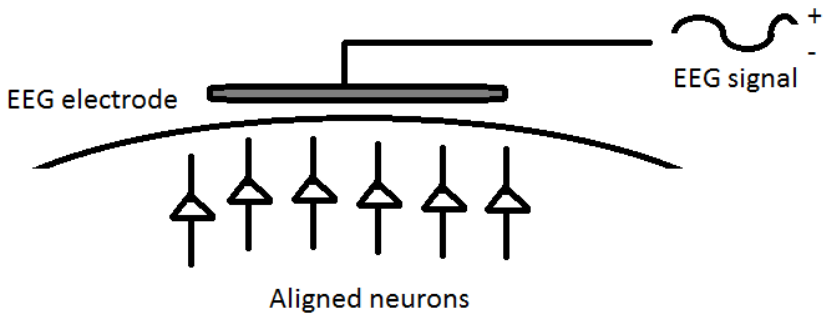

Figure 2. 5. This diagram illustrates the pyramidal neurons immediately beneath the skull. The weak electrical signals produced by the neurons mass action has a number of barriers to pass through to be detected at the scalp by the electrode.

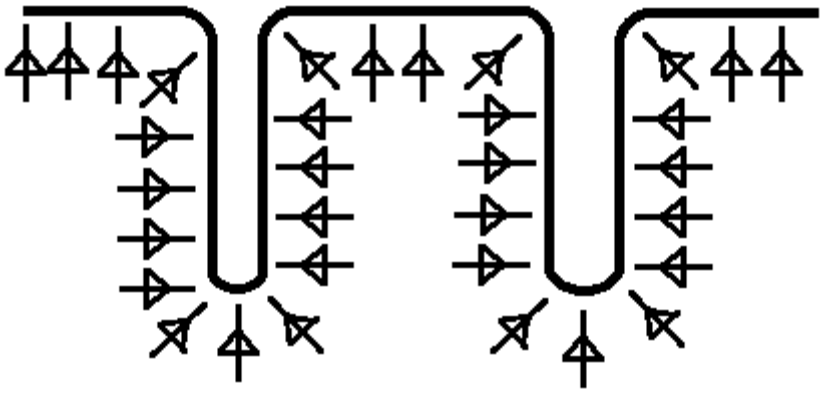

Figure 2. 6. This illustrates the parallel alignment of the pyramidal neurons that produce the mass action activity detectable by the EEG electrodes.

EEG electrodes are either passive or active. The active electrodes receive the signal then process it on site using localised circuits before transmission to a computer. Passive electrodes transmit the raw signal along wires to a central amplifier. The signal is further degraded by resistance in the wire and external signals the wire receives from electrical equipment. The active electrodes use an amplifier at the site of the electrode and transmit the EEG data in digital format.

The recordings in these experiments used wet passive electrodes made of silver chloride, AgCl. The passive electrodes have a smaller range of effective frequency detection than the active electrodes. Their signal to noise ratio, (SNR), is less favourable. The combination of the 1/f frequency power profile of EEG and the decreasing (SNR) means that reliable analysis of frequencies beyond 50Hz is limited.

The electrical impedance between the electrode and scalp is reduced by applying a small amount of conductive gel. Wet electrodes depend on the conductive gel to maintain an effective signal, while dry electrodes do not. The impedance at recording electrodes is reduced to no more than 10kΩ, the reference electrode ideally needs to have the lowest resistance of all.

The amplifier receives one data stream per electrode in the form of a weak signal in the order of microvolts. This is amplified and converted into digitalised discrete samples. The sampling rate is set at a constant level and the data fed in a constant stream to the controlling computer where it is processed and stored on the disc drive for offline processing. The flow of data is illustrated in figure 2.7. Increasing the sampling rate allows for smaller time interval

to be analysed, however, the volume of data and processing time increases proportionately. The number of channels and duration of a recording need to be considered to ensure that the data can be practically processed.

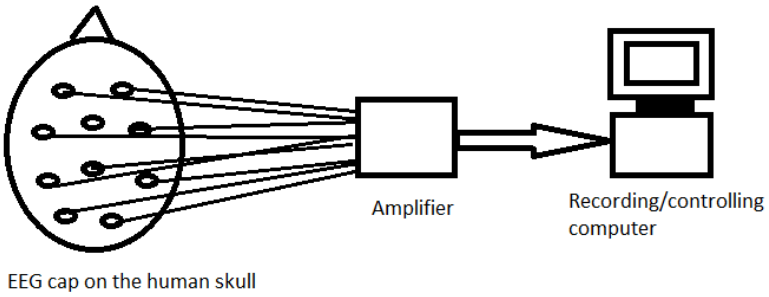

Figure 2. 7. This diagram illustrates the flow of the EEG data from the human scalp to the amplifier and then to the computer that stores the data and controls the experiment.

The EEG data stream needs to be co-registered with the subject's responses, and presentation of stimulus. The sampling rate of the computers keyboard limits the accuracy of response timing to within 15ms. This is found by measuring the smallest time interval between continuous repeating key presses on the Windows 7™ operating system. The presentation of the visual stimulus on the computer screen is subject to random variation. A monitor refresh rate of 60Hz can cause up to 16.6ms delay between image generation and appearance. The input and output timings vary independently and in parallel. Their combined accuracy is still within 16.67ms.

The controlling computer places event markers in the data stream that align the EEG data with the experimental events. The event markers are used to segment the EEG data stream into trials that are aligned with the stimulus onset. The reaction times are calculated from the difference between the stimulus onset marker and the response marker. The clock on the controlling computer is the single temporal reference point. The recorded and stored EEG time series data is co-registered with the input and output events of the controlling computer for offline analysis.

2.4.3 Artefact removal

The recorded EEG data will contain artefacts that can obscure the recorded brain activity. These must be removed for the EEG data to be accurately analysed. The artefacts originate from a variety of external sources, the 50Hz of the mains power the experimental apparatus requires, electronic devices such as mobile phones, radio and TV transmitters. The environment provides an ongoing stream of man-made electrical signals. Movements of the limbs, head, eyes, eye blinks and heart beat all emit electrical signals that the EEG recorder will detect [23 and 31]. Some of the artefacts can be avoided or minimised, however, they will always be some present in the EEG time series.

There are a range of methods of artefact detection and removal. The simplest is by visual inspection of the time series and deletion of any artefactual trial channels. This has two limitations, the total loss of data where artefacts occur, and the potential lack of consistency caused by human factors. There are solutions that allow greater retention of EEG by mathematically separating the noise and brain activity using blind source separation. Blind source separation estimates the original sources of the time series data that are maximally independent without prior knowledge of the origins of the data source [23, 39, 82 and 83].

There are a variety of independent component analysis (ICA) based methods used in order to estimate the original components. The Eigen decomposition uses a zero time lagged correlation matrix. The EEG time series channels may not be zero time lagged. The temporal decorrelation source separation (TDSEP) methods identifies the optimum time lag for maximally independent decomposition of the EEG time series. The independent components ICs are inspected manually or automatically and rejected if they are considered to be artefacts. The amplitude of clean EEG data is typically within +/-100µV [31]. The automatic testing of ICs for artefacts can be achieved using different methods, the kurtosis, amplitude and entropy. The kurtosis measure has been successfully used to detect artefacts [83]. It has been criticised for leading to false rejection of ICs and failing to detect artefacts [31]. The Renyi's entropy based selection methods reported being 92.6% accurate [31]. Other entropy scores tested in the same investigation but are less accurate.

The time series are reconstructed using only the components that are considered to be good EEG. A combination of automatic then manual inspection of the EEG data can yield the best results. The human inspector has a lower volume of work. The combined use of automatic

and human inspection can reduce the time required to perform the task and increase accuracy.

The cleaned EEG data may still contain noise and minor artefacts. A balance needs to be achieved between rejecting artefacts and not rejecting ICs that may contain valid information. The full details of the TDSEP ICA artefact removal procedure applied to the experimental EEG data are described in the methods chapter 4, section 4.3.

2.4.4 EEG data analysis – Phase-locking

The EEG data that is cleaned of artefacts as described in section 2.4.3 is ready for analysis. The analysis methods are designed to convert the time series data into information. The information gives insight into the cognitive processes correlated with particular experimental conditions. The time series data can be decomposed and compared using a variety of methods. Each method extracts a particular type of information about the cognitive state of the brain [62, 63 and 70].

The EEG time series contain amplitude, frequency and phase information. The amplitude is a measure of the magnitude or strength of the signal at an instant in time. The frequency is the rate at which the signal cycles between turning points. The phase is the angle or position within the oscillatory cycle the time series is at in an instant of time. These properties can be extracted from the time-series data. Phase locking analysis has reveals cognitive responses that signal magnitude alone do not [65 and 88].

The EEG time series are non-linear and non-stationary, they do not have consistent statistical properties throughout their duration [71]. The fast Fourier transformation, FFT, is a common method of decomposing EEG time series into its frequency, amplitude and phase components. The method is based on sine wave decomposition of the data. The EEG data is not a sine wave, and its degree of similarity to one is constantly changing. The method is known to introduce edge effects near the boundary of the sampling windows. A data driven approach would suit the data set because it does not make assumptions about the underlying mathematical properties of the time series.

Empirical mode decomposition developed by Huang et al is a data driven method of time series decomposition [41 and 42]. The time series are decomposed into mono frequency intrinsic mode functions, (IMF). The sum of all the IMFs and residual recreate the original

time series. Inspection of the first 20 to 30 samples of each IMF from real datasets exhibit initial edge effects. The accurate decomposition of the initial 30 sampling points is unlikely. The frequency, phase and amplitude of each IMF is calculated using the Hilbert-Huang transformation. The full details of the algorithm are provided in the methods chapter 4, section 4.4. One of the limitations of empirical mode decomposition, (EMD), is that it does not always separate combinations of frequency that are close in frequency, or those combinations that produce inflections where turning points used to occur: this effect also occurs in FFT. The frequency power spectra of EMD is sparse. Typically only 10 to 15 IMFs are produced per time series decomposition by EMD, which limits the selection of frequencies that will appear in the spectra. The details of the application of EMD are shown in Chapter 4, section 4.5.

Phase-locking gives a different measure of the time series dynamic than amplitude or frequency. The phase lock value is a numerical measure of how consistent the phase angle is between a pair of time series within a time interval [63, 71, 75, 115 and 116]. The equation for calculating the instantaneous phase of a time series is shown in equation 2.1. Figure 2.8 illustrates what perfect phase-locking between a pair of time series looks like.

$$Y(t) = \frac{1}{\pi}\, p.v. \int_{-\infty}^{\infty} \frac{x(t)}{t - \tau} d\tau$$

$$\theta(t) = \arctan\left(\frac{y(t)}{x(t)}\right) \qquad \text{Instantaneous frequency}$$

Equation 2. 1. The Hilbert-Huang transform for calculating the instantaneous phase and amplitude of a time-series, P.V is Cauchy principal value.

The measurement of phase-locking is between two time series. The phase-locking between pairs of electrodes is measured to establish the pattern of phase-locking between them during a time interval. The methods chapter 4, section 4.8 details how this method is applied to the experimental data. When all the combinations of electrode pairs have their phase-locking value calculated functional connectivity data results, see section 2.4.5 for details.

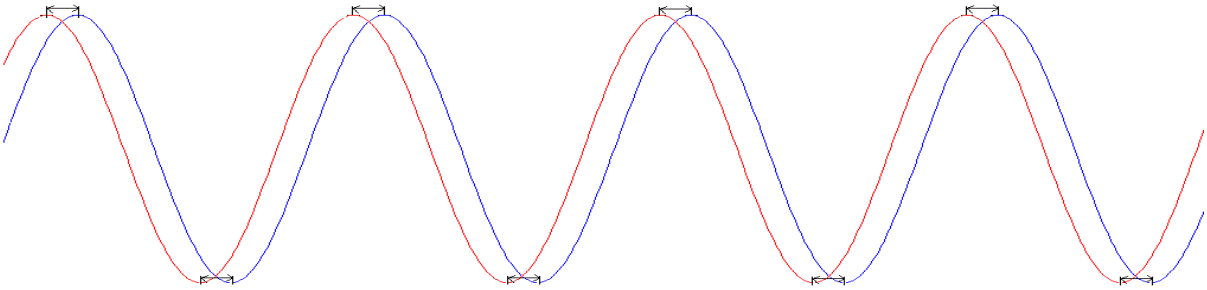

Figure 2. 8. This graph illustrates an example of perfect phase synchronisation between a pair of sine waves. The less variance in the set of phase offset values the greater the phase-locking value. The phase offsets are consistent throughout the time interval which means the phase locking value is 1, a value of 0 would mean no phase locking.

The phase-locking value found for a pair of time series may occur by chance due to the nature of the particular values. The significance of the phase lock is tested using bootstrapping. Bootstrapping is a data driven solution that uses reshuffled versions of the time series to find the probability of a chance result [113 and 114].

In visual spatial attention experiments phase coupling is found to increase between the prefrontal and posterior parietal regions during effective attention [112]. Phase synchrony within the posterior-parietal region was found to have a key role in working memory tasks [60]. The level of alpha phase locking is shown to forecast weather visual stimulus will be perceived. Phase locking between the frontal and parietal regions is required for successful response to attentional blink trials [70]. Beta phase synchrony in the frontal-parietal-occipital network was shown to predict perception of future stimulus. This revealed the presence of large scale phase locking networks [59]. These show that the presence of phase locking in the alpha and beta frequency bands across the frontal, parietal and occipital regions are related to successful visual attention and perception.

2.4.5 Functional connectivity

The task of train driving and the experiments conducted in this thesis involve multiple cognitive effects at the same time. The combination and magnitude of cognitive responses may vary over time according to the situation. Functional connectivity can reveal more information about the wider pattern of cognitive events without the need to separate out individual EEG features. The nature of the significant patterns of overall brain activity can reveal how cortices work as a collective.

Functional connectivity is the analysis of the interactions between regions of the brain or EEG electrodes. EEG data has been used to reveal activity in localised regions of the brain. Analysis of localised EEG features has been successful in identifying the EEG signatures of specific tasks. The EEG features of attention in particular frequency bands is identified in [51, 56, 68, 60 and 70]. Studies of this type capture significant localised changes that characterise different conditions over time. When important cognitive tasks occur in parallel they may not exhibit the same EEG features compared to a single primary task. A limitation of this method is that the influence of interactions between regions of the brain or EEG cap electrodes are overlooked.

The combination of empirical mode decomposition and phase-locking, (EMDPL), as described in section 2.4.4, can be used to map the functional connectivity in a time window [63, 71, 75, 115 and 116]. These can be modelled as networks that capture the overall pattern of brain activity. Figure 2.9 illustrates an EEG functional connectivity graph. The networks are complex structures that represent a time series of phase-locking patterns. Even with a relatively low number of electrodes each network or evolution of it can be complex. The characteristics of these can be assessed using graphs [47, 115 and 116]. Significant changes of the spatial and temporal dynamics of a graph metric can reveal how the whole brain is responding. These techniques give reproducible measurements when applied to MRI data [117, 119 and 120]. The combination of EMD and phase-locking detection has been successfully used for EEG analysis [71, 75, 84 and 87]. The detection of significant phase-locking is thought to be caused by long distance interactions between cortices. The timing and frequency that these transient interactions occur at is considered to give further information about the nature of the interaction [49]. Refer to the Methods chapter 4 section 4.7 for the method of application to the experimental data.

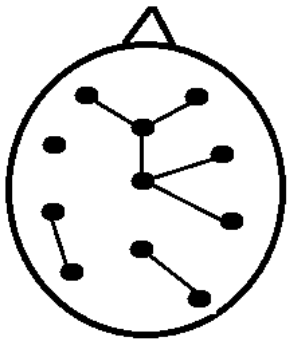

Figure 2. 9. This diagram illustrates functional connectivity. The dots represent the EEG electrodes and the lines between them phase-locking connections between them.

The combination of functional connectivity and EEG phase-locking have not been used to analyse car or train driving. Functional connectivity patterns in cognitive activity are more commonly studied in fMRI experiments [46, 49 et al]. Attention is a key factor in train driving; the role of functional connectivity in attention is studied by [62]. The discussion shows that both long and short range phase synchronisation are required for effective cognitive attention. The requirement for sufficient functional connectivity in successful visual recognition of faces is detailed in [53]. The link between increased levels of functional connectivity and positive task performance is shown in [54]. A study investigating the cognitive responses to repeated pictures found that the global count of phase synchrony links decreased with repeated presentations [24]. An MEG study of responses to visual stimulus found that the used graph metric of node degree in the occipital cortex decreased post-stimulus compared to pre-stimulus [58]. A relationship between functional connectivity and ability to perform a task has been demonstrated for a range of cognitive demands.

2.5 Behavioural and cognitive and effects

This section introduces the cognitive and behavioural effects that are related to the experiments. They directly relate to attentional activities involved when processing track-side signals. The cognitive effect is described, how it relates to the experiments and train driving, refer so section 2.2 for information about train driving. The task of tracking and responding to the sequences of track-side signals in the experiments includes these cognitive effects:

- repetition priming (RP)
- antipriming (AP)
- flanked distractor and negative priming (NP)
- target switching

These cognitive effects may be present at the same time to varying extents during the experiments and real train driving. A review of the cognitive effects and how they apply to this project are discussed in the sections 2.5.1 to 2.5.4. Each of these sections description what the cognitive effect is and how it applies to train driving and these experiments.

2.5.1 Repetition priming

Repetition priming is the cognitive effect caused by repeatedly experiencing the same stimulus without interruption [12, 14, 18, 20 and 21]. This results in the repetition suppression neurological effect [12 and 48]. Repetition suppression is the reduction in recorded EEG brain activity amplitude and spatial scale in cortices associated with the cognitive response. This is thought to indicate that the brain is becoming more efficient at performing the repeated task. The number of repetitions it took for habituation to occur in the experiment in [61] is five. This is consistent with the repetition priming results in the experiments conducted in this thesis.

Habituation has been considered to be bad for railway safety. However, the drivers training and route learning processes depend on repetition to the extent that the task and associated knowledge become second nature. If the driver performs well by the current standards it is considered “positive priming”, and when the same process results in a negative outcome it is called habituation. The accepted standards of operation are subject to change. This could be seen as an example of the disparity between the designs of a man-made system and the nature of human cognition. It is interesting to note the reported cognitive effects of habituation appear to be the same as repetition suppression.

Response accuracy to primed targets was found to be significantly higher than random baseline or antiprimed targets (see section 2.4.2 for antipriming) [15]. This supports the idea that repetition-priming and repetition suppression lead to enhanced performance. Repetition suppression was also found to cause a measured decrease in inter-electrode connectivity [48]. The experiments in this thesis have the repetition paradigm throughout. This occurs in conjunction with other cognitive effects.

The measured EEG effects of repetition priming, fatigue, and habituation are very similar, however the resulting behaviour is clearly different. When conducting EEG analysis of repetition priming other tests for fatigue are also required. These can exclude fatigue as a potential cause of the observed reduction of feature scale. The benefits of improved cognitive performance and response accuracy due to repetition priming should have a positive effect on train driver’s performance.

Repetition priming occurs when the train driver encounters a series of signals all showing the same pattern of colour light(s) [12, 14, 18, 20 and 21]. During a train journey the driver routinely experiences repeated sequences of green signals, see figure 2.10. This will

eventually be interrupted by a cautionary signal, when correct identification and positive response is vital. When trains are in congested areas it is common for the driver to experience repeated cautionary signals. The repeated sequence can lead to an expectation that the next signal is not at stop or a more restrictive indication. If the repetition priming effect reduces the driver's ability to respond correctly to the break in sequence the probability increases of a red signal being passed without authority. Repetition priming may help learning situations by improving cognitive efficiency, but once the task is familiar hinder correct responses.

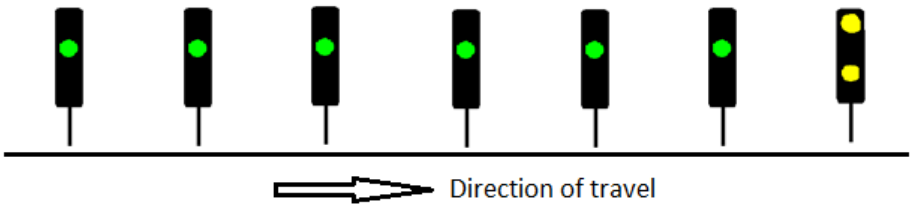

Figure 2. 10. This diagram illustrates a sequence of signal indications where repetition priming is followed by antipriming. The repeated signals cause repetition priming and the change in the sequence antipriming.

2.5.2 Antipriming

Antipriming (AP) is related to repetition priming. The effect of antipriming is investigated much less then repetition priming. It occurs when a repeated sequence of consecutive stimulus that cause repetition priming is broken. When the stimulus changes to one that requires some of the previously allocated cognitive resources they need to be reassigned to the new stimulus. The process of reassignment of cognitive resources is antipriming [13, 15 and 16].

Antipriming events have been found to have a higher error rate than the repeated trials surrounding them [16] and increase reaction time [15]. The size of the regions of the brain active and the amplitude of recorded EEG increase. The degree of similarity with the original priming stimulus has an effect upon the scale of the antipriming.

Antipriming can occur when the driver processes lineside signals. When a sequence of signals with the same structure and indication are encountered repetition priming occurs. Once the sequence is broken by a signal showing a different indication and sharing common structural elements antipriming can occur, see figure 2.10. When the new signal indication is cautionary a positive response from the driver is vital. This is because a cautionary signal warns the driver of a red signal ahead. Since antipriming increases response errors it suggests that a change

of signal indication will increase the risk of driver error. It may also cause an increase in cognitive workload impacting their ability to perform other required tasks.

2.5.3 Flanked distractors and negative priming

A flanked distractor is a non-target stimulus that is present at the same time as the target stimulus [90 and 95]. When attending the target cognitive effort is required to eliminate a response to the distractor. This situation can increase the cognitive workload because one target needs to be selected and the other inhibited [111]. Figure 2.11 illustrates a flanked distractor, only one stimulus is the target. In the example illustrated either the left or right stimulus can be the target.

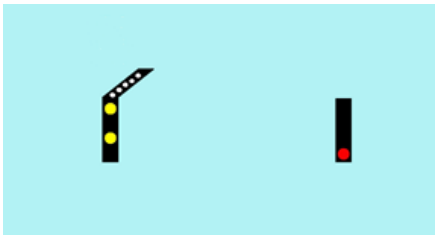

Figure 2. 11. This illustrate the target and flanked distractor stimuli used in an experiment trial. The left stimulus is the target and right one the flanked distractor.

The cognitive mechanism used to inhibit the distractor is negative priming. Negative priming (NP) is the identification and active non-attendance of the distracting stimulus [61]. Negative priming was discovered by Budayr and Dalrymple-Alford in 1966 [111]. This was proposed as the cognitive mechanism by which the distractors are suppressed allowing primary focus to be on the target [90, 95, 111, 118, 121]. The NP effect is associated with increased reaction time and error rate. The disabling of spatial pre-selection is suggested as the possible function [95]. Fixing the location of the stimulus in the field of view reduced the variation of reaction time [95].

The trials in experiment 2, see figure 2.11 for an example, involve a flanked distractor and negative priming; see chapter 3 section 3.5.6 for details of the experiment design. The position of target stimulus, left or right, changes in some trials during the experiment. There are junction trials that indicate a pending change of target position, as illustrated in figure

2.12. The sequence rules of stimulus apply throughout the change of spatial position. The target trials following the junction trial will be in the spatial position of the previous flanked distractor. The cognitive response to this is an increase reaction time and increase in response error rate [61 and 118]. The change of spatial position might have shorter reaction time recovery periods than for antipriming events [122]. Both the target and flanked distractor sequences follow the stimulus sequence rules. A shorter reaction time recovery period for flanked distractor changes suggests that potential targets in different spatial positions do not share the same cognitive resources to the same extent as purely repetition priming/antipriming tasks.

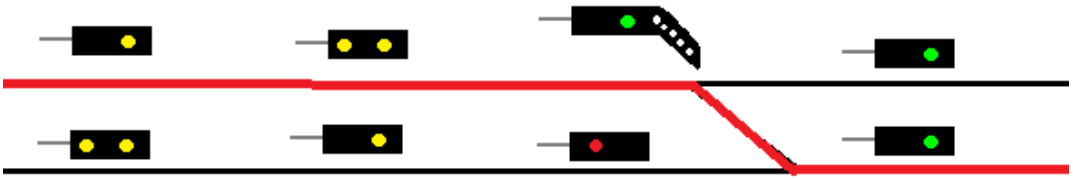

Figure 2. 12. This diagram illustrates a sequence of signals prior to and during a changing of track indicated by a junction signal. The red line marks the path that the subject follows, and the correct target stimulus are located immediately to the left of it.

When a train driver is working in an area with more than 2 tracks it is common for them to be faced with multiple signals at the same time. Only the signal immediately associated with their current track needs to be attended. Any other signal(s) facing them that are located on the other tracks need to be discarded. This situation is very similar to laboratory based flanked distractor-negative priming experiments. If the attends and responses to the flanked distractor they have made “read across error”. A read-across error that occurs on the approach to a red (stop) signal when the distractor is displaying a proceed indication can result in the red signal being passed at danger (SPAD).

Junction signals are located before a track junction that can route the train onto a new track. Figure 2.12 illustrates a junction signal being used to communicate a change of track from left to right. This driving situation is similar to the flanked distractor and target changing. One difference is that following the change of track the new target signal will be in the middle of the driver’s field of view; the old sequence of signals will be to one side. This means that relative spatial position of the new target may not change significantly. This may partly negate any cognitive effects related to the new spatial location [122].

Flanked distractors and negative priming directly relate to attending the track side signals with parallel tracks of the same direction of travel. It is a good model of the cognitive effects that can occur in this situation.

2.5.4 Summary

Repetition priming, antipriming and flanked distractor-negative priming are considered in the experiments. These can occur in parallel due to the design of the railway signalling system. On a sequence of signals where the driver only sees one facing him at a time repetition priming and antipriming occur. When there is another sequence of signals on a parallel track and they face the driver additional cognitive effects are present. The adjacent signal that needs to be ignored is a flanked distractor. The cognitive mechanism for discarding the distractor is negative priming. When trains operate in areas with multiple tracks they can change tracks at junctions. Here the driver needs to switch attention to the new sequence of signals.

The repetition priming and antipriming occur during all sequences of signals. Repetition priming occurs during the sequences of repeated signal indications that are common during driving. Antipriming occurs when there is a break in the repeated sequence. The previous and new stimulus have similarities requiring reallocation of cognitive resources. During this time the subject's reaction time and response accuracy can increase significantly.

The flanked distractors are found on parallel tracks that have additional signals that face the driver. These do not apply to them and need to be recognised as such an ignored. Negative priming is used to actively discard the flanked distractors that are present in all the trials in experiment 2. The flanked distractors also follow the same sequence grammar rules as the target sequence. All the experiment 2 trials have a combination of RP or AP, and NP. Target switching occurs at junctions where the first stimulus before the junction primes the driver of a pending change of spatial position and signal sequence to follow. After the junction the next stimulus on the new track is the start of the new sequence in a different spatial location.

2.6 Literature review conclusion

There are established experimental paradigms and analysis methods of measurement that can be applied to the experimental data. These assist in extending the understanding of the cognitive impact that the normal operation of the UK national railway signals have on the train driver.

Fatigue, alertness, visual attention and error related effects have been shown to consistently produce particular features in EEG data for phase-locking analysis. Basic indicators and precursors of these cognitive states have been developed. They provide insight into the particular cortical interactions and activity that is associated with them.

Functional-connectivity can be used to analyse the overall brain activity patterns. The nature of the large scale interactions within the brain highlights information about the operation of the whole brain that are not seen from localised analysis methods. The brain is not a set of isolated modules, despite the specialised function of each cortex their coordinated collective function is required for successful performance of real-world tasks.

The paradigms, repetition priming, antipriming, negative priming and flanked distractor-target switching can be used to model the cognitive effects the experimental stimulus may have upon the subjects. These paradigms have verified EEG responses from phase-locking analysis that have been shown to be robust and reproducible. The complexity arising from the multiple paradigms can be addressed with the application of these methods.

Chapter

3. Experiment design

3.1 Introduction

This chapter describes the design of the experiment and the decisions that influenced them. There are a range of real life and experimental factors to balance. Scientific experiments require simple and clearly identifiable measures. In contrast the real-world environment often has a complex range of rules and variables. Elements of these differing environments are successfully combined in the experiment design.

The purpose of the experiments is to capture the human responses to the repeated sequences of multiple aspect railway signals from the train driver's perspective. The signals are located next to the railway tracks and communicate key information to the train driver.

This ensures that the trains speed can be safely regulated such that they are kept a safe distance apart. The correct identification and response to these signals is therefore important.

The behavioural and cognitive effects of the repeated exposure to the same types and sequences of signal is of primary interest in these experiments. The simulated elements replicate the graphical presentation style and the grammar rules of the real signals. The full details of the railway operations being modelled are provided in chapter 2 – literature review. The behavioural and EEG data is captured during the experiment for off-line analysis.

This chapter describes the ergonomic considerations in section 3.2.1, and control of confounding factors in section 3.2.2, questionnaire design in section 3.3, the experiment design considerations in section 3.4, the final experiment designs in section 3.5 and the conclusion in section 3.6.

3.2 Ergonomic and confounding factors

Any experiment that involves human participation can be affected by factors external to its design. The introduction of these potentially confounding factors can be tested.

3.2.1 Ergonomic factors

The physical comfort of the subjects during the EEG recording is important. Distractions may affect their cognitive performance and lead to excessive movement based artefacts in the EEG recording. The subjects are asked to sit as still as possible during the EEG recording avoiding unnecessary movements and excessive eye blinks.

Sitting still at a keyboard and computer screen for an extended time can be uncomfortable. The recording session is divided into two experiments. The subjects are free to move and rest during the breaks between experiments. The amount of resting time between each experiment is the subject's free choice. They also complete sections of a questionnaire that records information enabling potential confounding factors to be tested. The expected time for the experiment to run is between 45 and 50 minutes, each of the experiments runs at a fixed pace and pattern of stimuli that is the same for all subjects.

Ethical approval was obtained through the School of Systems Engineering's standard procedures.

3.2.2 Confounding factors

Any uncontrolled factor outside the experiment design may affect the result. Careful experimental design and subject monitoring can help to control any such factors.

The subjects' physiological states are invisible to the outside observer yet have the potential to significantly impact their performance and effect behaviour patterns. The subjects hunger, thirst [3], caffeine consumption [1 and 2], alertness and perceived task difficulty could have an effect on their response accuracy. These are self-rated and the information is collected using a questionnaire. These factors will be compared against the reaction time and response accuracy for significant effect.

The Easycap EEG recording cap is used because it does not produce pressure spots beneath the electrodes. If the EEG cap causes physical discomfort more movement artefacts are produced and the subjects are likely to be distracted from the experimental tasks. It is preferable that the EEG cap is not unplugged and then reconnected during the recording session. Therefore, the subjects are reminded to attend to any personal needs before the EEG cap is placed on their head.

3.3 Questionnaire design

Key information about each subject is recorded in a questionnaire that is the same for each subject. This information is used during the results analysis. It is used to identify any links between the subjects' physical and EEG responses, and their statistics or physiological states.

The initial questions record the subject's statistics and their perceived physiological state. The subjects are assigned unique numbers to anonymise the data. Information about factors that may have an effect on the subject's behavioural and cognitive performance is recorded. The significance of the effect that any potential confounding factors have will be tested. The full questionnaire is provided in Appendix A.

This is a summary of the questionnaire:

- Pre-experiment questions:
    - Have you consumed any caffeine in the last 12 hours?

    - Age range
    - Gender
    - Handedness (left, right or both)
    - Train driving experience (no experience or qualified)
    - How alert to you feel?
    - How hungry are you?
    - How thirsty do you feel?
- After experiment 1:
    - How alert do you feel?
    - How difficult did you find the task?
- After experiment 2:
    - How alert do you feel?
    - How difficult did you find the task?
- After experiment 3:
    - How alert do you feel?
    - How difficult did you find the task?
- General comments or feedback

The age range may affect performance due to the effects of aging and experience [9]. The gender of the subjects is recorded to verify this is not a factor [9]. There are no known performance differences due to gender in the population of train drivers. The handedness is recorded because all the subjects operate the keyboard using their right hand regardless of their natural handedness. This ensures consistent motor cortex activation in the EEG data. The subjects are recorded as left or right handed, or ambidextrous. The level of prior train driving experience is important because prior knowledge and developed skill at processing the stimuli and sequences correctly may improve response accuracy.

The subject's perceived alertness, hunger and thirst are scored using a numerical multiple choice scale. Fatigue, hunger and thirst could affect their performance or be a significant distraction. A balanced choice of responses has been chosen providing a neutral response and an equal number and weighting of positive and negative answers. The Karolinska Sleepiness Scale, KSS, has been used as the basis for the scale [4, 5]. It is important to recognise the subjective nature of the answers. A score of 6 from one individual may not represent the same physiological state in another. The overall trend of the factors is tested for significant correlation with reaction time and response accuracy. Significant correlation could indicate that the observed results are due primarily to the subject's physiological state rather than the experimental stimuli.

After each of the experiments the subjects score their alertness level and perceived difficulty level of the experiment using the KSS based scoring system. General feedback can be given at the end of the recording, which includes any information not already captured in the questionnaire. All the questionnaire data is combined for analysis in conjunction with the final results.

3.4 Simulating aspects of train driving

This section describes the features of the real-world environment to be modelled and related systems. The different methods of modelling these for the experiment are discussed.

3.4.1 Summary of the train driver's role

The cognitive processes associated with the drivers processing of the lineside signalling multiple aspect signals are the focus of the experiment. Multiple aspect signals look like traffic lights and indicate to the driver if the track ahead is clear or not, see figure 3.1. Additional information is provided to explain their purpose.

The railway environment is a complex collection of highly integrated systems involving human-system interactions.

Successful performance of the task of train driving requires:

- Signalling information, both present and pending.
- Situational awareness.
- Application of route specific knowledge.
- Knowledge of the particular train types physical handling characteristics.
- Remembering current and pending speed limits.
- Knowledge of station stops.
- The length of the train (this relates to platform and siding holding capacity).
- Application of operational rules and procedures.
- Judgement of speed and distance.
- Responding to weather and environmental conditions.
- Ensuring safe operations at all times.

The driver's cognitive processing of track side signalling information in the present is the focus of the experiment. Correct observation, memorisation and response to the signalling is

vitally important to the safe movement of trains. These use patterns of coloured lights to communicate routing information and give advanced warning of stop (red) signals. Figure 3.1 illustrates examples of real signals in use on the UK's national railway network. The signal has a number of visual features, however, the coloured light(s) and line of white lights are the primary source of information during this experiment. The visual presentation of the signals is simplified for the experiments.

Train braking distances are significant, a passenger train stopping smoothly from 60mph, (100km/h), requires approximately 800m, and from 125mph, (200km/h) approximately 3,500m under favourable conditions. Figure 3.2 illustrates the minimum sequence of signals preceding a red (stop) signal. Advanced warning is given before a stop signal by cautionary signals displaying a single or double-yellow indication. The 4-aspect multiple aspect system of signalling provides a minimum of two cautionary signals prior to the red signal as illustrated in figure 3.2, additional cautionary signals can be present [7]. Failure to recognise or respond to cautionary signals may result in the red signal being passed without authority. This is one of the causes of real railway operational incidents. They can create the risk of serious accidents.

Figure 3. 1. The left photograph is of a junction signal used on the UK's national railway network. The yellow light means that the next signal is at red, meaning stop. The line of white lights indicate that the junction ahead is set for a right hand route. The right photograph is of a plain line (no junctions) signal that can display 4 possible aspects. This type is commonly found on busy sections of track.

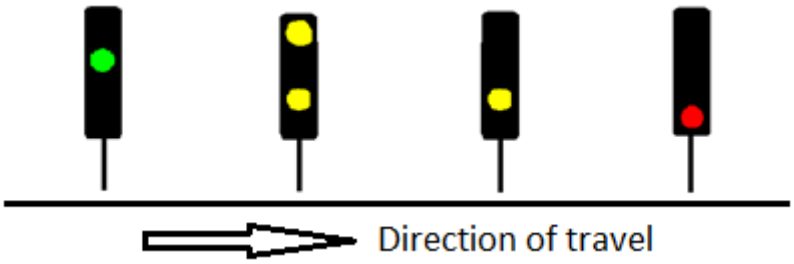

Figure 3. 2. This diagram illustrates the minimum sequence of cautionary signals that precede a red (stop) signal under the 4-aspect signalling system on the UK's national railway network. A cautionary signal is one that displays a single or double-yellow light. The braking distance is between the double-yellow and red signals.

3.4.2 Experiment environment

The type and realism of the experiment stimulus and environment are discussed in this section. These are the environments considered for the experiment:

- recording real train driving
- commercial train driving simulators
- desktop computer based 3D simulation
- desktop computer based 2D simulation that is animated
- desktop computer based 2D simulation using fixed size images

Making an EEG recording during real train driving would provide the data from the actual driving experience. The 20 to 30 minutes of setup time for the EEG cap, restriction on the driver's movement caused by the cabling, and the potential for distracting the driver in a safety critical situation prohibit this option. Trains have high voltage or high current electrical systems that are not fully shielded. These are likely to cause significant artefacts in the EEG data. The complex nature of the real-world stimuli would make it difficult to reliably map a specific stimulus to a physical or EEG feature. This is not a practical option for this project.

Commercial train driving simulators used by train operating companies solve many of the problems associated with making EEG recordings during real train driving. Access and time on this equipment is limited and involves a staffing cost to the simulators owners. The EEG recording needs to be co-registered accurately with the stimuli and responses of the subjects. These systems do not have a co-registration facility. The subject population is a mixture of experienced train drivers and novices with no prior knowledge. The training time for the

novice subjects to learn to operate a realistic simulator unsupervised is prohibitive. This option was discarded.

Desktop computer based simulations can be conducted under laboratory conditions and are free of any limitations caused by external organisations. A bespoke simulation based on existing computer games technology can be used and co-registered directly with the EEG recording. This option is the most practical and is explored in detail in sections 3.4.3 and 3.4.4.

3.4.3 3D simulation

A desktop computer 3D simulation would provide a simpler driving experience than a commercial simulator. The simplified stimulus assists with accurate mapping of EEG features to specific stimulus or responses.

The simulation's purpose is to present the subjects with visual stimuli that replicate the appearance, sequencing rules and meaning of the track side signals used on the UK's national rail network. 3D simulation includes additional information such as the speed of the train, environmental scenery and driving control settings. The presentation of stimulus and the subjects' responses can be accurately co-registered with the EEG data. The simulation can be controlled using a custom built train driving joystick, generic joystick or standard keyboard. The experiment can be run in a laboratory using standard desktop computing technology.

If the simulation is setup with realistic physics and some of the complexities of real train driving the subjects will require many hours of practice and training to operate the simulation unsupervised. Smoothly and accurately stopping a passenger train travelling at 60mph requires approximately 800m, and from 125mph approximately 3,500m, freight trains require greater distances. This means that prior in-depth knowledge of the route being driven is important. Proof of concept evaluation reveals that a significant amount of time is required for all the subjects to develop sufficient knowledge and operational skills. The time that volunteers can be reasonably expected to donate is limited. There is likely to be significantly different levels of proficiency between subjects which is a potential confounding factor. The subjects are presented with multiple stimuli in parallel in addition to the track side signals such as the ground, track and scenery. Accurately matching the EEG patterns to particular stimulus is problematic. This option has been discarded and a simpler solution selected.

3.4.4 2D simulation

A 2D simulation that only displays images of the signals limits the information the subjects are processing. The purpose of the experiment is to gain insight into the cognitive processes that are involved in visually processing the track side signal sequences.

A 2D presentation can be animated according to speed and distance. The animated signal images grow in size as the subject moves towards them. The approach speed and time would need to be governed by the meaning of the signals to remove the need for speed control. The journey from a yellow to red signal stopping before it would take longer than the journey between a pair of green signals. Changes to the colour light(s) during approach are possible. The duration of each trial is between 30 and 120 seconds. This limits the number of trials and therefore the number of sequence repetitions.

A 2D fixed size image only requires identification once. Any changes to the signal indication displayed would look the same regardless of the location. Only the stimulus and its associated meaning are presented. The first response to the first indication of each signal is recorded. The fixed size 2D image is the final design. Only the subject's response to the meaning and sequence of initial signal indications is recorded by the EEG and behavioural data. This type of trial presentation allows up to 30 trials per minute to be displayed. Any patterns within the EEG and behavioural response data are related directly to the question being investigated.

3.4.5 Capturing the subjects behavioural responses

The subjects' responses are captured using a standard keyboard. The keyboard is operated with the right hand and one key press required per trial. Only the first key press of one of the 4 marked keys for each trial is captured. The keyboard is illustrated in figure 3.3. If no valid response is made during the trial there is no opportunity to catch up. The inter-stimulus interval (ISI) has been designed to allow enough time to respond without reaction time being a factor. The response can be made in the time between the stimuli presentation and the end of the blank screen phase that follows it, the stimulus onset asynchrony. The temporal structure of a trial is illustrated in figure 3.8.

If multiple key responses are captured for each trial the additional cases need to be considered. Is a right response followed by a wrong one to be treated as a right or wrong

response? Is a wrong response followed by a right response less correct than other combinations that include right responses? Are two right responses different to one? How many secondary key presses are inadvertent? Only the first marked keyboard response is recorded to ensure a clear behavioural data set and clearly thought out responses.

The reaction time is measured between the stimulus presentation and the key press event. The error in the timing accuracy is between 0 and 16ms and is caused by the Windows operating systems sampling rate of the USB keyboard and the 60Hz refresh rate of the computer screen. The reaction time, key press response and stimulus type are recorded for each trial.

Figure 3. 3. The keyboard used to capture the subjects responses. The colour coded stickers mark the 4 keys that correspond to the 4 different signal indications used. The key to stimulus mapping is red to red signal, yellow to single yellow signal, orange with 2 dots to double yellow signal and green to the green signal.

3.5 Experiment structure

3.5.1 Overview

The experiments use 2D images with fixed size and screen location. The behavioural responses are recorded by a standard keyboard with colour coded keys, as illustrated in figure 3.3. The keys are grouped together so that they can be operated with the right hand without excessive movement. Multiple recordings of each stimuli type and sequence of stimuli are required so that the distributions can be analysed. This highlights the features of the EEG signals and behavioural responses that are consistently associated with them.

The hardware used is a Deymed 19 channel recorder sampling at 256Hz using passive AgCl electrodes. An IBM type PC running Windows 7 ™, standard keyboard with colour coded keys and 21.5 inch flat screen monitor. Event markers are co-registered with the EEG data stream marking the stimulus display and hide markers, and any key press markers.

The sequences and timing of the stimulus are the same for all subjects. The trial duration times and sequences of stimuli change throughout each experiment. All the sequences follow a set of rules that the subjects are trained in before the recorded sessions. The subject data and subjective assessment of their physiological are recorded on a paper questionnaire. The behavioural and EEG data is stored for off-line analysis.

The purpose of experiment one is to capture the responses to sequences of signal aspects, sequence grammar rules and effects of repeated sequences of the same signal(s). Experiment two is more complex using dual stimuli, one is the target and the other a flanked distractor. The flanked distractor replicates the signalling information presented on a 4 track mainline such as the route from Paddington to Didcot. The correct target needs to be followed in addition to correctly responding to the sequencing grammar rules.

3.5.2 The stimulus

The stimuli are fixed size 2D images of present day UK national railway network multiple aspect signals. This section describes the on-screen presentation method, visual appearance and sequencing grammar rules of the signals used in the experiments. Experiment one is a series of single stimulus trials. Figure 3.4 illustrates the stimuli presented during experiment one. Experiment two displays a pair of stimuli simultaneously, one is the target the other a flanked distractor. The junction signals indicate the changes of track. The types of stimuli used are illustrated in figure 3.4 and 3.5.

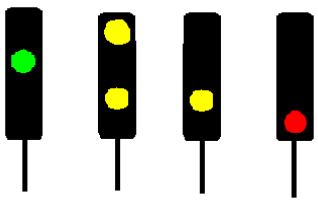

Figure 3. 4. These are the basic stimuli used in this experiment. These are 2D images of UK national railway 4-aspect signals. The green means proceed, the double-yellow means expect the next signal to be yellow, yellow means expect the next signal to be red. Red means stop.

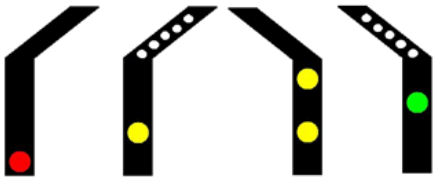

Figure 3. 5. These are examples of the additional stimuli that appear in experiment two. These are junction signals. When the angled bar above the signal is illuminated it means there is a change of track at the next trial. The change can be to the left or right. If the bar is not illuminated there is no change of track.

All the stimuli follow the same sequencing grammar rules. An example is illustrated in figure 3.6. The red signal must be preceded by a red or yellow signal. A yellow can be preceded by a red, yellow or double yellow signal. Double yellow and green signals can be preceded by any of the signals.

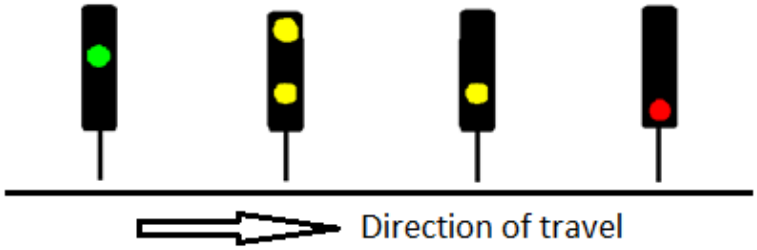

Figure 3. 6. This diagram illustrates the sequencing rules for 4-aspect signals. The progressive sequence of cautionary signals prior to the red stop signal provide a vital advance warning.

The junction signals indicate changes of track. If the angled arm is illuminated to the left or right it means there will be the respective change of track after the signal. If the arm is blank then no change of track will occur. Figure 3.7 illustrates an example of a sequence of signals at a junction.

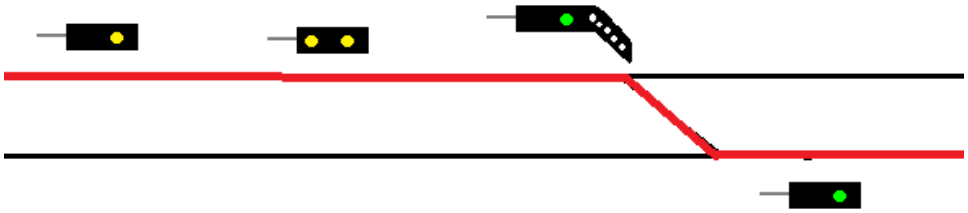

Figure 3. 7. This diagram illustrates a sequence of signals prior to and during a changing of track indicated by a junction signal. The angled white lights mean that the change is from the left to right track.

3.5.3 The trial timing

The trial timings are important, they need to be set such that the subjects have enough time to respond without reaction time being a critical factor. They also need to be short enough to keep the subjects engaged in the task and to allow as many trials as possible. Multiple recordings of the same events are required for the behavioural and EEG data analysis. A pilot study was used find the optimal timings. Figure 3.8 illustrates the temporal structure of a trial. The stimulus display duration is a constant time throughout each experiment. The inter-stimulus interval variation is uniformly random. Table 3.1 lists the timing ranges that apply to each experiment. The display duration is sufficient for positive recognition of the stimulus. The first response within the stimulus onset asynchrony is recorded against the trial. There should be enough time to respond without reaction time being the primary factor.

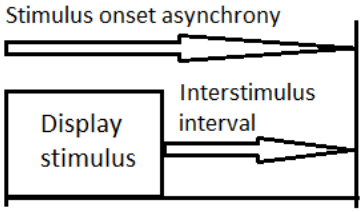

Figure 3. 8. This diagram illustrates the temporal structure of each trial. The display duration is a constant time for each experiment and the inter-stimulus interval varies within a uniformly random range.

Experiment	**Stimulus duration (ms)**	**Stimulus onset asynchrony (ms)**	**Quantity**	**Total duration (minutes)**
1	500	1,500 to 2,500	420	13
2	750	1,500 to 2,500	480	16
Training	500 to 3,000	2,000 to 5,000	85	4.67

Table 3. 1. This table lists the timing data and trial counts for each part of the EEG recording session.

3.5.4 Training and familiarisation

The training session provides the experience and knowledge to independently complete each experiment. Prior to the recorded experiments all the subjects receive a briefing and read printed instructions. The signal sequencing grammar rules are explained prior to the training session. The training session can be repeated if required. The printed instructions can be reviewed between experiments if required.

The training session is composed of 25 single stimulus trials, 30 dual stimuli trials. The display durations vary between 500 and 3,000ms, and the stimulus onset asynchrony between 2,000 and 5,000ms, are progressively reduced to allow time for the subjects to learn. The session runs at a fixed pace lasting 280 seconds. It is not scored nor is EEG recorded.

3.5.5 Experiment one – trial structure

Experiment one displays a single stimulus in each trial. There are 420 trials with a stimulus display duration of 500ms and a stimulus onset asynchrony with a uniformly random value between 1,500 and 2,500ms. Figure 3.9 shows a screen shot from an experiment one trial. The order and timing of stimuli presentation is the same for all subjects and runs at a fixed pace. If the subject fails to respond during the stimulus onset asynchrony the experiment advances to the next trial. The subject's reaction time has no effect upon the duration of each trial. The quantity of each type of stimulus for experiment one is listed in table 3.2.

The monitor size is 21.5" and resolution is 1920 x 1080 pixels with a refresh rate of 60Hz and the stimulus images 45 x 176 pixels. The images are drawn in the centre of the screen. The background colour is light blue, RGB code 178, 242, 244. A blank screen is presented between the displayed stimuli during the stimulus onset asynchrony.

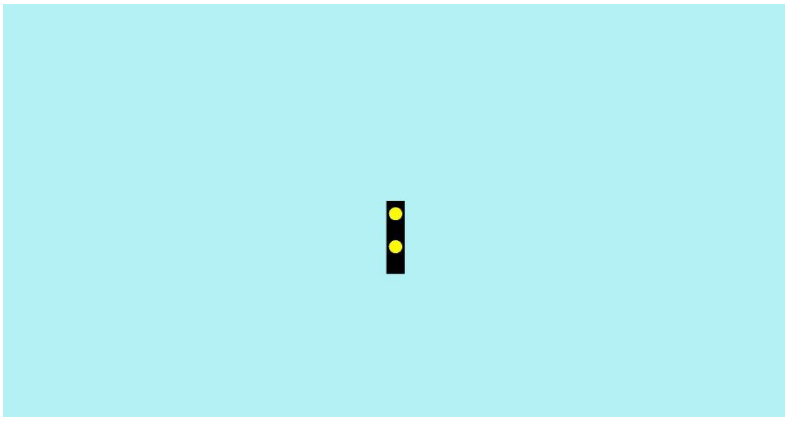

Figure 3. 9. This is a screen shot of an experiment one trial. These stimuli are all the same size and drawn at the same central location of the screen. The background colour is constant throughout the experiment.

Experiment	**Stimuli type**						
	Red	**Yellow**	**Double yellow**	**Green**	**Junction left**	**Junction right**	**Junction blank**
1	72	96	96	156	n/a	n/a	n/a
2	72	96	96	216	24	24	48

Table 3. 2. This lists the quantity of each type of stimulus in experiments one and two.

3.5.6 Experiment two – trial structure

Experiment two is an extension of experiment one. There are a number of differences between the experiments. A pair of stimuli are displayed simultaneously. There are 480 trials with a stimuli display duration of 750ms and a stimulus onset asynchrony with a uniformly random value between 1,500 and 2,500ms. Figure 3.10 shows a screen shot from an experiment two trial. The quantity of each type of stimulus for experiment 2 is listed in table 3.2.

The subjects follow the stimulus in the same lateral position until a shift of position to the left or right is indicated by an angled line of white lights at the current lateral position. The junction stimulus indicating changes of lateral tracking position use images that are 144 x 258 pixels. Initially the left stimulus is the target. A red arrow is displayed above the correct stimulus every 20th trial. This prevents large scale loss of data if the subjects focus on the wrong stimulus. The left and right lateral positions are the target stimulus for 240 trials each. There are 24 of each left and right junctions, there are also 24 left and right hand blank junctions that do not indicate a change of track.

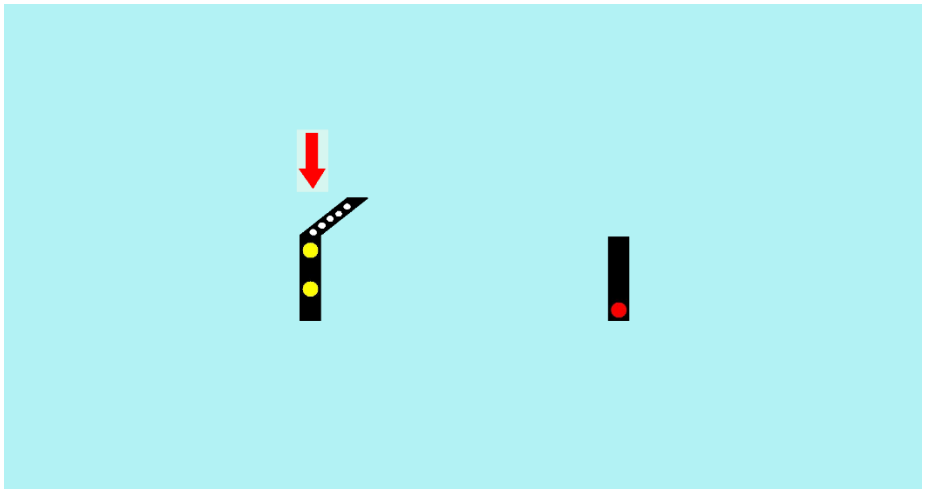

Figure 3. 10. This is a screen shot of an experiment two trial. The red arrow above one of the stimuli indicates the correct track to follow. The red arrow above one of the stimulus indicates the correct lateral position to target. The red arrow is shown every 20th trial. The background colour is constant throughout the experiment.

3.5.7 Experiment protocols

The procedure for each recording session is the same. Subjects must be healthy and free from neurological conditions such as epilepsy. The subjects first read and are briefed on the initial requirements for participation, then if they meet the conditions sign a consent form. They are free to leave the experiment at any time. A briefing of the whole experimental process is given which includes:

- The fitting of the EEG cap and application of the conductive jel
- The washing facilities available to remove the jel
- An introduction to the desktop computer hardware
- Printed instructions for the experiment
    - The right handed operation of the keyboard
    - The meaning of the colour coded keys
    - The rules of the signal sequences
    - The visual appearance of the signals
    - Correct operation of the simulation
- They are reminded to attend to any personal needs before the EEG cap is fitted
- The EEG cap is fitted and the resistance of all the electrodes is reduced to no more than 10KΩ

- The subjects are requested to avoid excessive head or body movements, eye blinks and putting their tongue on the roof of their mouth
- The first section of the questionnaire is completed
- The training sessions are completed
- The first experiment is completed using single stimulus trials
- The second section of the questionnaire is completed
- The second experiment is completed using dual stimuli trials
- The final section of the questionnaire is completed
- The recording is now complete and the EEG cap is removed
- The subjects role is completed

3.6 Conclusion

The high fidelity solutions of 3D simulation or real train driving have practical and EEG feature extraction limitations. The use of simplified 2D simulation was found to be the most practical solution. A simulation that uses 3D graphics would be the next logical step, once a baseline for the expected EEG and behavioural responses to the individual stimulus is understood.

The experimental design uses simple fixed size 2D images to ensure that the EEG and behavioural data relate as closely as possible to individual stimulus and their sequences. Each EEG recording uses a standard set of protocols to ensure consistency. Experiment one is a series of single images, while experiment two display two images simultaneously. Only one of the images displayed in each trial in experiment two is the target, all others are flanked distractors. There are prompts every 20^{th} trial in experiment two to prevent large scale responses to the wrong stimulus. The subjects follow the stimulus in the same lateral position until a shift of position to the left or right is indicated by an angled line of white lights in the stimulus in the current lateral position.

The data gathered during these experiments will be analysed for significant behavioural patterns. The methods used to analyse the EEG and behavioural data off-line are described in chapter 4. The behavioural and EEG analysis results are detailed in chapters 5 and 6 for experiments one and two respectively.

Chapter

4. Methods

4.1 Introduction

This chapter describes the procedures and formulae used to analyse the behavioural and EEG data. The experiment subjects are described in section 4.2. The survey data analysis method that is used to test for confounding factors is detailed in section 4.3. The EEG recording and behavioural data capture methods are described in section 4.4. The EEG data is cleaned of artefacts prior to analysis, this process is detailed in section 4.5. The cleaned EEG data is decomposed into mono frequency components using EMD in section 4.6. The mono frequency components are compared against each other for inter-channel phase locking, section 4.7. The inter-channel phase locking data is used to build graphs that contain information about the overall pattern of cognitive activity, section 4.8. The differences between sets of cognitive activity graphs are compared to identify any significant features that predict response accuracy and cognitive responses to repetition priming and antipriming, see section 4.8.3. The behavioural data analysis methods are detailed in section

4.9. The method used to objectively measure cognitive alertness/fatigue are described in section 4.10.

The procedures described in this chapter are applied to the experimental data in chapters 5 and 6 for the behavioural data and EEG analysis.

4.2 The subjects

There are initially 22 volunteer participants. Two are excluded because they found the EEG cap uncomfortable resulting in excessive movement based artefacts. There are three subject groups to consider, the novices (13) and the experts (seven), experienced train drivers. The experienced train drivers have service durations of 0.2, five, five, nine, 10, 10 and 13 years. Experienced train drivers have prior knowledge and experience of the stimuli used in the experiments and knowledge of successful processing of the stimulus grammar rules.

The genders of the subjects are 11 males and nine females. The mean age is 37.4 years and standard deviation 14.2 years, with a minimum age of 21 years and maximum 65 years. Thirst, hunger, alertness, age, caffeine consumption within 12 hours, gender, handedness, perceived task difficulty and experience are all tested for significant effect upon reaction time and accuracy of response. All the subjects are healthy. The statistical calculations are performed in Matlab 2013a. The full details of the experimental designs are documented in chapter 3.

4.3 Survey and confounding factors analysis

The subject's survey data and subject response data are used to test for possible confounding factors. The statistical tests are listed in tables 4.1 and 4.2 for survey data and response data. A significant strong correlation or significant t-test difference indicates a potential confounding effect. Any confounding effects could affect the behavioural and EEG analysis.

Factor compared		Statistical type
First factor	**Second factor**	
Self-rated hunger	Reaction time	Pearson's correlation, 2 tails, alpha = 0.05
Self-rated hunger	Response error rate	Pearson's correlation, 2 tails, alpha = 0.05
Self-rated thirst	Reaction time	Pearson's correlation, 2 tails, alpha = 0.05
Self-rated thirst	Response error rate	Pearson's correlation, 2 tails, alpha = 0.05
Self-rated alertness	Reaction time	Pearson's correlation, 2 tails, alpha = 0.05
Self-rated alertness	Response error rate	Pearson's correlation, 2 tails, alpha = 0.05
Self-rated task difficulty	Reaction time	Pearson's correlation, 2 tails, alpha = 0.05
Self-rated task difficulty	Response error rate	Pearson's correlation, 2 tails, alpha = 0.05
Caffeine consumption	Reaction time	Pearson's correlation, 2 tails, alpha = 0.05
Caffeine consumption	Response error rate	Pearson's correlation, 2 tails, alpha = 0.05
Caffeine consumers	Non-Caffeine consumers	T-test, 2 tails, alpha = 0.05, unequal variation
Male distribution of mean per subject reaction time	Female distribution of mean per subject reaction time	T-test, 2 tails, alpha = 0.05, unequal variation
Male distribution of per subject response error rate	Female distribution of per subject response error rate	T-test, 2 tails, alpha = 0.05, unequal variation
Novices	Expert train drivers	T-test, 2 tails, alpha = 0.05, unequal variation
Novices	Expert train drivers	T-test, 2 tails, alpha = 0.05, unequal variation
Age	Mean subject reaction time for an experiment	Pearson's correlation, 2 tails, alpha = 0.05
Age	Subject's response error rate for an experiment	Pearson's correlation, 2 tails, alpha = 0.05

Table 4. 1. This is a summary of the statistical tested performed on the subject's survey data. A significant strong correlation or t-test difference indicates a potential confounding effect.

Factor compared		Statistical type
First factor	**Second factor**	**First factor**
Reaction time in the first half of an experiment. The distribution is of the mean per subject response error rates.	Reaction time in the second half of an experiment. The distribution is of the mean per subject response error rates.	T-test, 2 tails, alpha = 0.05, unequal variation
Response error rate in the first half of an experiment. The distribution is of the mean per subject response error rates.	Response error rate in the second half of an experiment. The distribution is of the mean per subject response error rates.	T-test, 2 tails, alpha = 0.05, unequal variation

Table 4. 2. This is a summary of the statistical methods used to find significant large scale learning effects. A significant t-test difference indicates a potential confounding effect.

4.4 EEG and Behavioural data recording

This section describes the EEG data recording equipment, computer hardware and method of co-registering the EEG and keyboard response data.

The EEG data was recorded with a Deymed 19 channel recorder using AgCl passive electrodes. The standard 10-20 electrode cap layout is used with 19 channels. The EEG data sampling rate is 256 samples per second. Each channel's recorded voltage difference is between an electrode and the single reference electrode located in the central area of the EEG cap. The reference electrode provides a common point of reference for all the other electrodes. The cap is placed centrally in both lateral and contralateral plains. The resistance of the electrodes is reduced to no more than 10KΩ using conductive gel. Isopropyl alcohol 70% solution is used to clean the area of skin immediately beneath the electrodes [34, 80 et al].

The captured EEG data is processed on an IBM type desktop computer running Windows 7 ™ service pack 1, 64 bit, and standard keyboard with colour coded keys. The CPU was 3.3GHz with 32GB of RAM. A 21.5 inch flat screen monitor set to 60Hz refresh rate, having a 1920 x 1080 resolution is used.

The stimulus onset, stimulus hide events and keyboard responses are co-registered with the EEG data stream by the stimulus presentation program. All the events are synchronised and time stamped from a single clock by the presentation program. The accuracy of the co-

registration process is determined by the screen refresh rate of 60Hz, operating system time slicing and poling rate of the USB port. Both the USB port and screen presentation have the same timing variations that occur independently, therefore the timing variations are not additive. The co-registration accuracy is +/-15ms, which is equivalent to +/- 4 time series sampling windows at an EEG data sampling rate of 256Hz. The data is stored in files on the hard disc for offline analysis.

Once the EEG data recording is completed the data needs to be prepared for analysis using the process described in section 4.5.

4.5 Artefact removal and EEG time series division

The raw recorded EEG data will contain artefacts. Some artefacts originating from the subjects can be reduced by asking them to avoid excessive eye blinks, unnecessary muscle, eye and head movements, and touching the roof of their mouths with the tongue. Switching off electrical devices such as mobile phones removes a potential source of artefactual signals. The mains electricity supply, heart beat and essential body movements related to the experiment are unavoidable. These artefacts must be removed for further analysis to be effective.

A combination of automatic and manual artefact detection and removal is used to prepare the EEG data. Manual inspection and removal of artefacts of the data from 20 subjects, 19 channels and up to 60 minutes of recording time is a considerable task. The performance and consistency of a human is likely to vary throughout the task. Not all human inspectors of the EEG data will agree all the time about whether part of the data is artefactual or not.

The majority of the artefactual components can be detected using an automatic artefact detection method. The Renyi's entropy and temporal decorrelation source separation ICA, TDSEP-ICA based method was chosen. The authors of the method report a 92.6% detection rate with minimal false rejection of data [23]. The algorithm was implemented in Matlab and utilises TDSEP-ICA, code developed by A. Ziehe 1998. TDSEP finds the temporal correlation matrix offset that is best for each segment of the EEG data [39].

The EEG time series is first divided into individual trials aligned to the stimulus onset. The trials are concatenated together in sets of two for this process to ensure there are enough consecutive EEG data samples to ensure accurate decomposition by the ICA process. The

negative effect of trial concatenation is that when channels or trials are rejected there is greater data loss, even when the artefact only affects one trial. The temporal decorrelation source separation (TDSEP) method is used to decompose the raw data into independent components, ICs [39]. Each IC is maximally statistically independent from each other. A key property of the process is that similar sub components of the original EEG data are grouped into single ICs.

The TDSEP process whitens the data to maximise the statistical independence of the decomposition. The joint diagonalisation of the time lagged correlation matrices finds the optimal correlation time lag for that particular time series. The best time lag offset is typically between zero and four samples. The result is an estimated blind source separation mixing matrix. The inverse of the mixing matrix gives the unmixing matrix. The matrix product of the unmixing matrix and the original data give the independent components, ICs. These are estimated source components for the original data. Only ICs that are not considered to contain artefacts are selected for reconstruction of the cleaned EEG signal. The columns of the mixing matrix that correspond to rejected ICs are set to zero, preventing their inclusion in the clean data. The matrix product of the modified mixing matrix and estimated sources matrix yield the cleaned EEG data. The additional benefit of this method is the retention of trials and channels that would otherwise have been discarded.

The individual ICs are inspected automatically using the Renyi's-entropy method [23]. It is important to note that the signal must not be band pass filtered prior to entropy testing. This is because some filters such as the Butterworth rebuild the signal using sine wave components. This significantly changes the entropy characteristics of the signal preventing the artefacts and good data from being distinguished.

The Renyi's entropy method calculates the entropy level of non-overlapping windows of each IC. Windows with a standard normalised entropy value outside the range +/- 1.2 are marked as artefacts. The normalisation is applied on a per trial level. If more than 20% of the windows in a component are marked for rejection the whole IC is rejected. ICs with an amplitude greater than -/+ 100µV are rejected. Some artefacts are highly structured while others are almost random. The mains 50Hz noise has an orderly structure with an entropy of 37 which is the value expected for sine waves. The full details of the algorithm and testing procedure are detailed in the authors' original paper [23].

The good EEG data falls within a narrow range of entropy values and typically has an amplitude of no more than +/-100µV. The data was also visually inspected following this

process to check that it has the characteristics of good EEG [31]. Any post-Renyi's entropy filter EEG data that is seen to be an artefact is discarded. A "pop" on the reference electrode causes loss of signal from all the channels resulting in the affected trials being discarded. The Renyi's entropy method does not detect the "pops" consistently, these events are clearly visible during visual inspection. This is the Renyi's entropy calculation:

$$h = \frac{H}{\sum_{i=1}^{n} x_i}$$

$$P = \sum_{j=1}^{m} h_j{}^{alpha}$$

$$Renyi's\ entropy = \frac{\log(P)}{(1 - alpha)}$$

Equation 4. 1. The equations for calculating the Renyi's entropy of a time series. "X" is the time series of random variables. "H" is a histogram of X. Alpha is the order of the entropy. The optimal value is 2, alpha ≠1 [23].

Once the EEG data has been cleaned the pairs of trials are cut into individual trials. A trial is defined as the segment of EEG data between the displaying of one stimulus and the moment before the appearance of the next. The first 1,500ms of each trial is of primary interest since this time interval is common to all trials. The duration of the trials is between 1,500 and 2,500ms varying uniformly randomly. The EEG time series beyond 1,500ms stimulus onset becomes increasingly less likely to be related to it.

The EEG data remaining was still not purely the result of brain activity because it was an extra-cranial recording. The identifiable artefacts that are known to obscure the true cognitive activity have been removed to the maximum extent possible. The cleaned EEG data was then ready for further analysis.

4.6 Empirical mode decomposition

The cleaned EEG data is processed to obtain information about the frequency and phase content of each electrodes data channel. The non-linear, non-stationary nature of EEG time series means that a data driven approach is a suitable solution. Empirical mode

decomposition, EMD, is a data driven approach that decomposes the time series into instantaneous frequency and phase information. Empirical mode decomposition was originally developed by Huang et al [41 and 42]. The Matlab implementation developed by G. Rilling, 2007 is used [43].

The method decomposes a time series into mono frequency components. The time series must have a zero mean and the number of minima and maxima differ by no more than one. The maxima and minima of the time series are used to construct an envelope above and below the time series. The cubic spline method of envelope calculation produces the most accurate decomposition [43]. The midline between the upper and lower envelope boundaries forms the intrinsic mode function (IMF) zero baseline. The offset of each maxima and minima from the midline is use to generate the IMF time series as illustrated in figure 4.2. The IMF is subtracted from the signal and the process repeated until the variation of the residual signal is below a 0.0001. The resultant IMFs contain progressively lower frequencies, each IMF has a narrow frequency range that has a low enough variance to be treated as a mono frequency. The sum of all the IMFs and the residual reproduce the original signal.

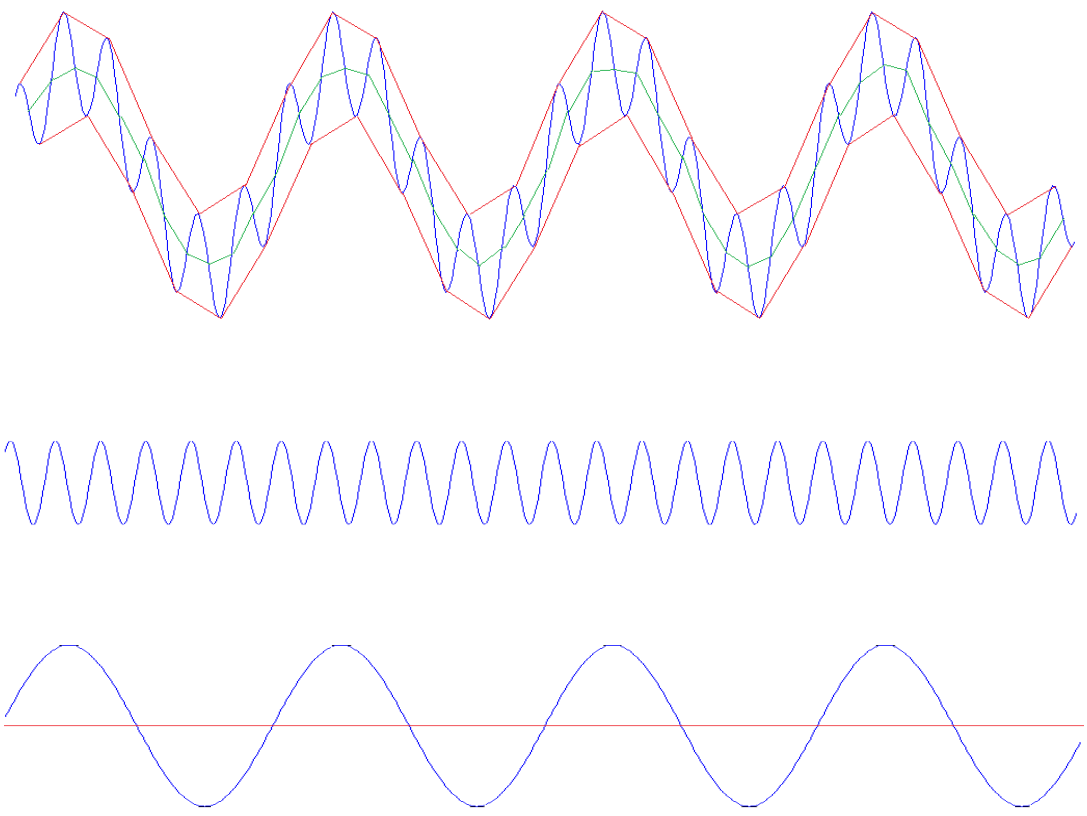

Figure 4. 1. The top graph illustrates the original multiple frequency time series. This example is composed of two frequencies 1 and 6Hz. The blue line shows the original time series, the red lines are the upper and lower spline envelope boundaries and the green the midline of the envelope. The middle graph is the first IMF that has a frequency of 6Hz. The bottom graph illustrates the residual following the second decomposition of the IMF which is 1Hz. The red line in the lower graph is the final residual following the decomposition of the 1Hz residual from the second IMF.

The EMD algorithm has some limitations. Certain combinations of frequencies cannot be accurately separated if they are within a few hertz of each other, or if the component frequencies combine to produce inflections in the new time series are there used to be turning points. The pre-pending of a short section of noise to the start of the time series has been found to reduce these effects [42]. Tests with this method on simulated sine wave time series showed an improvement in decomposition performance. A 500ms pre-pended time series composed of frequencies between 2 and 40Hz separated by 1Hz is used during the decomposition of the experimental data.

The 19 EEG time series for each trial have each been decomposed into a number of mono frequency IMFs that contain both phase and amplitude information. These will be used to investigate the level and timing, of phase synchronisation and locking between electrodes which is described in section 4.7.

4.7 Phase-locking analysis

Phase-locking and synchronisation provide completely different information to that contained in the amplitude of a signal. Amplitude analysis methods consider the power of the signal at particular frequencies and times. The phase-locking and the resulting synchronisation is a measure of synchrony between a pair of channels [75].

Empirical mode decomposition, EMD, is used to decompose each channel into mono frequency intrinsic mode functions, IMFs. Each trial has 19 channels with 171 possible channel pairings, each has a set of IMFs. Each mono frequency IMF pair is a component for the significant phase-locking/synchronisation. There are typically 10 IMFs per channel. The phase-locking between pairs of channels is tested by comparing all the combinations of IMFs in one channel with the IMFs in the other. This is referred to as an edge in a network. The IMFs are used to find regions of phase synchronisation between channel pairs. There is a

maximum of approximately 171 x 9 x 10 = 15,390 IMF combinations to test for significant phase-locking on a network.

The sets of IMFs between each channel pair are compared if they have similar frequencies. IMF pairs that are within 5Hz are compared and the phase-locking value (PLV) calculated for a time interval. The PLV is a numerical measurement of how consistently the phase angles of a pair of time series are separated.

The constraint of the minimum average frequency difference between IMF pairs excludes the majority of the combinations. The cognitive processes that are shorter than the trial duration may go undetected if the whole trial is analysed in one operation. Therefore the EEG time series for each trial is examined using a sliding window. An epoch width of 500ms, 128 samples is used and the overlap of the epochs is 75%, 96 time series samples. The overlapping epochs prevent loss of data due to any edge effects or events that overlap a window boundary. The epoch duration is selected to ensure reliable measurement of phase synchronisation in the range of frequencies between 4 and 40Hz. Frequencies above 40Hz in the gamma band range have increasingly less favourable signal to noise ratios. The delta band frequencies up to 4Hz are associated primarily with sleep so have been excluded from this investigation.

Phase synchronisation is a measure of how consistently the phase angles of a pair of time series are offset. EEG data has varying phase separations within it. The variation of the distribution of these gives the measure of phase synchronisation which is used to calculate the PLV. Each time series is converted into its amplitude and instantaneous phase angle using the Hilbert-Huang transform.

The Hilbert-transform calculates the analytic signal of the original signal. The imaginary component of the analytic signal holds the phase instantaneous angle of the original signal, the amplitude is stored in the real component [41]. This process is applied to every IMF that the EMD algorithm produces. The Matlab code developed [47] is used to find the significant phase locks between IMFs.

The phase angle of each time series is unwrapped so that they can be compared. The comparison produces a distribution of phase offsets between the time series. Figure 4.4 illustrates the distribution of phase differences and distribution used to measure the PLV between the pair of time series. The smaller the standard deviation of the distribution of

PLVs the higher the PLV. A PLV of one would mean perfect phase-locking, while zero means no phase-locking.

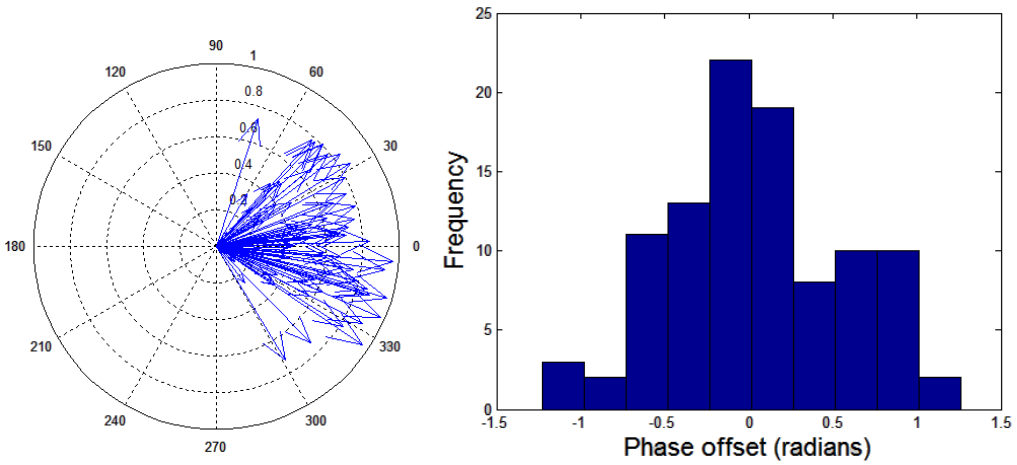

Figure 4. 2. These graphs illustrate the phase offset and phase offset distribution. The mean length of the arrows in the left hand diagram is the mean amplitude. The mean phase offset is 0.0417 and the standard deviation 0.5065 radians.

The PLVs found between each IMF-channel pair could be the result of chance rather than a real pattern in the time series. The data driven method of bootstrapping is used to test the significance of the phase-locking since the time series are non-linear and non-stationary. The bootstrapping method used in this project uses random permutations of the original time series values. The distribution of the values and there statistical properties are preserved, except for the instantaneous phase which is randomly scattered [72]. The PLV for each of these randomised versions of the time series is calculated. The process is repeated 200 times. If more than 5%, (10), of the randomly selected time series have a higher PLV than the original PLV it is treated as non-significant and rejected [47].

The high number of multiple comparisons introduces the problem of false discoveries. This is solved by applying the Benjamini-Hochberg method of false discovery rate control to each channel pairs set of multiple IMF comparisons [44 and 45].

The significant inter-channel phase locks for each frequency band and epoch are used to construct adjacency matrices and networks as illustrated in figure 4.5. The adjacency matrices can hold either binary flags indicating the presence of an edge, or real unitary values that store the PLV. The standard frequency band labels of theta (4 to 8Hz), alpha (8 to 13Hz) and beta (13 to 30Hz) are used [63].

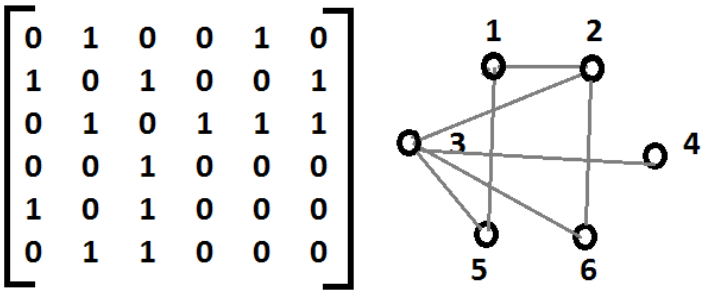

Figure 4. 3. The left diagram illustrates an adjacency matrix for six channels and the right diagram the network of the adjacency matrix. The adjacency matrix is symmetrical because the network edges are undirected.

The phase-locking adjacency matrices are ready for more detailed analysis of particular conditions. This is investigated in section 4.8.

4.8 Graph metrics and condition comparison

This section describes the graph metrics and comparison methods used to analyse large scale patterns of cognitive activity. Graph metrics are used to extract meaningful information from the graphs. The adjacency matrices generated by the method described in section 4.7 hold complex multi-dimensional data about trial sampling windows, EEG channels, conditions, frequencies and subjects.

The pairs and sequences of conditions are compared for significant difference or patterns. Features that are potential significant predictors of response accuracy are sort. Sequences surrounding repetition priming and antipriming are also analysed for significant changes due to antipriming.

The methods described in this section are applied to the experimental data in chapter 5, section 5.7 and chapter 6 section 6.9.

4.8.1 Graph structures

The networks in the experiments have 19 channels (nodes), and 171 possible edges, an edge connects a pair of nodes. If the edges are treated as present or absent there are 2^{171} possible combinations. Reducing the level of data complexity makes comparison of sets of networks

possible with existing technology. The resultant data can also be inspected directly by experimenters for meaningful patterns.

Each graph edge represent significant phase locking between two EEG electrodes during a time window. An edge can be a binary state or a 0 to 1 continuously variable scale. The binary edge states can make the analysis of the graphs simpler, though some details are lost. Figure 4.3 illustrates a simple graph and associated adjacency matrix.

Each adjacency matrix represents the significant phase locking between EEG electrodes within a given frequency band during a 500ms window.

4.8.2 Graph metrics

Each of the 19 nodes can have up to 18 edges connecting it to the other nodes in the graph. There are no closed loops, self-referencing nodes in this model. The node degree is the count of active edges connected to it. The node degree is used to calculate a number of other metrics. An active edge is one that has a statistically significant PLV, otherwise it is considered to be absent. The graph metrics are and these description are listed in table 4.3.

Graph metric	**Description**
node degree	The number of active edges that connect to a node
nearest neighbour degree	The sum of node degrees of the connected neighbours
nearest neighbour PLV	the sum of the node's nearest neighbours PLV's
betweenness centrality	$\sum_{x,y\neq u}^{no.of\ nodes} \frac{no.of\ shorest\ paths\ from\ x\ to\ y\ through\ u}{total\ no.of\ shortest\ paths\ from\ x\ to\ y}$
closeness centrality	$\left(\frac{\text{No.of reachable nodes}}{(\text{ no.of nodes in the graph} - 1)}\right)^2 \times \frac{1}{\text{the sum of distances from the node to all reachable nodes}}$

Table 4. 3. The graph metrics used and their descriptions.

The Regions:

Cortical region	EEG cap channels
Frontal	Fp1, Fp2, F7, F3, Fz, F4 and F8
Temporal left	T3 and T5
Temporal right	T4 and T6
Central	C3, Cz and C4
Occipital	O1 and O2
Parietal	P3, Pz and P4
Global	All 19 channels

Table 4. 4. The EEG cap channels included in each region of the brain.

The graph metrics for each cortical region for one time window and frequency band are the mean of the graph metric for each channel within it. The mean node degree for the central cortical region is the node degree of the channels (C3 + Cz + C4) / 3. The frequency bands analysed are 4 to 40Hz, alpha, theta, beta and lower gamma (30 to 40Hz). There are 7 windows because the minimum trial duration in all experiments is 1,500ms. The time windows of each trial are structured as shown in figure 4.4. The 500ms window duration ensures that phase locking features are reliably detected. The window overlap of 75% ensures that features near or overlapping the edge of any time window are not overlooked or obscured. The graph metrics are calculated for each cortical region, time window, and frequency band trial combination. This produces 5 x 7 x 7 x 420 values per graph metric for experiment one, and 5 x 7 x 7 x 480 values per graph metric for experiment two.

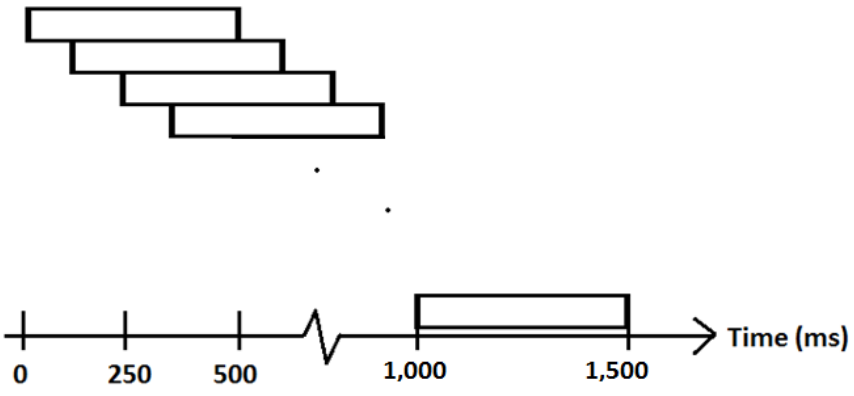

Figure 4. 4 The organisation of the overlapping sampling windows. The inter-node phase locking pattern for each windows is expressed as an adjacency matrix. Each window is represented by an adjacency matrix. Each window is 500ms in duration and overlaps the following by 75%. The time is post stimulus onset. 1,500ms is the minimum duration of a trial in all experiments.

4.8.3 Comparison of conditions

The graph metrics are obtained using the method detailed in section 4.8.2. The graph metric data is used to compare the precursors to correct and erroneous responses. The patterns of cognitive activity surrounding changes of stimulus and junction trials are evaluated using a similar method to response accuracy.

Correct and erroneous response trials are selected using the following method. The set trials correct trials that have not been sampled before are found for each subject. Up to the three trials that precede the correct response are also selected. The same method of trial selection is used for erroneous responses and the up to the three preceding trials. No trial is selected more than once and all the trials that precede the response trials have correct responses. Figure 4.5 illustrates the structure of the trials selected.

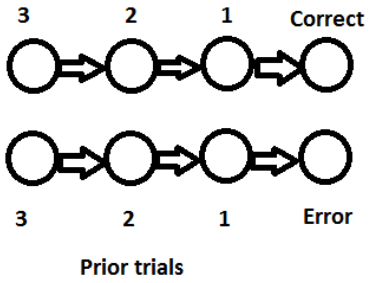

Figure 4. 5. The structure of the sequence of trials that compare the precursors to correct and erroneous responses. The sets that hold the three proceeding trials are used for analysis. Each circle holds the average values of all the trials within its dataset.

The mean graph metric values of all the trials in a set are calculated removing one dimension. Figure 4.5 illustrates the structure of the precursory trials sequences analysed. The three preceding sets of trials before a response type are concatenated resulting in a series of 21 sampling windows. The result is a data set of 21 x 5 x 7 values per graph metric per condition. The conditions are correct and erroneous responses. A 3-way ANOVA is performed using the factors (condition x frequency x cortical region), (2 x 5 x 7) where there are 21 sampling window values for each combination of factors. This method is applied to the sequence of trials preceding correct and error responses where the response trial is either a change of

stimulus, no change of stimulus, junction trial (in experiment two), or all. Interactions between factors are analysed using marginal means and the Tukey-Kramer method of multiple comparison control. The interactions that can be analysed between factors when required are (condition x frequency band), (condition x cortical region) and (frequency band vs cortical region). The patterns of marginal mean interactions distinguish which combinations of results are significantly different. The precursors to zero and high response error rate trials are also analysed using the same method.

The trials surrounding changes of stimulus and junctions are analysed using a similar method. The purpose is to investigate the effects of repetition priming and antipriming. Figure 4.6 illustrates the sequence of trials. The difference in graph metric between each adjacent trial set is calculated for each combination of frequency band and cortical region. The seven sampling windows per trial set are the values for each factor combination. A 3-way ANOVA (trials x frequency x cortical region) 3 x 5 x 7 is performed to check for any significant differences in the sequence associated with the change of stimulus or junction trial events. Interactions between factors are analysed using the same method as previously described.

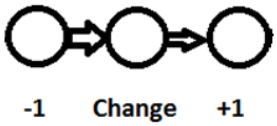

Figure 4. 6. The sequence of trials that surround the change of stimulus or junction trial. The differences between the three trials prior to seven trials post event are analysed.

4.9 Stimulus response behavioural analysis

The behavioural responses to the sequences of stimuli are analysed to test for meaningful patterns. Each sequence of stimuli occur a number of times with a known count of response errors. The final stimulus type has a known erroneous response rate. The binomial distribution is used to analyse the sequence response outcomes. The equations are shown in equation 4.1.

$$prob(\ event\ count = k\ ) = \binom{n}{k} p^k (1-p)^{n-k}$$

$$Where\ \binom{n}{k} = \frac{n!}{k!\,(n-k)!}$$

$$Mean = np$$

$$Variance = np\ (\ 1-p\ )$$

Equation 4. 1. The binomial distribution. p = the probability of the event occurring independently, n = sample size and k = the number of events that occur. The result is the probability of k out of n events occurring in given the expected probability.

The expected probability of erroneous responses for a set of stimuli sequences is:

n = the total number of sequences in the set

k = the number of sequences with a response error in the set

p = the expected probability of the final stimulus resulting in a response error

If the sum of all the probabilities from k to n are less than 0.05 than the event probability is significantly high. Otherwise if the sum of all the probabilities from 0 to k are less than 0.05 the event probability is significantly low.

4.10 Alertness – EEG measurement indexes

The objective measurement of alertness or fatigue provides an additional assessment of the subject's cognitive engagement with the experiment. The definitions of alertness or fatigue varies between authors with overlapping usage and meanings. A paper published by Jap et al uses the term fatigue to describe what may be considered cognitive alertness [52 and 79]. In these experiments alertness refers to the subject's active engagement with the task.

The objective levels of alertness can be assessed by analysis of the amplitude of the alpha, beta and theta frequency bands of the EEG time series [37, 52, 77 and 78]. The methods used in this section are those developed and evaluated by Jap et al [52]. The methods use the relative amplitudes of the frequency bands to measure cognitive fatigue levels in real time.

The cleaned EEG data is obtained from the artefact removal process described in section 4.4. Each channel in each trial is decomposed into frequency bands using a 4th order Butterworth filter. The frequency bands theta 4 to 8Hz, alpha 8 to 13Hz and beta 13 to 30Hz are used. The

mean amplitude of each frequency band per channel per trial between 0 and 900ms is calculated.

The five frequency band amplitude based measures used are listed below. The (alpha + theta) / beta measure is reported to be the most sensitive test [52]:

- alpha
- beta
- theta
- alpha + theta
- (alpha + theta) / beta

A standard ANOVA is used to compare the correct and erroneous response trials. The structure of the analysis is illustrated in figure 4.11. The mean of the indexes for each condition and trial relative to the response are compared for significant difference using an ANOVA.

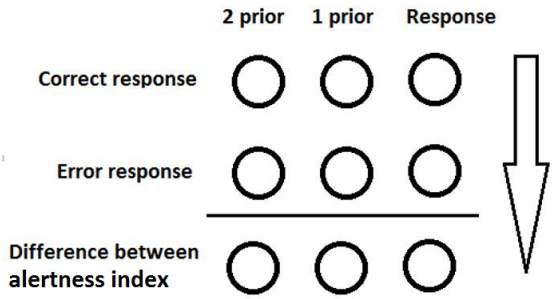

Figure 4. 7. This diagram illustrates the structure of the analysis of the difference in the fatigue indexes, measured by EEG, between correct and erroneous error trial sets at and surrounding the response. Each circle represents a set of trials for the conditions at a specific trial. Its value is the mean of the relevant trials from all the subjects.

The response trials are selected by the response type, (correct or error) and all the preceding trials are correct responses that have not been selected in any previously selected sequence of three trials.

4.11 Conclusion

The raw EEG data is first cleaned of artefacts using a combination of an established automatic method and visual inspection. The behavioural data is been analysed using standard statistical methods to identify which combination of conditions within the EEG time series to

investigate. EMD and phase-locking detection is used to extract the phase-locking data. The phase-locking is stored as adjacency matrices of overlapping epochs for each trial. The adjacency matrices are reduced to a range of graph metrics to simplify the data and reveal different properties. The distributions of the graph metrics are constructed for contrasting experimental conditions. The significant spatial and temporal differences in the distributions for a particular graph metric highlight how the cognitive responses to the conditions compare.

Chapter

5. Experiment one results

5.1 Introduction

This chapter details the results of the behavioural and EEG data analysis from experiment one. The effects of repetition priming, antipriming [10-22] and negative priming are the primary focus of the investigation [90, 95 and 111]. Repetition priming is the improvement in performance caused by repeated experience of a stimulus. Antipriming is a reversal of

priming caused by the primed stimulus occurring in combination with a new stimulus. Negative priming is inhibition of an irrelevant stimulus that is a potential distractors.

This chapter describes the results of behavioural and EEG time series analysis. The full details of the related areas of railway operations simulated are detailed in chapter 2 sections 2.2 and 2.3. The design of the experiment is detailed in chapter 3. The methods of analysis and subject details are provided in chapter 4.

The behavioural analysis is used to guide the structure of the EEG analysis, it is also used to discount any potential confounding factors. EEG based objective measures of fatigue/alertness are tested as a possible explanation of the results. The behavioural results of the analysis of the subject's responses to stimulus is detailed in section 5.5. The graph metric analysis of precursors that predict response accuracy are detailed in sections 5.6. Graph metrics that characterise the patterns of cognitive activity linked to repetition priming and antipriming are described in section 5.7. The results of experiment one are summarised in section 5.8.

5.2 Human factors – confounding effects on the observed results

The experiment is designed to minimise any potential confounding factors and to ensure a consistent context for the results. Undetected or uncontrolled confounding factors have the potential to obscure the experimental results or make accurate interpretation of them difficult. Confounding factors can be introduced by the subject's physiological or mental state, or through environmental causes. The environmental factors can be observed, and thus controlled. However, internal human physiological states are not always externally visible.

Each subject completed a questionnaire to provide information about their age, train driving experience and self-rated levels of hunger, thirst, alertness and caffeine consumption [1, 2 and 3]. The full details of the questionnaire design and content are provided in chapter 3, section 3.3. The questionnaire uses multiple choice responses that use an evenly weighted scale with an equal number and weighting of negative and positive options as well as a neutral option. The Karolinska Sleepiness Scale, KSS, is used for the multiple choice questions [4, 5]. The subjects self-rated levels are likely to vary between subjects; two thirst scores of six may not refer to exactly the same internal states. At the end of the EEG recording session the subjects are asked for feedback.

During the analysis the first trial in each experimental run is excluded. It was observed that the subjects where using this time to optimise their hand, body and seating position. Their attention was always not fully on the experiment and there was a high risk of EEG artefacts from eye movements, blinks and muscle movements during the initial two to three seconds.

Hunger, thirst, alertness (fatigue), task difficulty and caffeine consumption are unobservable states that have the potential to affect the subjects' cognitive performance [1- 3]. These are tested against reaction time and response error rates for significant correlation. The Pearson's correlation test for two tails and alpha = 0.05 is used. No significant correlation was found between any of the states and response accuracy or reaction time. The results of the comparison of the questionnaire factors and the response error rates are listed in table 5.1.

Factor	**Correlation**
Hunger	No correlation
thirst	No correlation
alertness (fatigue)	No correlation
task difficulty	No correlation
caffeine consumption	No correlation

Table 5. 1. The results of the tests for confounding factors. The questionnaire responses are compared against the reaction time for any significant correlation. The Pearson's correlation with two tails, alpha = 0.05 is used.

The response error rate of sub-groups of the subjects was compared for significant difference. The male vs female, and caffeine vs non- caffeine users are compared using the t-test, alpha = 0.05 and two tails. No significant differences are found. Analysis of the handedness groups, left, right and ambidextrous, was not possible because of the small sizes of the left handed and ambidextrous groups. The group sizes are left handed (2), right handed (15) and ambidextrous (3). There is no known evidence that handedness has any effect on the train driver's performance. No significant correlation was found between experience and response accuracy during the experiments using the Pearson's correlation test.

The subject's age was compared to response accuracy using the Pearson's correlation test for two tails and alpha = 0.05. Age has not been previously found to be a factor in train driving

performance [9]. The age correlates with a significant improvement in response accuracy. A significant correlation of r = -0.6650 at p-value = 0.0014 was found showing an improvement in response accuracy with age. This indicates that between the ages of 21 to 65 years response accuracy improves significantly. Reaction time tends to increase with ageing [9]. A subject's life experience may improve their judgement of the balance between reaction time and accuracy, or make the subject more careful. The correlation between reaction time and age is r = 0.6506, p = 0.0014. This increase in reaction time may have a positive influence on the response accuracy. However, reaction time is not significantly correlated with response accuracy across all the subjects and trials.

The repeated trials and sequences of stimuli may produce learning or a conditioned response in the subjects. An experiment-wide learning process would result in significantly fewer response errors and decreased reaction time in the second half of the experiment compared to the first. The distribution of the per subject mean reaction times for all the correct responses and for error response are compared. The t-test for two samples, unequal variation, two tails and alpha = 0.05 is used. There is no significant difference in error rate between correct and error response trials for any of the subject groups, (all, novice and expert).

The distributions of the mean per subject reaction times where compared for the first and second halves of the experiment using the t-test, alpha = 0.05, unequal variance and two tails. This analysis was performed for novice, expert and both subject groups. No significant differences are found within any subject groups. The same process was repeated for the response error rates with no significant differences. This indicates that no significant learning effects occurred between the first and second halves of the experiment.

No confounding factors are found to have any significant effect upon the behavioural analysis data. The experience of the subjects did not have any significant effect on reaction or accuracy.

5.3 Priming and antipriming – behavioural analysis

The stimulus sequences have a detectable effect on reaction time. The mean trial reaction times appear to vary randomly during the experiment as illustrated in figure 5.3. The distribution of the reaction times for all trials and all subjects with its peak in the 500-600ms range is illustrated in figure 5.4.

Inspection of the mean reaction time for one stimulus type reveals a progressive decrease with each successive repetition of the same stimulus, figures 5.1, 5.2 and 5.5. This effect can be seen for each type of stimulus. The reaction time increases after each change of stimulus in the sequences. This effect is consistent with repetition priming and repetition suppression during the repeated sequence, and antipriming during the change of stimulus [13, 15, 16 and 22].

Closer inspection of the long repeated sequences in figure 5.3 show some correlation between the reaction time and error rate plot turning points in the longer sequences of green stimulus. The local peaks and troughs suggest that individual trial error rate increases can result in an increase in the immediate reaction time, conversely improvements in local response accuracy tend to decrease immediate reaction time. There are no repeated sequences of red, yellow or double-yellow stimuli that are comparable with the green stimulus sequence lengths. However, they do show the same reaction time patterns around the change of stimulus events, see figure 5.5.

The mean and standard deviation of the reaction times of the first 85 trials that display a green stimulus are illustrated in figure 5.4. Only six adjacent trials have significant difference when the t-test is applied to adjacent trials. However, the initial decreasing trend in the reaction time over repeated trials can be clearly observed.

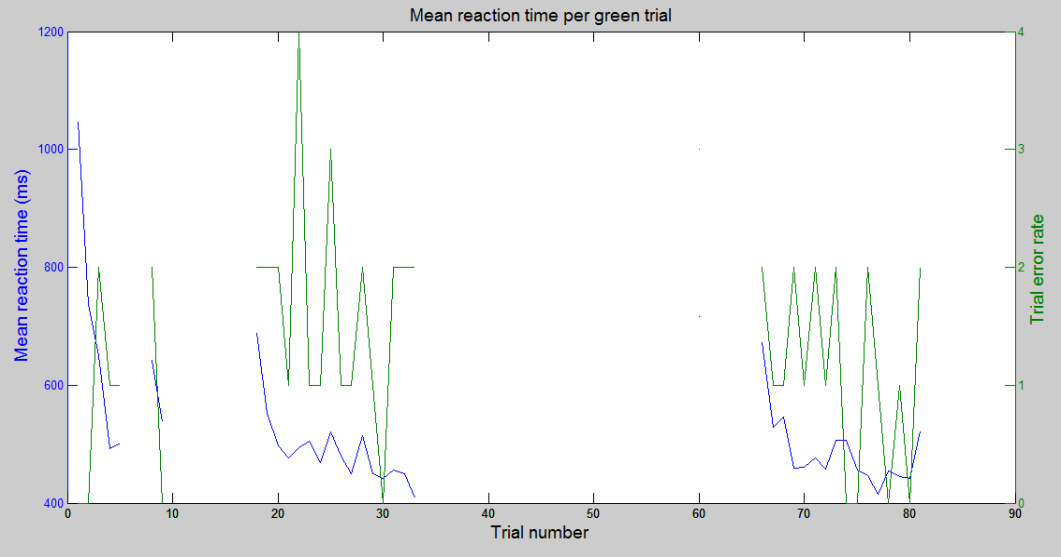

Figure 5. 1. This graph illustrates the mean reaction times and error rates for the first 85 trials that display green stimulus. The blue line is the mean trial reaction time and the green line the number of errors per trial. The two long running sequences of repeated trials are of particular interest because there is some correlation between the changes in error rate and mean reaction time.

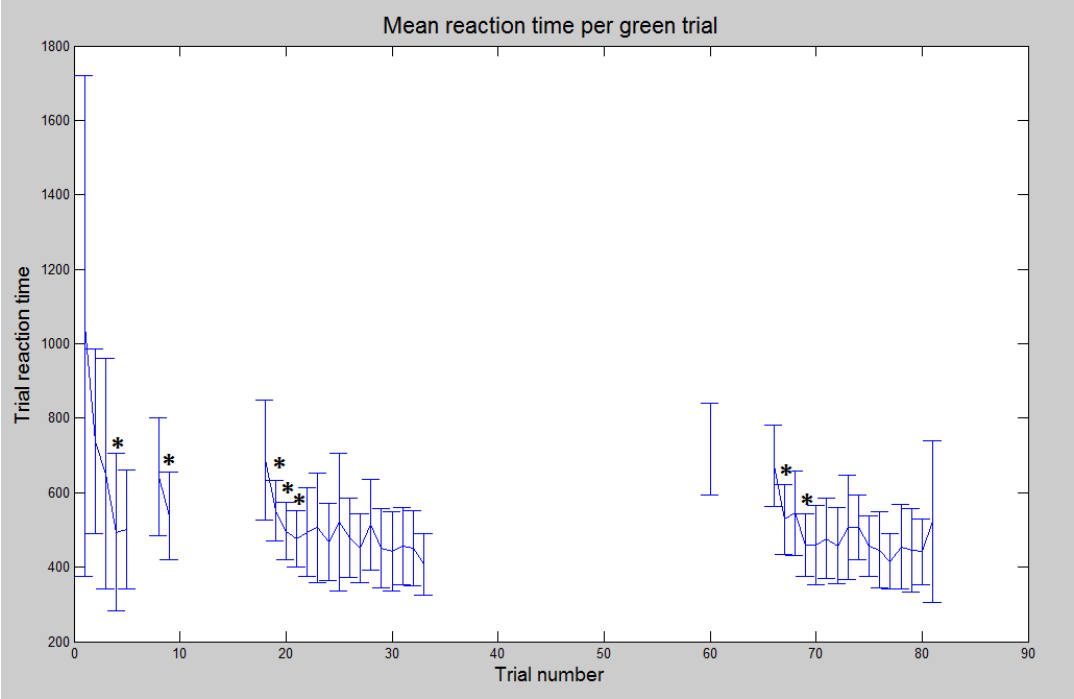

Figure 5. 2. The mean and standard deviation of the reaction times of the first 85 trials that display green stimulus. * = significant difference between the marked trial and its predecessor using the t-test with unequal variance, two tails and alpha = 0.05.

The Pearson's linear correlation of the smoothed per-trial error rate and the reaction time is compared using a window size of five, (p = 0 and r = 0.3955). There is a significant but weak experiment-wide correlation between the measures.

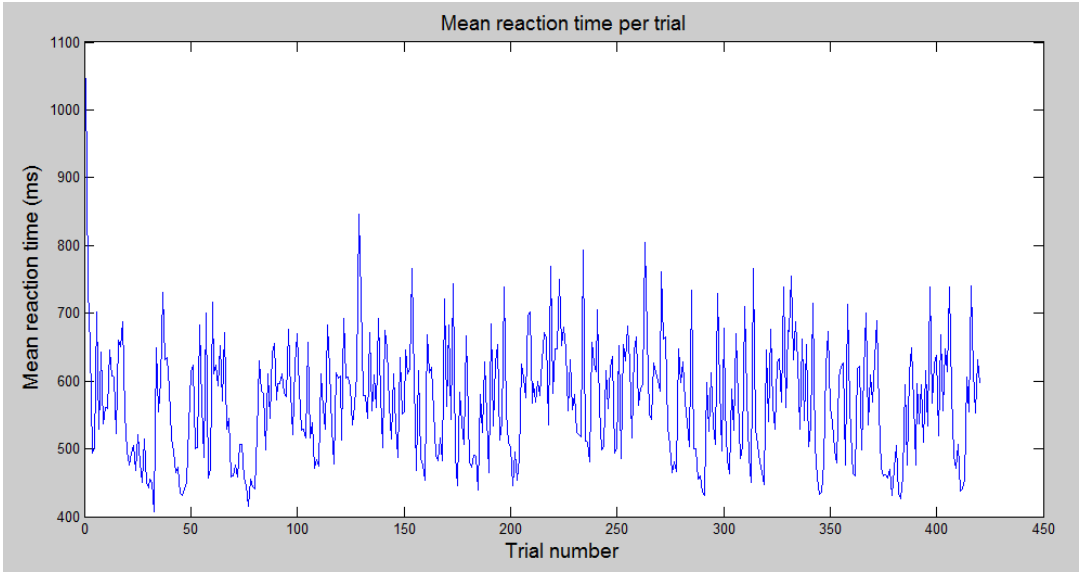

Figure 5. 3. This graph illustrates the mean reaction time for each trial in experiment one.

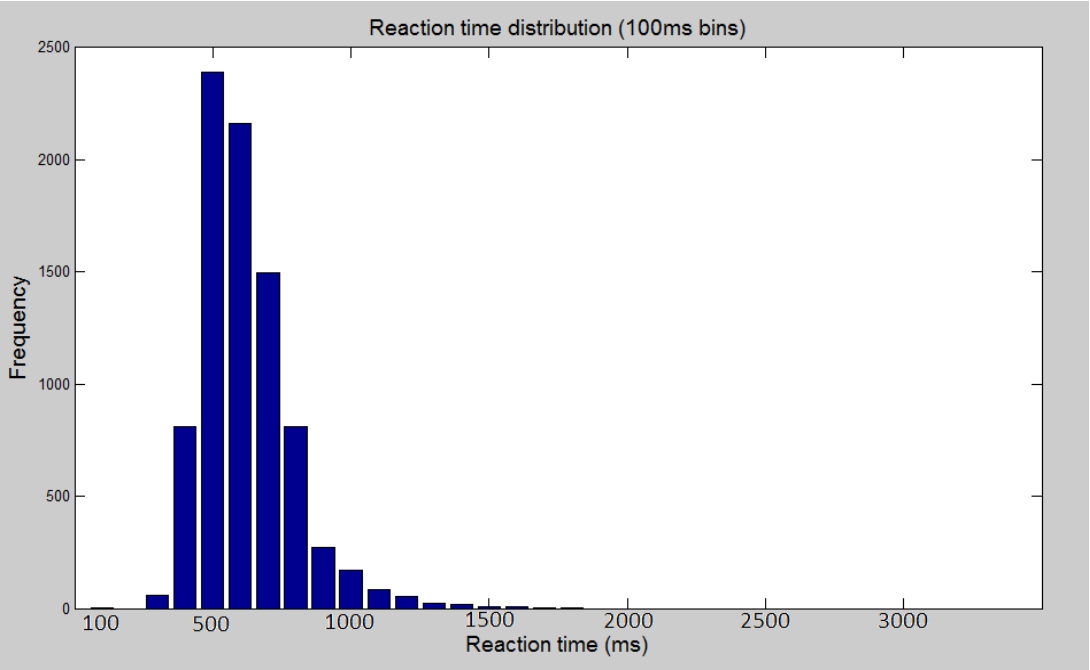

Figure 5. 4. The distribution of the reaction times for all trials and all subjects in 100ms bins in experiment one.

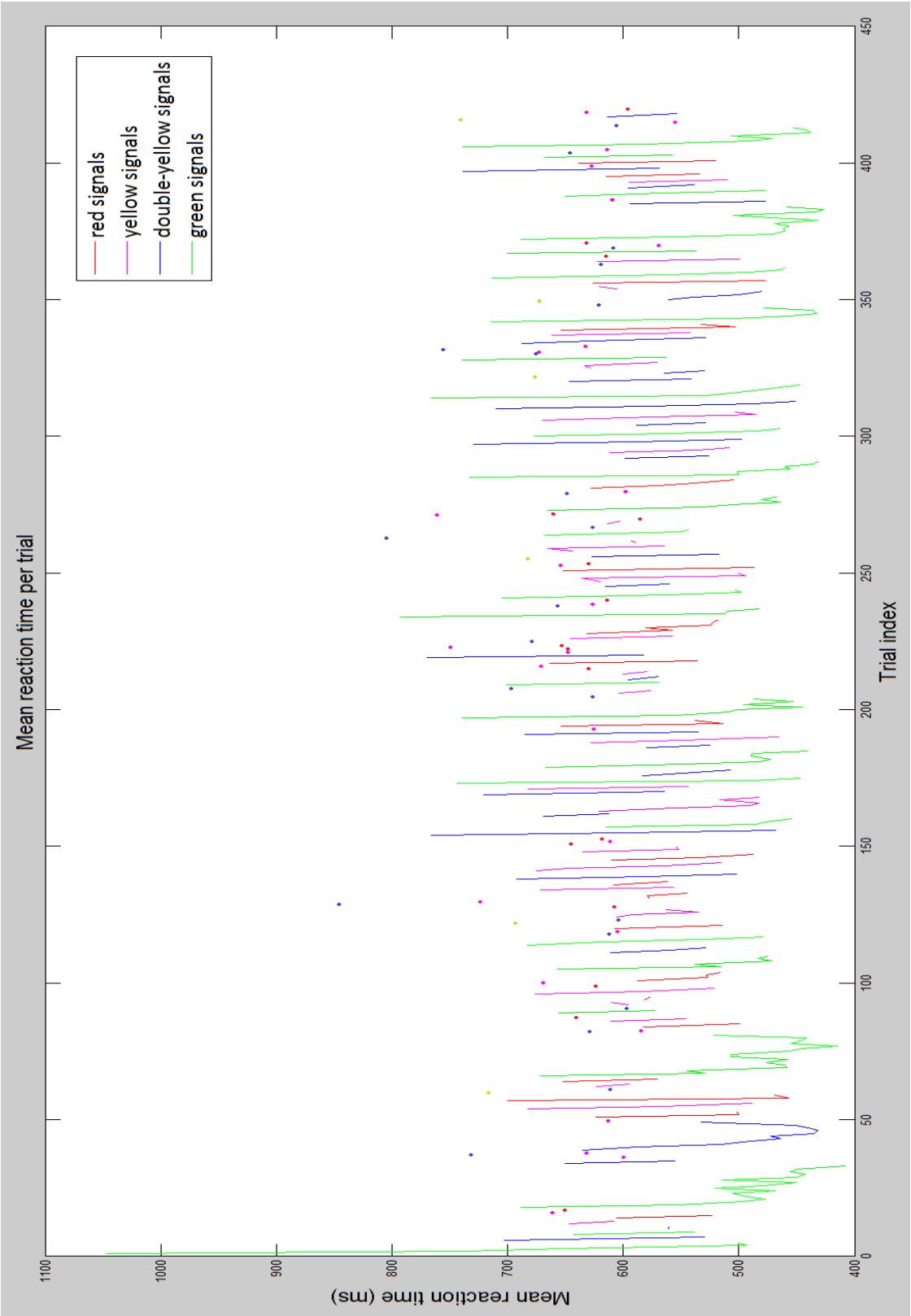

Figure 5. 5. This graph illustrates the mean reaction time of each stimulus type. There are four separate discontinuous lines for the red, yellow, double-yellow and green stimulus. The red line is for the red stimulus, the magenta line for yellow stimulus, blue line for double-yellow stimulus and green line for green stimulus. The dots are individual trials.

5.4 EEG alertness indexes measurements

The subject's cognitive alertness or fatigue is a possible cause of variations in their response accuracy. The levels of fatigue may vary without the subject's immediate awareness. Fatigue can be measured objectively using EEG time series data or reaction times. The analysis of the amplitude at particular frequencies within the EEG time series provides a potential method of measuring the subjects' fatigue level objectively. The methods applied here where developed by Jap et al [37 and 52], details in chapter 4 section 4.10.

Table 5.2 lists the results of the ANOVA comparison of the correct and erroneous responses. There are no significant differences between any of the alertness-fatigue indexes during the response trial and the two trials prior to it.

Fatigue measure Using frequency bands	**F**	**p-value**
Alpha	0.25	0.7938
Alpha + theta	0.31	0.7551
(Alpha +Theta)/Beta	0.08	0.925
Beta	0.54	0.6318
Theta	0.44	0.6784

Table 5. 2. The results of the ANOVA comparison of fatigue-alertness indexes for the correct and erroneous response during experiment one.

5.5 Behavioural responses

5.5.1 Effect of repeated sequence lengths

The effect of the repeated sequence lengths and response error probabilities at the break in the sequences are analysed. The lengths of the repeated sequences of stimuli and their type vary throughout the experiment. The change of stimulus trials located at the end of the repeated sequences have a significantly higher observed error probability of 15.38%. Figure 5.6 shows the sequence length error probabilities and statistical significance test results.

The sequences of length one have a significantly higher than average error rate which is consistent with the changes of stimuli having higher error rates. Sequences of length two, three, four, six, seven and eight where significantly lower than the mean error rates, all others have no significant difference. There are sequences of length seven, none ended in a response error. Sequences of length five have no significant difference because of the small

sample size. The results suggest that the sequence length has no significant effect upon sequence break response error rate for sequences up to eight repetitions long.

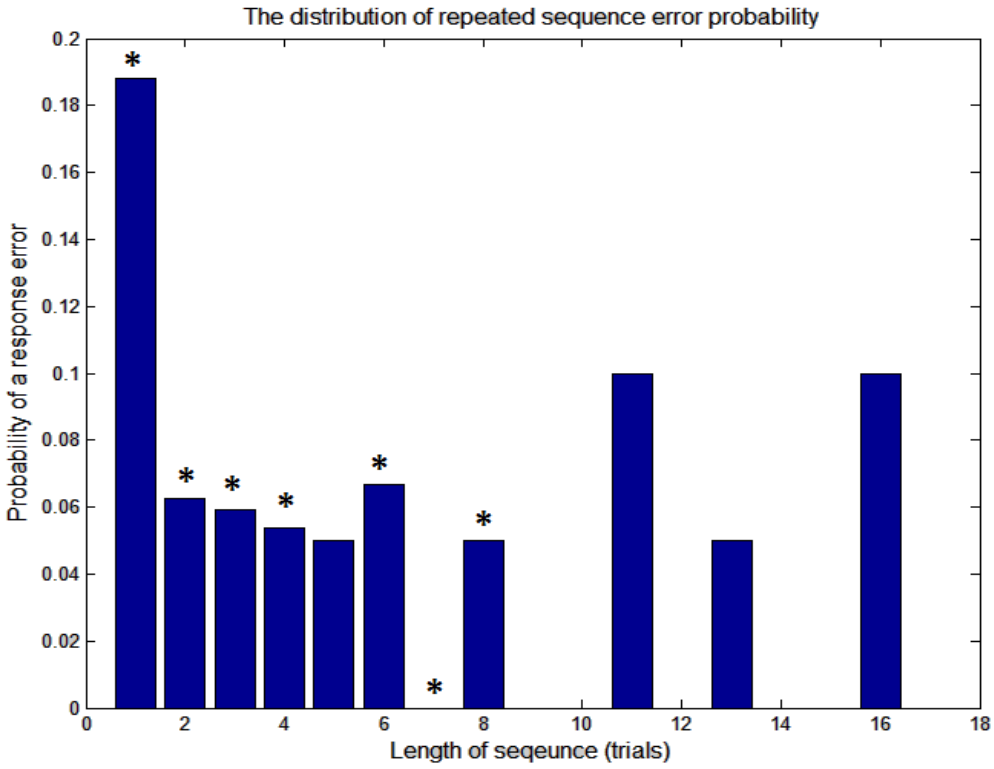

Figure 5. 6. This graph illustrates the probabilities of repeated sequences of different lengths of repeated stimuli sequences ending with a response error. Some bars are missing because there are no sequences of these lengths except for seven which has an error rate of zero. The * marks the sequence lengths that have significant error probabilities. The binomial test with two tails, alpha = 0.05 and probability = 0.1538 is applied to the data.

5.5.2 Conditioned response errors

The repeated sequences of stimuli create the possibility of conditioned response errors when the change of stimulus finally occurs. A conditioned response error is a special type of response error. It occurs when the subject's response to the new stimulus wrong and matches the previous stimulus. This may indicate that the subjects have become conditioned to repeated response regardless of the stimulus that is presented.

Table 5.3 lists the frequencies and probabilities of the change of stimulus response errors for the sequence stimulus types, all, green, double-yellow, yellow and red stimulus. The probabilities of a response error are similar for all types of stimulus, between 11.97 and 17.84%. The subset of response errors at changes of stimuli have much higher response error probabilities of between 58.23% from green signal sequences, to 74.73% for yellow signal

sequences. The red, yellow and double yellow signal have similar conditioned response probabilities between 71.19 and 74.73%. The green sequences have the lowest conditioned response error probability of 58.23%, which also tend to have the longest sequences. The results clearly show a conditioned response occurring during repeated sequences. This could be a results of the repetition priming and repetition suppression effects.

Sequence stimulus type	**Number of sequence breaks**	**Number of sequence break response errors**	**Probability of sequence break response errors (%)**	**Number of sequence break conditioned response errors**	**Probability of sequence break conditioned response errors (%)**
All	3380	520	15.38	367	70.58
Red	720	118	16.39	84	71.19
Yellow	1020	182	17.84	136	74.73
Double yellow	980	141	14.39	101	71.63
Green	660	79	11.97	46	58.23

Table 5. 3. These are the probabilities of response errors when a repeated sequence of stimuli ends. The overall response error rates, and conditioned response error rates are listed. A conditioned response error occurs when the response matches the repeated sequence stimulus type, not the new stimulus.

5.5.3 Position in sequence effects

Repeated sequence positions of 2, 3, 4, 5, 7, 10 and 13 have error rates significantly lower compared to the experiment mean of 9.71%, all the others are not significantly different, as illustrated in figure 5.7. There appears to be a significant decrease in error rate for trials two to seven. Beyond this there is no consistent trend because of the smaller sample sizes. The decresed response error rate is consistent with the reported effects of repetition priming and repetition suppression [13, 15, 16 and 22].

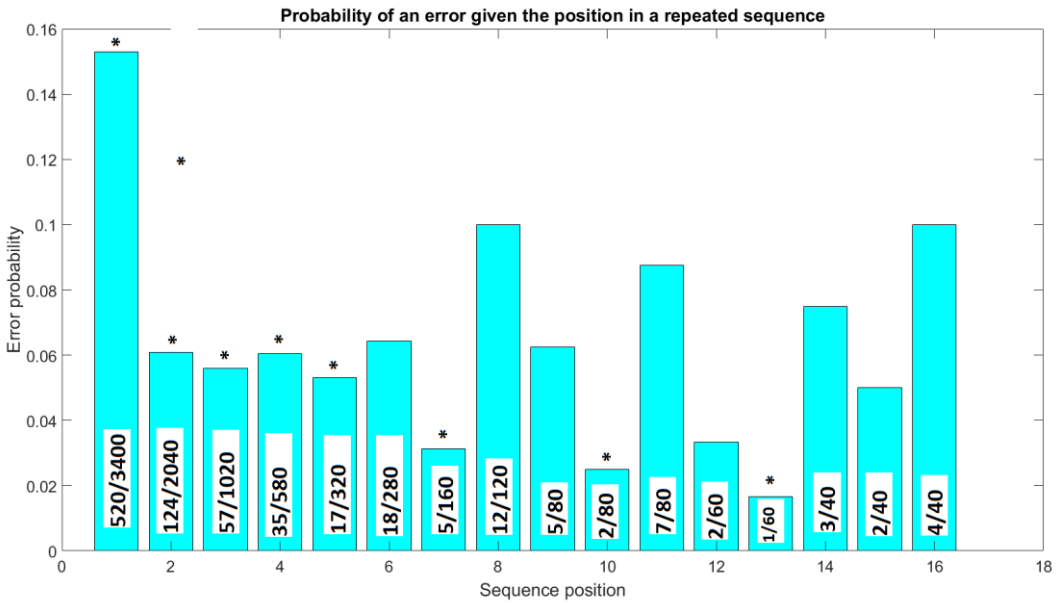

Figure 5. 7. This bar chart illustrates the observed error probabilities for individual positions within the repeated sequences. * = significantly different from the experiments overall error probability of 0.0971 using the binominal test with two tails and alpha = 0.05.

5.5.4 Sequence internal errors and sequence length

The length of the sequences of the repeated stimuli may have an effect on response error rates. The results of the statistical analysis of sequence length vs response error probability within the sequence are shown in table 5.4. The maximum number of within sequence errors is five and maximum sequence length is 16. The distribution of sequence lengths is shown in figure 5.8. The probability of a given number of errors within a sequence is generally the same regardless of its length. Repeating the same stimulus type reduces the local observed error rate. This suggests that repetition priming and repetition suppression are occurring [13, 15, 16 and 22]. This also suggests an absence of any significant cognitive fatigue due to repeated stimuli.

Sequence length	**Number of error within the repeated sequence**					
	0	**1**	**2**	**3**	**4**	**5**
1	1088 (0.812)	252 (0.188)				
2	840 (0.824)	169 (0.166)	11 (0.0108)			
3	317 (0.72)	108 (0.245)	15 (0.034)	0		
4	201 (0.773)	53 (0.204)	6 (0.023)	0	0	
5	36 (0.9)	3 (0.075)	0	1 (0.025)	0	0
6	87 (0.725)	26 (0.217)	6 (0.05)	1 (0.0083)	0	0

7	24 (0.6)	12 (0.3)	3 (0.075)	1 (0.025)	0	0
8	22 (0.55)	16 (0.4)	1 (0.025)	0	1 (0.025)	0
11	11 (0.55)	7 (0.35)	2 (0.1)	0	0	0
13	10 (0.5)	4 (0.2)	4 (0.2)	1 (0.05)	1 (0.05)	0
16	16 (0.4)	11 (0.275)	8 (0.2)	3 (0.075)	1 (0.025)	1 (0.025)

Table 5. 4. This shows the frequency and probability, in brackets, of the number of response errors within repeated sequences. The missing rows (9, 10, 12, 14 and 15) indicate that no sequences of those lengths occurred.

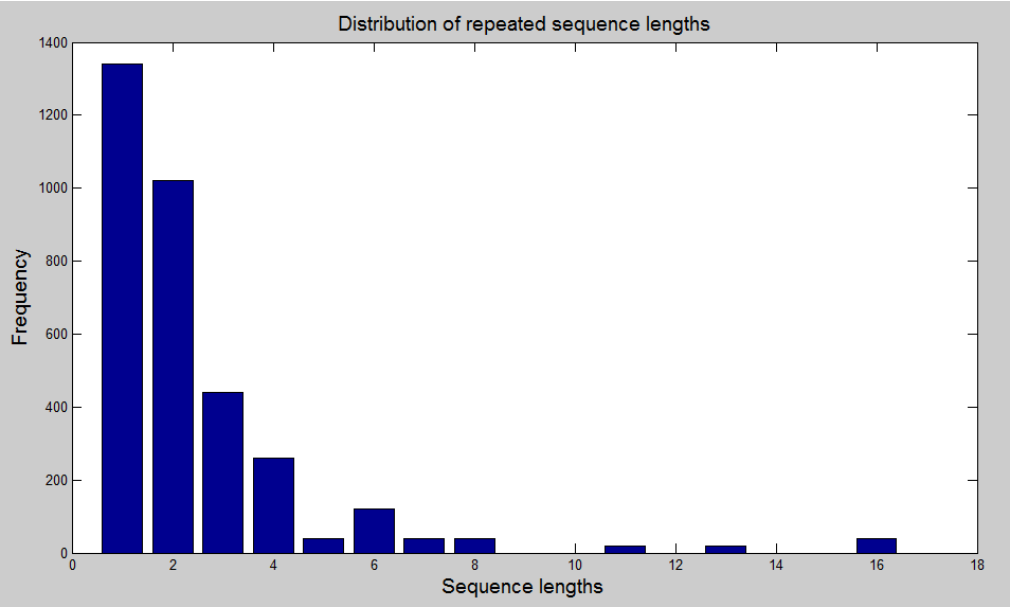

Figure 5. 8. This bar chart illustrates the frequency and distribution of the repeated sequence lengths. Sequence lengths 9, 10, 12, 14, and 15 did not occur during experiment one.

5.5.5 Effect of errors on future response accuracy

Do the subjects learn and improve their response accuracy in the short term from their errors? The number of response errors in five consecutive trials was compared to a window of the same length immediately following it. Window lengths greater than five produce very low or zero-counts and are therefore unrevealing. Figure 5.9 illustrates the structure of the moving windows of trials being analysed. The window is moved along the time axis one trial at a time.

The results of the analysis for a window of length five are shown in figure 5.10. The probability of making a particular number of errors in the future trials window is not altered by the number of response errors in the current window. The subjects do not get any real-time

feedback of their response accuracy during experiment one. The results indicate that the subjects are not improving their response accuracy based on prior response errors in the short term.

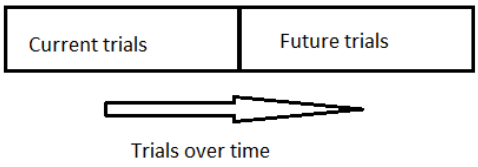

Figure 5. 9. The current and future trials sets are of the same length of five trials. The pair of windows is moved along the time axis one trial at a time until the end of the future trial set reaches the end of experiment one.

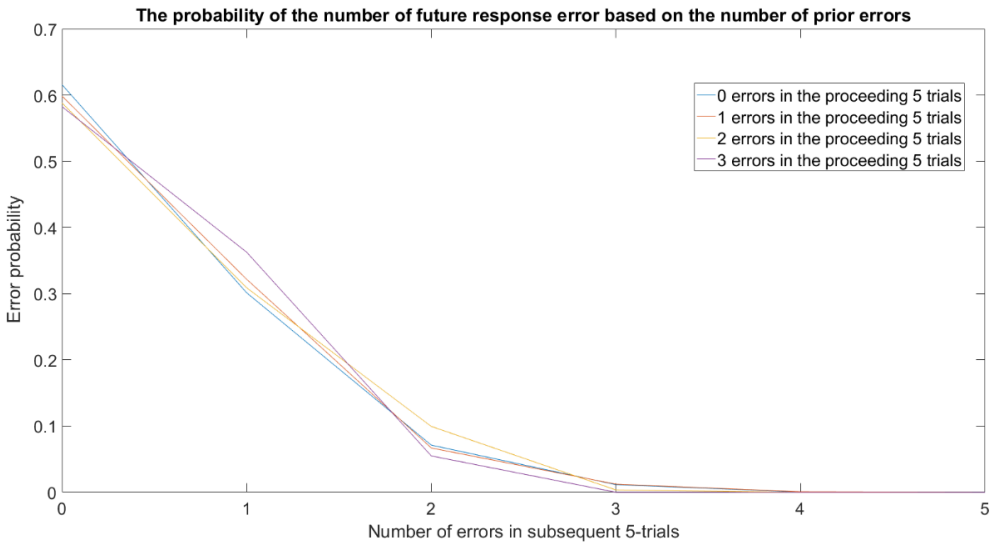

Figure 5. 10. This table compares the frequency and error probability of the number of response error counts for the current windows of length five and following windows of the same length. The probability is in the brackets.

5.5.6 Types of response error

There is a fixed set of possible response errors to any stimulus type. The subjects respond by pressing one of four colour-coded keys, or they can fail to respond. The observed probabilities for each stimulus and response are detailed in tables 5.5, B.1 and B.2 in appendix B. The diagonals show the correct response statistics. There is no significant difference in response error rate between novice and expert subjects for any of the stimulus types using the t-test, alpha = 0.05 with two tails.

The probability of a red stimulus response error is 14.17%, yellow is 10.99%, double-yellow is 10.36% and green is 6.45% for all subjects. Table 5.5 is a summary of error probabilities for all the subjects. The change of stimulus trials have an overall error rate of 15.38%, the error rates for each stimulus type within this trial type are red 21.08%, yellow 15.59%, double-yellow 14.39% and green 10%. The probability of no response was similar for all stimulus types.

These shows that the more frequently the stimulus occurs the lower the response error. Change of stimulus trials are more likely to produce response errors. This is further evidence for repetition priming and antipriming effects [13, 15, 16 and 22].

	Response type									
	Red		**Yellow**		**Double**		**Green**		**None**	
Stimuli type	**count**	**Prob-ability**	**count**	**prob-ability**	**count**	**prob-ability**	**count**	**prob-ability**	**Count**	**prob-ability**
Red	1236	0.8583	129	0.0896	1	0.0007	9	0.0063	65	0.0451
Yellow	29	0.0151	1709	0.8901	94	0.049	19	0.0099	69	0.0359
Double-yellow	25	0.013	22	0.0115	1721	0.8964	79	0.0411	73	0.038
Green	35	0.011	4	0.0013	22	0.0071	2900	0. 935	139	0.0448

Table 5. 5. This table shows the stimulus response combination counts and associated probabilities for all subjects. The probability of a red stimulus response error is 0.1417, yellow is 0.1099, double-yellow is 0.1036 and green is 0.0645. The yellow highlights indicate the correct responses.

5.5.7 High and zero error rate trials

Some trials have no response errors while others have high response error rates. The mean observed error rate for the trials is 9.69%, some individual trials have zero error counts and others have counts as high as 19 out of 20 presentations. The high error count trials are displayed in figures 5.11 as the tallest lines, and the distribution of per trial error rate frequency in figure 5.12. The probability of a red, yellow, double-yellow or green stimulus trial having an error count of six or more is 12.5%, 6.25%, 4.17% and 1.29% respectively. This is consistent with less frequent stimulus having a higher response error than more frequent ones.

The trials with error counts of zero and those greater than six (high) are considered. There are 23 trials with error rates over six which is 5.95% of all trials. All the high error rate trials are change of stimulus trials. Only 27 out of 95 of the zero error rate trials are change of stimulus trials. This is consistent with change of stimulus trials having significantly high response error rates. The reason why some change of stimulus trials have a zero response error rate while others are high is not clear from the behavioural analysis.

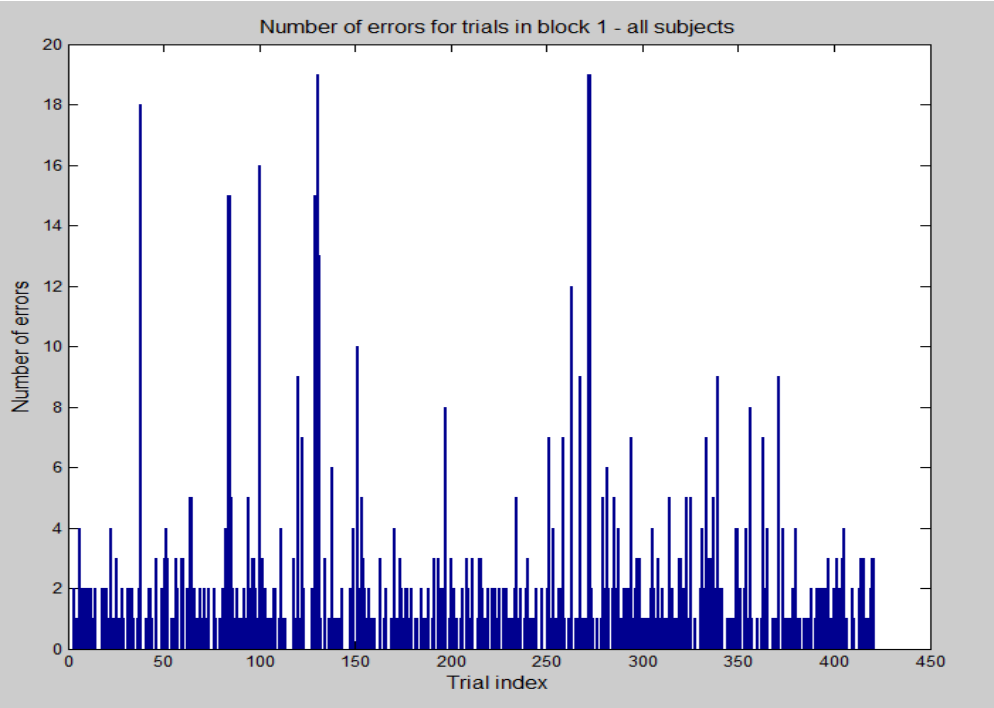

Figure 5. 11. The number of errors made in each trial by all 20 subjects. The expected number of errors per trial is 1.94.

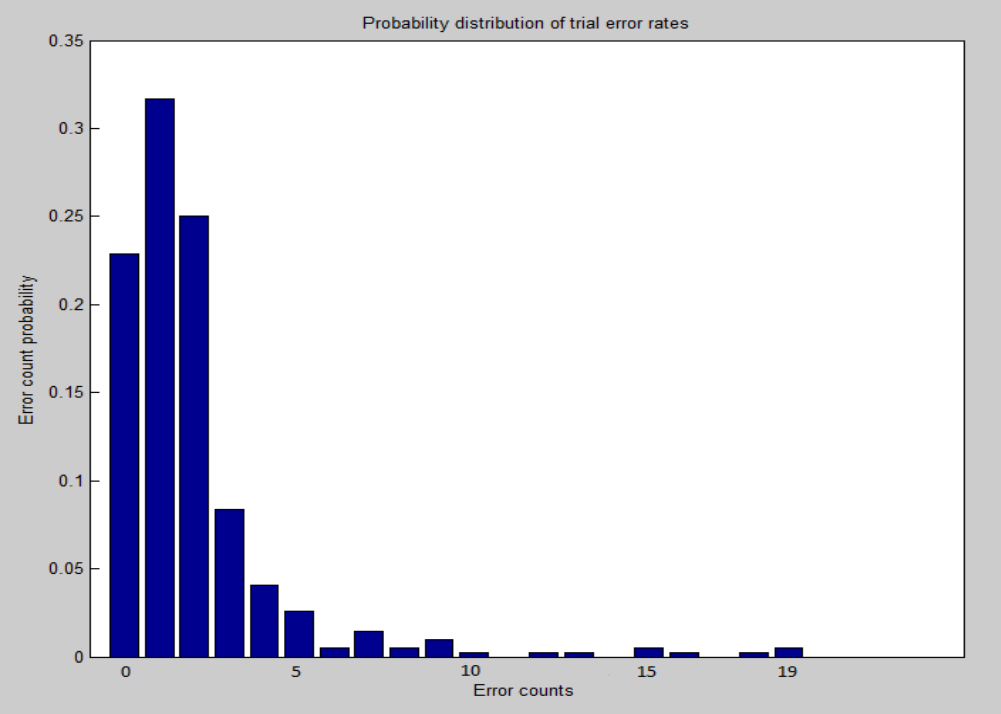

Figure 5. 12. The histogram of the probability distribution of the trial error counts for experiment one. The trials with error rates greater than or equal to 6, are 5.95% of all trials.

5.6 Response errors and stimuli sequence histories

This section details the investigation of the effect that sequences of stimuli have on the response error rates of the following trials. The pattern of stimuli prior to particular types of trial may have a significant influence upon response accuracy. Those with the significantly high or low probability of error can be compared for differences.

The probability of each sequence of trials immediately prior to a given trial type is analysed. The maximum number of combinations grows rapidly with the length of sequence. The maximum number of legal combinations is 13, 40 and 121 for sequences of length two, three and four. Sequences beyond this length can result in many small sample sets being produced making meaningful statistical analysis impractical. Sequence lengths of two, three and four will be analysed in the following sections to ensure the number of samples is sufficient. There are restrictions on the valid sequences of stimuli in this experiment as described in chapter 2, section 2.2.2. The method of calculation is described in chapter 4, section 4.10.

5.6.1 Preceding individual trial type effect on response accuracy

This section investigates the effect of individual prior stimulus of a given type on future response accuracy. The number of trials prior to the current trial is varied between one and seven. The current trial response is either correct or an error. The stimuli types considered in the prior trials are (red, yellow, double-yellow or green), response error, or change in stimuli sequence. The potential long range effects of the individual prior trials is assessed.

For example: the probability of a red stimulus preceding a response error by four trials is the number of times a red stimulus occurs four trials before a response error, divided by the total number of times a red stimulus occurs four trials before any stimulus. Cases where the observed error rate is significantly different to the expected error rate are of interest.

The details of the statistical tests for each trial type are listed in tables B.3 to B.9 in appendix B, table B.9 is the summary of the results, the results are also summarised in table 5.6. The individual red stimuli are significantly more likely than the observed error rate for all trials to precede a response error by one or two trials. The individual yellow stimuli are significantly more likely to precede a response error by one to four trials. The individual double-yellow stimuli are not significantly more or less likely to precede a response error. The individual green stimuli are significantly less likely to precede a response error by one or two trials. The change of stimulus trials are significantly less likely to precede a response error by one to three trials. The response error trials are not significantly more or less likely to precede a response error.

The individual red and yellow stimulus preceding a response error are consistent with their association with higher observed response error rates. They are also likely to occur in close proximity to changes-of-stimulus which have the highest observed response error rate of 15.38%. The preceding green stimulus having significantly lower observed error probabilities is consistent with the green stimulus's low error rate. The trials preceding change of stimulus trials have significantly lower observed error probabilities.

Some of the individual stimuli types that precede response errors by a number of trials have significantly different error rates. The results show that stimulus that primes the drivers of future stimulus changes are more likely to be associated with them. These results are consistent with the change of stimulus trials being a significantly higher response error risk. The maximum range of any detectable effect is four trials prior to a response error which is the extent of the information provided by the four-aspect signalling.

Number of preceding trial	Stimulus type					
	Red	Yellow	Double yellow	Green	Change	All
1	High	High	-	Low	High	-
2	High	High	-	Low	High	-
3	-	High	-	-	Low	-
4	-	High	-	-	-	-
5	-	-	-	-	-	-
6	-	-	-	-	-	-
7	-	-	-	-	-	-

Table 5. 6. This table summarises the results of the significance tests of stimulus types that precede response error trials by a number of trials.

5.6.2 Stimuli sequences of length two that precede response errors

The collective effect of sequences of two stimuli immediately prior to response trials are investigated in this section. There are 13 legal combinations of stimuli defined by the sequencing grammar rules. The probabilities of a response error following each sequence are calculated for each combination of preceding stimulus.

The binomial test is used to test for significant difference between sequence error probabilities and the current trial type observed error probability. The full statistical test results are shown in tables B.10 to B.17 in appendix B. Tables 5.7 and 5.8 is a summary of the significant results.

Table 5.7 listed the number of changes along with the number of low and high response error probabilities. It shows that the number of changes in a sequence increases the likelihood of it having a significantly high response error rate. Sequences are the final change of stimulus is has a lower level of warning, (red to green), are prone to defensive response errors.

Prior sequences ending with a green stimulus with significant response error probabilities are all low. Prior sequences ending with a red or yellow stimulus with significant response errors have 5 out of 7 high probability cases each, double yellow stimulus have 3 out of 7 significantly high response error cases. This result is consistent with the more common stimulus being less likely to be associated with response errors.

Sequences of red, yellow or double yellow stimulus without change of stimulus within them have significantly low response error probabilities. Sequences ending in a green stimulus that

have significant erroneous response error probabilities are all low. Any sequence with two changes of stimuli with significant response error probabilities are all high. Significant erroneous response probabilities for sequences with one change of stimulus have 3 out of 7 high results. These results support the previous observation that indicate the changes of stimulus increase the probability of response errors as do rarer stimulus.

Table 5.8 lists the number of changes along with the number of low and high response error probabilities. It shows that the number of changes in a sequence increases the likelihood of it having a significantly high response error rate. Sequences are the final change of stimulus has a lower level of warning, (red to green), are prone to defensive response errors. A defensive error is one where the response is for a more restrictive signal than shown, which can be considered as a cautious response. Sequences composed of the same stimulus have a significantly low response error probability or no significant erroneous response rate. Sequences ending in changes-of-stimulus tend to have significantly higher error rates than those without such changes. These results are consistent with the effects of repetition priming and antipriming [12-16].

Sequence	**Stimulus type**				**Trial type**	
	Red	**Yellow**	**Double-yellow**	**Green**	**Change of stimuli**	**Response errors**
R–R	L (6.43%)	-	H (28.75%)	H (16.00%)	-	H (12.29%)
Y-R	L (7.14%)	H (23.00%)	H (33.33%)	-	-	-
R-Y	H (20.71%)	-	-	-	-	H (15.83%)
Y-Y	-	L (5.79%)	-	-	-	-
D-Y	H (30.00%)	L (5.00%)	-	-	H (21.39%)	H (12.56%)
R-D	n/a	H (47.50%)	-	-	H (31.67%)	H (16.43%)
Y-D	n/a	H (62.50%)	-	-	H (45.00%)	H (21.11%)
D-D	n/a	-	L (5.00%)	-	L (11.61%)	-
G-D	n/a	-	L (6.67%)	H (20.00%)	L (10.00%)	-
R-G	n/a	n/a	-	-	-	L (6.18%)
Y-G	n/a	n/a	-	-	-	L (3.00%)
D-G	n/a	n/a	-	-	-	-
G-G	n/a	n/a	-	-	-	L (7.24%)

Table 5. 7. This is a summary of the sequences of the two stimuli that preceded significant error probabilities in the final stimuli or trial types. The symbols are R=red stimulus, Y = yellow stimulus, D = double-yellow stimulus, G = green stimulus, H = significantly higher response error probability, L = significantly lower response error probability, and "-"means that there is no significant result. "n/a" means that the stimulus cannot occur in that combination. The observed error probability for each sequence preceding the current trial types is in brackets. The preceding sequence of stimuli is listed oldest to most recent.

Number of changes	**Low probability sequences**	**High probability sequences**
0	3	0
1	3	3
2	0	6

Table 5. 8. The number of sequences of stimuli ending in red, yellow, double-yellow or green stimulus with significantly low or high response error probabilities. Sequences with two prior stimuli and one response are analysed. The more changes within the sequence the more likely an erroneous response at the end of sequence.

5.6.3 Stimuli sequences of length three that precede response errors

This is an extension of the analysis conducted in sub-section 5.6.2 with preceding sequences of length three. There are 40 legal stimuli sequences for a series of three stimuli, only those that have a significantly high or low probability of an erroneous response are considered. The full statistical test results are shown in tables B.18 to B.25 in appendix B. Tables 5.9 and 5.10 are a summary of the significant results.

Table 5.9 lists the number of changes along with the number of low and high response error probabilities. It shows that the number of changes in a sequence increases the likelihood of it having a significantly high response error rate. The results are very similar to and consistent with those in section 5.6.2 for sequences of length two.

Preceding sequence	Final stimulus type				Final trial type	
	Red	Yellow	Double-yellow	Green	Change of stimulus	Response error
R-R-R	L (6%)	-	-	H (18.3%)	-	-
Y-R-R	L (6.7%)	-	H (28.75%)	H (12.5%)	-	H (12.9%)
Y-Y-R	L (4.5%)	H (26.75%)	H (75%)	-	H (26.49%)	-
D-Y-R	-	-	-	-	L (5%)	-
R-R-Y	L (0%)	-	-	-	L (0%)	-
Y-R-Y	-	-	-	-	H (29%)	H (29%)
Y-Y-Y	-	L (5%)	-	-	-	-
D-Y-Y	-	L (5.6%)	-	-	-	-
D-D-Y	-	L (4.3%)	-	-	-	L (6.4%)
G-D-Y	H (42%)	-	-	-	H (28.8%)	H (18.9%)
R-R-D	-	-	-	-	-	L (2.5%)
Y-R-D	-	H (47.5%)	-	-	H (47.5%)	H (35%)
D-Y-D	-	H (62.5%)	-	-	H (62.5%)	H (35%)
D-D-D	-	-	L (6%)	-	-	-
G-G-D	-	-	L (6.4%)	H (20%)	L (10.8%)	-
R-R-G	-	-	-	-	-	L (4.5%)
D-Y-G	-	-	-	-	-	L (1.67%)
D-D-G	-	-	H (25%)	-	-	-
D-G-G	-	-	-	-	-	L (5%)
G-G-G	-	-	-	-	-	L (7.4%)

Table 5. 9. This is a summary of the sequences of three stimuli that preceded significant error probabilities in the final stimuli or trial types. The symbols are R=red stimulus, Y = yellow stimulus, D = double-yellow stimulus, G = green stimulus, H = significantly higher, L = significantly lower, and "-"means that there was no significant difference in the response error probability. "n/a" means that the stimulus cannot occur on that combination. The observed error probability for each sequence preceding the current trial types is in brackets. The preceding sequence of stimuli is listed oldest to most recent.

Number of changes	Low probability sequences	High probability sequences
0	3	0
1	5	2
2	1	5
3	0	3

Table 5. 10. The number of sequences of stimuli ending in red, yellow, double-yellow or green stimulus with significantly low or high response error probabilities. Sequences with three prior stimuli and one response are analysed. The more changes within the sequence the more likely an erroneous response at the end of sequence.

5.6.4 Stimuli sequences of length four that precede response errors

This is a modification of the tests conducted in sub-section 5.6.3 with preceding sequences of length four. The full statistical test results are shown in tables B.26 to B.32 in appendix B. Tables 5.11 and 5.12 is a summary of the significant results. There are 40 legal stimuli sequences for a series of three stimuli, only those that have a significantly high or low probability of an erroneous response are considered. The analysis results of sequences of length four are consistent with those of length two and three.

Table 5.11 lists the number of changes along with the number of low and high response error probabilities. It shows that the number of changes in a sequence increases the likelihood of it having a significantly high response error rate. The results are very similar to and consistent with those in sections 5.6.2 and 5.6.3 for sequences of length two and three. These results reveal the effects of repetition priming and antipriming [12-16].

Preceding sequence	Final stimulus type				Final trial type	
	Red	Yellow	Double-yellow	Green	Change-of-stimuli	All response errors
R-R-R-R	-	-	-	H (18.33%)	-	-
Y-R-R-R	L (5.00%)	-	-	H (18.33%)	-	-
R-R-Y-Y	-	-	H (35.00%)	-	-	H (15.83%)
D-Y-R-R	L (2.50%)	-	-	H (20.00%)	-	-
Y-Y-Y-R	L (2.50%)	H (45.00%)	H (75.00%)	-	H (55.00%)	H (25.00%)
D-Y-Y-R	L (5.71%)	-	-	-	L (5.00%)	L (5.50%)
G-D-Y-R	-	-	-	-	L (2.50%)	-

Y-R-R-Y	L (0.00%)	-	-	-	L (0.00%)	-
Y-Y-R-Y	H (35.00%)	-	-	-	H (35.00%)	H (35.00%)
R-Y-Y-Y	-	-	-	-	-	H (21.67%)
Y-Y-Y-Y	-	L (0.00%)	-	-	-	-
D-D-Y-Y	H (24.00%)	-	-	-	H (22.50%)	H (13.21%)
Y-R-D-Y	H (65.00%)	-	-	-	H (65.00%)	H (37.50%)
G-D-D-Y	-	L (3.50%)	-	-	-	L (5.38%)
G-G-D-Y	H (42.00%)	-	-	-	H (28.75%)	H (21.67%)
Y-R-R-D	n/a	-	-	-	-	L (2.50%)
Y-Y-R-D	n/a	H (95.00%)	-	-	H (95.00%)	H (95.00%)
D-D-Y-D	n/a	H (90.00%)	-	-	H (90.00%)	H (90.00%)
G-D-Y-D	n/a	H (35.00%)	-	-	H (35.00%)	H (35.00%)
Y-D-D-D	n/a	H (25.00%)	-	-	-	-
D-D-D-D	n/a	-	-	H (25.00%)	-	-
R-G-D-D	n/a	H (35.00%)	-	-	H (35.00%)	H (35.00%)
D-G-D-D	n/a	H (25.00%)	-	-	-	-
G-G-D-D	n/a	-	-	-	L (9.17%)	-
G-G-G-D	n/a	-	-	H (20.00%)	L (10.00%)	-
R-R-R-G	n/a	n/a	-	-	-	L (3.33%)
G-D-D-G	n/a	n/a	H (25.00%)	-	-	-
D-D-G-G	n/a	n/a	-	-	-	L (3.33%)
D-G-G-G	n/a	n/a	H (45.00%)	-	H (45.00%)	-
G-G-G-G	n/a	n/a	-	-	-	L (7.27%)

Table 5. 11. This is a summary of the sequences of four stimuli that preceded significant error probabilities in the final stimuli or trial types. The symbols are R=red stimulus, Y = yellow stimulus, D = double-yellow stimulus, G = green stimulus, H = significantly higher, L = significantly lower, and "-"means that there was no significant difference in the response error probability. "n/a" means that the stimulus cannot occur on that combination. The observed error probability for each sequence preceding the current trial types is in brackets. The preceding sequence of stimuli is listed oldest to most recent.

Number of changes	Low probability sequences	High probability sequences
0	1	0
1	2	1
2	3	6
3	1	8
4	0	1

Table 5. 12. The number of sequences of stimuli ending in red, yellow, double-yellow or green stimulus with significantly low or high response error probabilities. Sequences with four prior stimuli and one response are analysed. The more changes within the sequence the more likely an erroneous response at the end of sequence.

5.7 EEG results - Phase-locking analysis

This section details the significant results of the inter-channel phase-locking patterns measured using graph metrics. The methods analysis are detailed in chapter 4, sections 4.7 and 4.8. The phase-locking pattern differences reveals the characteristics of the cognitive activity associated with particular conditions. The use of graph metrics allowed complex patterns of functional-connectivity to be analysed. The trends of the graph metrics preceding changes-of-stimulus trials for the correct and erroneous responses show how the brains cognitive dynamics evolved prior to and during the events.

The correlations between the graph metrics and subject behaviour is analysed using the following graph metrics:

- node degree, (ND)
- node phase locking value
- node nearest neighbour degree, (NNND)
- node nearest neighbour phase locking value, (NNNPLV)
- betweenness centrality
- closeness centrality

Each of the two trials graph metrics preceding the current behavioural measure are independently compared to the behavioural data. A preceding trial is a leading indicator that can act as the response metric for forecasting response accuracy. There are no significant

strong correlations between any of the selected graph metrics and a reaction-time or response error rate.

5.7.1 Leading indicators for response errors

The graph metrics of the three trials that precede difference response type trials is compared for significant difference. A 3-way ANOVA (condition x frequency band x cortical region) is used as described in chapter 4, section 4.8.

The results for zero vs high response error rate trials, change of stimulus, no-change of stimulus and all correct vs erroneous response trials are listed in table 5.13. The critical graph metric ranges for correct and erroneous responses are listed in table 5.14. The results of the 3-way ANOVA for the comparison of zero and high error rate trials using the node degree are shown in table 5.15. The node PLV graph metric did not have any significant results. The node degree, NNND, NNNPLV, betweenness centrality and closeness centrality have the same results for each group of trial types. There are significant differences between all the cortical regions in the 4-40Hz or alpha frequency bands.

	Node degree	**Node nearest neighbour degree**	**Node nearest neighbour phase locking value**	**Betweenness centrality**	**Closeness centrality**
Zero vs high	4-40Hz, alpha, all regions	4-40Hz, all regions	4-40Hz, all regions	4-40Hz, alpha, all regions	4-40Hz, alpha, all regions
Change correct vs error	4-40Hz, alpha, all regions	4-40Hz, all regions	4-40Hz, all regions	4-40Hz, alpha, all regions	4-40Hz, alpha, all regions
No change correct vs error	4-40Hz, alpha, all regions	4-40Hz, all regions	4-40Hz, all regions	4-40Hz, alpha, all regions	4-40Hz, alpha, all regions
All correct vs error	4-40Hz, alpha, all regions	4-40Hz, all regions	4-40Hz, all regions	4-40Hz, alpha, all regions	4-40Hz, alpha, all regions

Table 5. 13. The summary of all the significant marginal mean difference between the three trials immediately preceding either correct or erroneous response trials. The upper section of each graph metric-trial selection type for frequency, and the lower section for cortical region.

Response error range / Correct response range	Node degree	Node nearest neighbour degree	Node nearest neighbour phase locking value	Betweenness centrality	Closeness centrality
Zero vs high	0.65 to 0.85	6 to 7.5	5 to 6.5	0.32 to 0.48	3 to 3.5
	1 to 1.1	9 to 10.5	8.75 to 10	0.53 to 0.64	4.3 to 4.7
Change correct vs error	0.65 to 0.75	6 to 7.5	5.5 to 6.75	0.32 to 0.48	2.9 to 3.3
	0.97 to 1.05	9 to 10.5	8 to 9.3	0.5 to 0.6	4.1 to 4.4
No change correct vs error	1.15 to 1.25	11.7 to 13.2	10 to 11.5	0.55 to 0.7	5 to 5.3
	1.65 to 1.85	16.75 to 18.75	14 to 16.5	0.8 to 0.95	7 to 7.5
All correct vs error	0.8 to 0.95	8 to 9.5	7 to 8.5	0.42 to 0.55	3.5 to 4
	1.1 to 1.2	11 to 12.5	9.5 to 10.75	0.58 to 0.65	4.7 to 5

Table 5. 14. The range of response accuracy forecasting graph metrics for correct and erroneous responses.

The results of marginal means analysis between response types for the range of cortical regions are illustrated in figure 5.13. The significant difference between the correct and erroneous response trial sets for each cortical region can be seen. This pattern is typical for response trial set comparisons and for cortical regions. Figure 5.14 shows the marginal means of the change of stimulus responses for the betweenness centrality graph metric marginal means for response accuracy vs frequency band. The correct and erroneous marginal means differ significantly for the 4-40Hz and alpha frequency bands. The frequency band marginal ranges are typically smaller than those for cortical regions.

The significant differences in the node degree for the alpha frequency band and global region prior to correct vs erroneous responses are illustrated in figure 5.15. The node degree is lower in the trials before the response error.

Source	Sum sq.	d.f.	Mean Sq.	F	p-value
condition	41.5111	1	41.5111	881.0308	1.36E-150
frequency	2,910	4	727.8304	15,400	0
region	0.2834	6	0.0472	1.0024	0.4221
condition*frequency	88.1613	4	22.0403	467.7837	4.02E-256
condition*region	0.2525	6	0.0421	0.8933	0.4989
frequency*region	0.5656	24	0.0236	0.5001	0.9794
condition*frequency*region	0.4677	24	0.0195	0.4136	0.9947
Error	65.9631	1400	0.0471		
Total	3,110	1469			

Table 5. 15. The 3-way ANOVA (condition x frequency band x region) results for the node degree graph metric for zero vs high response error rate trials, condition refers to zero and high error rate.

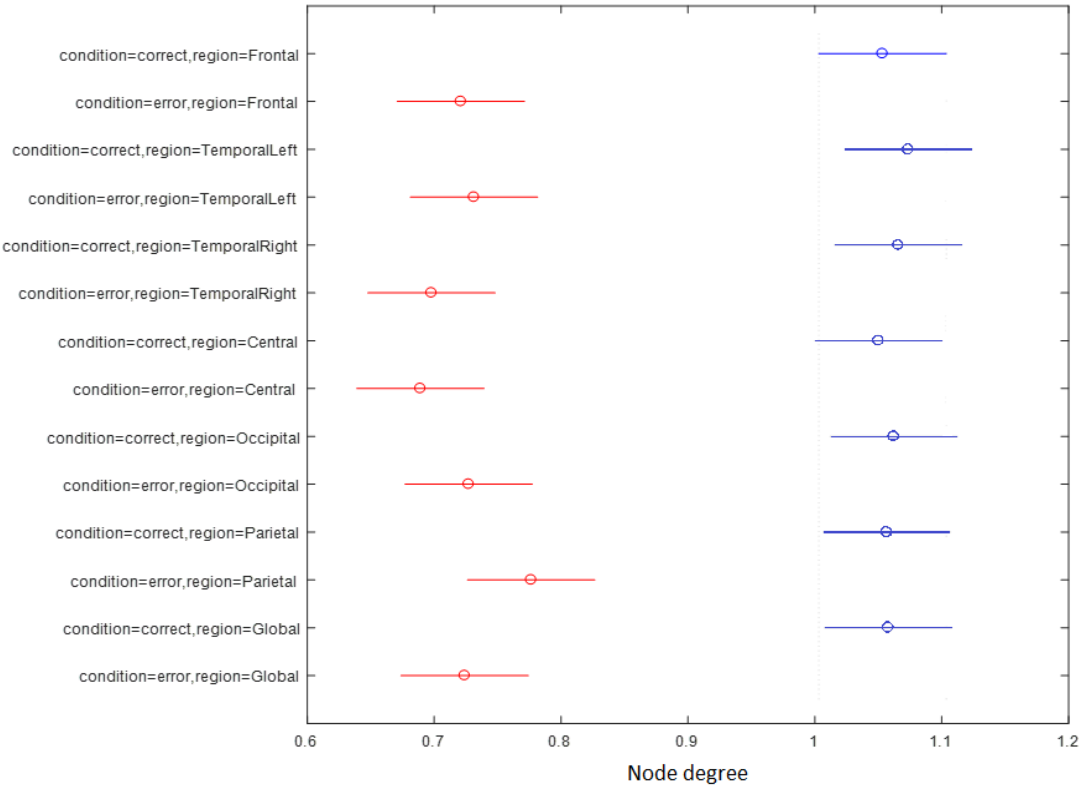

Figure 5. 13. The node degree graph metric marginal means of response accuracies and cortical regions. The correct and erroneous marginal means significantly differ for all cortical regions. Zero vs high response error rate trials. The erroneous responses data is red and correct blue.

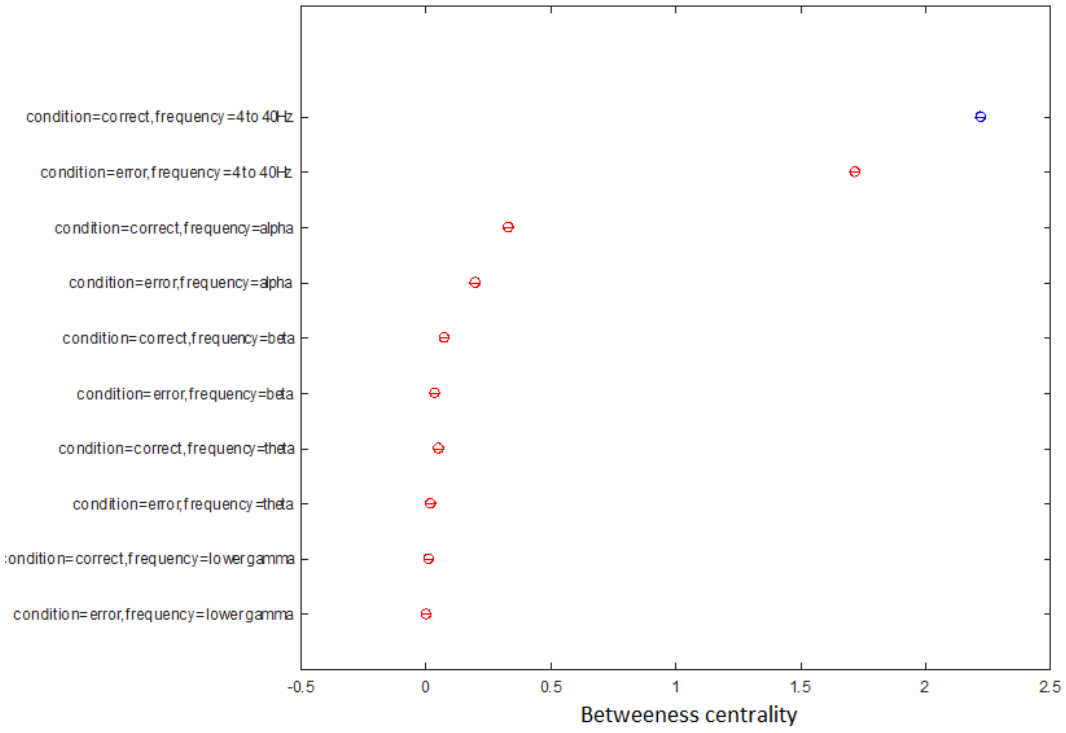

Figure 5. 14. The betweenness centrality graph metric marginal means for response accuracy vs frequency band. The correct and erroneous marginal means differ significantly for 4-40Hz and alpha frequency bands. Change of stimulus response trials.

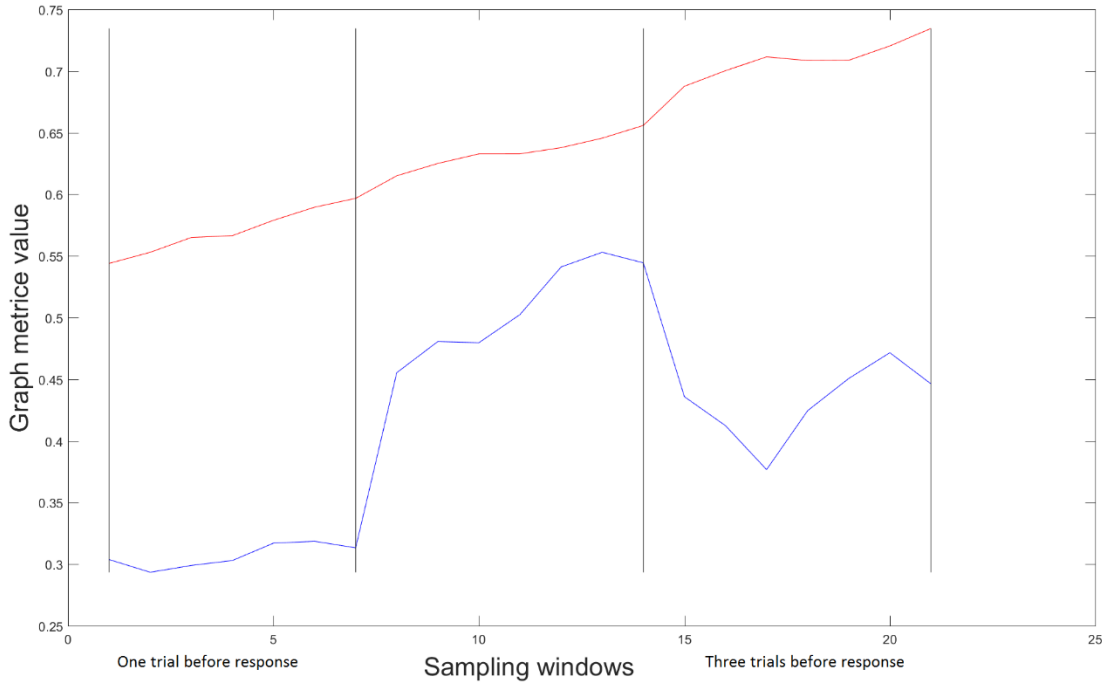

Figure 5. 15. The evolution of the node degree graph metric for the alpha frequency band and global mean. The time windows on the left are immediately before the response event. The red line is for the correct responses and the blue line for erroneous responses. There is a significant difference between the response accuracy precursors. All correct vs erroneous response error trials.

5.7.2 Repetition priming and antipriming

The graph metrics of the trials that surround the change of stimulus trials are analysed for significant differences. The graph metrics reflect the nature of the overall cognitive activity dynamics. These cognitive response differences reflect the effect antipriming and repetition priming have upon cognitive activity. The method of analysis is described in chapter 4, section 4.8. The 3-way ANOVA is performed for each graph metric type.

Figure 5.16 illustrates the node PLV graph metric evolution in the 4-40Hz frequency band for the right temporal region surrounding change of stimulus trials. There is a significant increase in node PLV during the change of stimulus events.

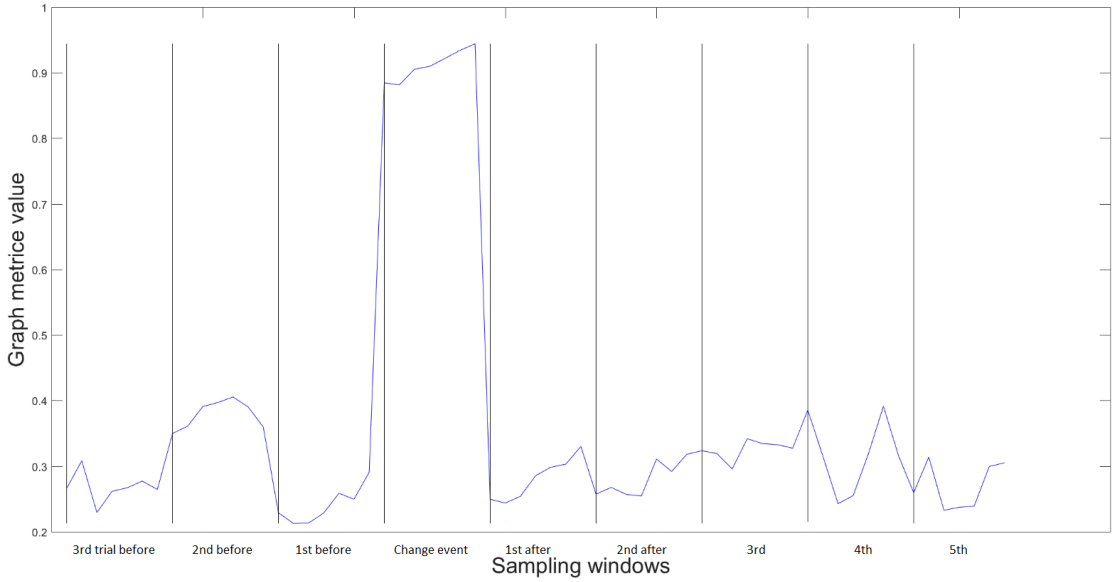

Figure 5. 16. The node PLV graph metric for the 4-40Hz frequency band in the right temporal region. The sampling windows run from the 3rd trial prior to the change trial to the 5th trial post change. The change trial has a significantly difference to the no-change trials surrounding it.

5.8 Conclusion

The first key discovery within experiment one's behavioural dataset is that priming and antipriming occurred consistently [13, 15, 16 and 22]. The mean reaction time per trial progressively decreases with each repetition of a stimulus until it stabilises. When a change of stimulus occurs the reaction time increases, then progressively decreases over five trials.

The second key observation is that the changes-of-stimulus and rarity of stimulus type effect the response error probabilities. The most common stimulus have the lowest observed error rate while the rarest have the highest. Changes-of-stimulus type trials have the highest error rate even though they are not the rarest trial type. The greater the number of changes of stimuli in the two to four trials proceeding a response the greater the probability of a response error at the end. Not all the response errors are hazardous, for example pressing a non-red key when a red stimulus is displayed. Sequences of yellow and red stimuli that precede a green stimulus result in significantly high response errors that are cautious.

The key EEG analysis results using graph metrics reveal patterns of cognitive activity that predict the response accuracy. There are also graph metrics that characterise the cognitive responses to changes of stimulus. The node degree, NNND, NNNPLV, betweenness centrality and closeness centrality in the 4-40Hz and alpha frequency bands are forecasters of response accuracy for the groups of trial type. The global levels of connectivity within regions are important for correct responses to immediately pending trials.

The significant RP and AP related graph metrics are the node PLV graph metric in the 4-40Hz frequency band in the right temporal cortical region. The cognitive responses to RP and AP appear to be distinct from those related to response accuracy.

Chapter

6. Experiment two results

6.1 Introduction

The key results are the effects of repetition priming and antipriming in the behavioural and EEG graph metric data. There are predictors of response accuracy in the EEG graph metrics that differ from those in chapter 5. Negative priming is present in the behavioural response relating to the flanked distractors.

The experiment described in this chapter is designed to investigate the effects of a pair of simultaneous stimuli on the behavioural and cognitive responses. This chapter focuses on the behavioural effects which will be used to guide the EEG analysis of the cognitive effects. Experiment two is more complex than experiment one. A distractor is presented adjacent to the target stimulus. The additional task of remembering which lateral position to follow increases the cognitive work load. The new stimuli are illustrated in figure 6.1. The design of this experiment, stimuli displayed and their meaning are detailed in chapter 2, section 2.2 and chapter 3, section 3.4.

The subject receives an initial visual indication of the lateral position of the stimulus to follow, either on the left or right half of the screen, as illustrated in figure 6.2. The lateral positions of the stimuli represent two parallel railway tracks with the same direction of travel, each with its own sequence of stimuli. The changes of lateral position are each displayed once, so the subjects are required to remember which lateral position to follow.

To prevent lateral position errors resulting in large scale loss of data the subjects receive a prompt in the form of a large red arrow every 20th trial reminding them of the lateral position to which they should be paying attention. Any subset of 20 consecutive trials that has nine or more errors in total is discarded from all analysis. This is because the subjects may not be aware they are attending and responding to the wrong stimuli. Table C.1 in appendix C lists the sets of 20 trials that have been excluded for each of the 20 subjects. Subject number 10 was not included in the analysis for experiment two because the EEG data files for that subject are corrupted.

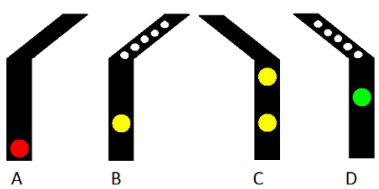

Figure 6. 1. The types of stimuli used in experiment two. The patterns of red, yellow and green lights have exactly the same meaning in both experiments, as stated in figure 6.1. The angled bars above the coloured lights are "junction indicators". When a junction indicator displays a line of white lights (they can only display white lights or be blank) it means that the subjects should move their attention one lateral position to the left or right at the next trial, according to the direction indicated by the junction indicator. When the bar is blank there is to be no change of lateral position.

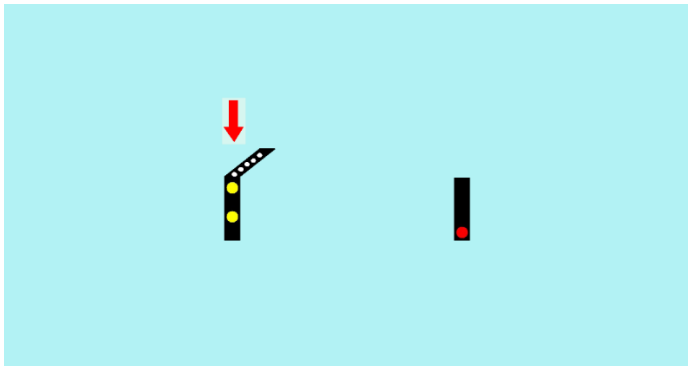

Figure 6. 2. This is a screen shot of an experiment two trial. The red arrow above one of the stimuli indicates the correct lateral position to attend. The red arrow is displayed every 20th trial.

6.2 Confounding factors

The confounding factors are tested using the same methods as experiment one, and are detailed in chapter 4, section 4.3.

The states tested where hunger, thirst, pre-experiment alertness, post experiment alertness, gender, handedness, caffeine consumption, perceived task difficulty experience and age. Ageing has a significant correlation with reaction time ($r = 0.604$, $p = 0.006$), which is consistent with the known effects of ageing [9]. Neither the novice nor the expert subjects display any significant differences in mean reaction times or error rates. No confounding factors are present.

6.3 Learning effects and conditions responses

The same learning effects and conditioned response tests have been applied to this experiment as to experiment one's behavioural data, as detailed in chapter 5 sections 5.2 and 5.5.2. The error rates between the first and second halves of the experiment, short-term error rate and conditioned response errors display no significant differences. The repeated

stimuli sequence length have no effect on error rate. The position of a trial within a repeated sequence has no significant effect upon error rate. There are no significant conditioned response errors or learning effects in experiment two's behavioural data.

6.4 Trial type response analysis

The observed response error rates for the stimulus and trial types are analysed. There are five types of key board response: the red key, yellow key, double-yellow key, green key; and no response. There are four primary types of stimuli type red, yellow, double-yellow and green lights. The overall non-response error rate is 9.67%. The overall response error rate for all trials is 14.29%. The change of stimulus trial response error rate is 26.86% and the response error rate for the junction trials 23.9%, both are significantly high. The response error rate for each primary stimulus types red, yellow, double-yellow and green are 18.92%, 21.19%, 19.53% and 7.61%, the green stimulus errors are significantly low and the other significantly high. The most common stimuli have a lower error response rate than the rarer stimuli. Changes of stimulus type or spatial position in have significantly high response error rates.

Change of stimulus and junction trials are trial types that display the highest risk of error. The probability of an erroneous response matching the distracters stimulus type is 4.57%. This is a potential "read across error" caused by the subject responding to the distractor rather than the target stimulus. This type of response error is a real hazard for trains operating at major stations on the railway network. Table 6.1 lists the stimulus and response combinations, and their response error counts and probabilities. The yellow response for red stimuli, and double-yellow response for yellow stimuli have probabilities of 12.96% and 12.78% respectively. These have the highest erroneous response rate of any error type in the table.

	Response type									
	Red		**Yellow**		**Double**		**Green**		**None**	
Stimulus type	**count**	**prob-ability**	**count**	**prob-ability**	**count**	**prob-ability**	**count**	**prob-ability**	**count**	**prob-ability**
Red	1020	0.8108	163	0.1296	7	0.0056	33	0.0262	35	0.0278
Yellow	67	0.0400	1320	0.7881	214	0.1278	32	0.0191	42	0.0251
Double-yellow	58	0.0340	81	0.0475	1372	0.8047	148	0.0868	46	0.0270
Green	77	0.0196	81	0.0206	75	0.0191	3627	0.9238	66	0.0168

Table 6. 1. The stimulus and response combination error counts and probabilities. The highlighted cells are the correct responses. All other cells are response error types.

Table 6.2 lists the count and probability of a response error for each trial type. The left and right junction trials have similar response error rates. Junction stimuli have erroneous response error rates of 23.85%, 32.31% and 19.04% for yellow, double-yellow and green stimuli respectively. The junctions with double-yellow stimuli have a significantly higher response error rate than other types of junction. It is not clear why this result occurs. Junctions have a similar response probability to changes of stimuli, 23.9% and 26.86% respectively.

Trial type	**All subjects**		
	Number of errors	**Number of trials**	**Error probability**
Red stimuli	238	1258	0.1892
Yellow stimuli	355	1675	0.2119
Double-yellow stimuli	333	1705	0.1953
Green stimuli	300	3942	0.0761
Change-of-stimuli	1049	3905	0.2686
All trials	1226	8580	0.1429
All junctions	201	841	0.239
Junction movements to the left	103	419	0.2458
Junction movements to the right	98	422	0.2322
Junctions with yellow signals	52	218	0.2385
Junctions with double-yellow signals	74	229	0.3231
Junctions with green signals	75	394	0.1904

Table 6. 2. The response error counts and probabilities for each stimulus and trial type.

6.5 EEG alertness indexes measurements

The method of analysis and its purpose are the same as in chapter 5 section 5.4. The alertness-fatigue indexes described by Jap et al are used to test for objective fatigue effects on response accuracy [37 and 52]. The method of analysis is detailed in chapter 4, section 4.10.

Table 6.3 lists the results of the ANOVA comparison of the correct and erroneous responses. There are no significant differences between any of the alertness-fatigue indexes during the response trial and the two trials prior to it.

Fatigue measure Using frequency bands	**F**	**p-value**
Alpha	0.84	0.5125
Alpha + theta	0.71	0.5596
(Alpha +Theta)/Beta	4.86	0.1296
Beta	1.03	0.4576
Theta	0.61	0.5993

Table 6. 3. The results of the ANOVA comparison of fatigue-alertness indexes for the correct and erroneous response during experiment two.

6.6 Paired stimuli sequence analysis - Priming and antipriming

This section reveals the processes of priming and antipriming effects in the subject's behavioural responses. Experiment two's trials present a pair of stimuli simultaneously. There are images that graphically indicate changes of lateral position every 20th trial. The combined effect that pairs of stimuli have on behavioural characteristics is investigated.

These are stimuli sequences considered:

- The combination of target and distractors.
- The target stimuli.
- The distractor stimuli.

The priming and antipriming effects observed in the reaction time and response error rate trends for the target and distractor sequences are consistent with the results of experiment one. The target stimuli sequence exhibits the repetition priming and antipriming effects [12, 13, 14, 15, 16, 18, 20 and 21]. The distractor sequence follows the same sequence rules as the targets, and has a different pattern of stimuli. The distractor has a clear repetition priming-anti priming pattern which indicates that the subjects are cognitively processing it in order to inhibit responses to the wrong stimulus. This is consistent with the negative priming effect [90, 95,111,118,121].

6.6.1 The combination of target and distractors

In this section the combined effect that both target and distractor sequences have on response accuracy and error rate are examined.

A change in either the target or distracter sequences is treated as the end of a repeated sequence. Figure 6.3 illustrates the progressive decrease in mean reaction time during the first six repeated pairs of trials following a change of either target or distractor sequences. This further supports the presence of repetition priming during the repeated stimuli, and antipriming during a change of stimulus. The trend in the reaction time is consistent with a priming-antipriming cycle that is caused by changes to the pair of stimuli. This suggests that both stimuli are effecting the subject's behaviour in parallel.

The mean error rate decreases between the change of stimulus and first repetition, then stabilises, which is illustrated in figure 6.4. The adverse effect on response accuracy that the change of stimulus cause disappears as soon as a new repeated sequence starts. The target and distractor sequences are independently investigated in sections 6.5.2 and 6.5.3 respectively.

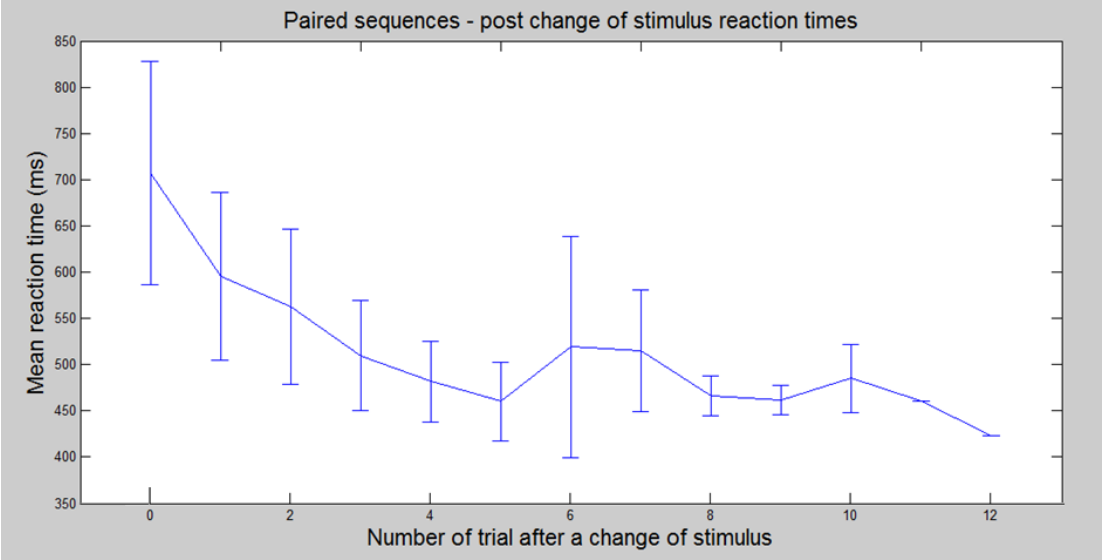

Figure 6. 3. The mean reaction time and standard deviation for no change-of-stimuli trials that follow a change of stimulus in either target or distractor sequences. The first trial on the left is the change of stimulus trial and the following are non-change trials.

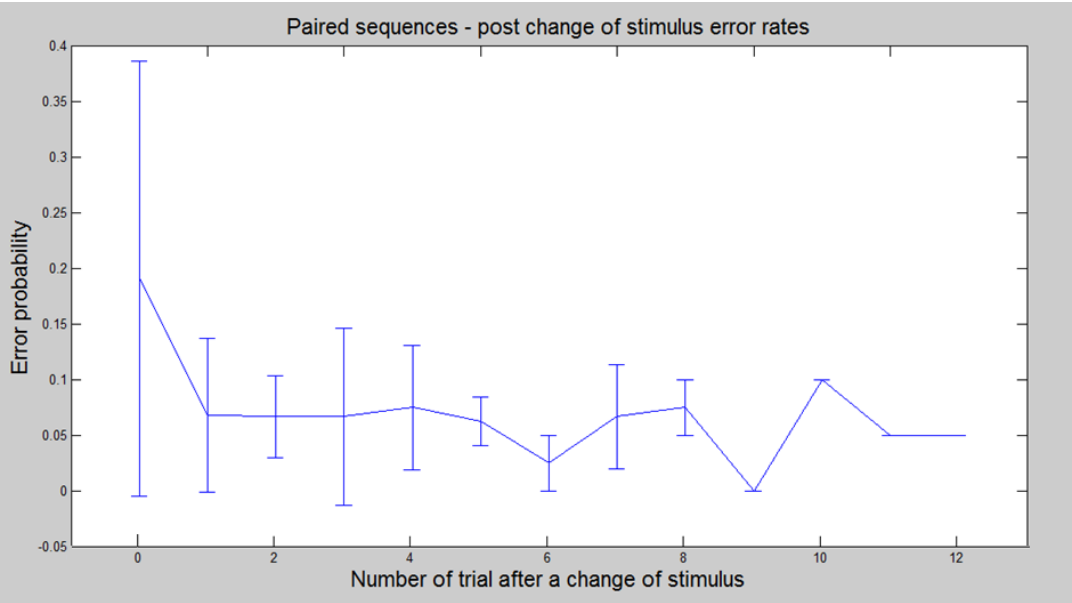

Figure 6. 4. The error rate and standard deviation for trials within no change of stimulus sequences in either target or distractor sequences. The first trial on the left is the change of stimulus trial and the following are non-change trials.

6.6.2 The target sequence

The effect that changes of stimulus and repetition within the target sequence have on behavioural responses are investigated in this section.

The mean reaction time increases during the change of stimulus trial, then decreases during the first six trials following the change of stimulus, as illustrated in figure 6.5. The response error rate increases at the change of stimulus trial. It then decreases and stabilises immediately after the target trial stimulus changes, as illustrated in figure 6.6. This indicates the presence of antipriming then, repetition and antipriming effects in the subject's behaviour. This indicates that the target sequences are the primary influence on the subject's behavioural responses.

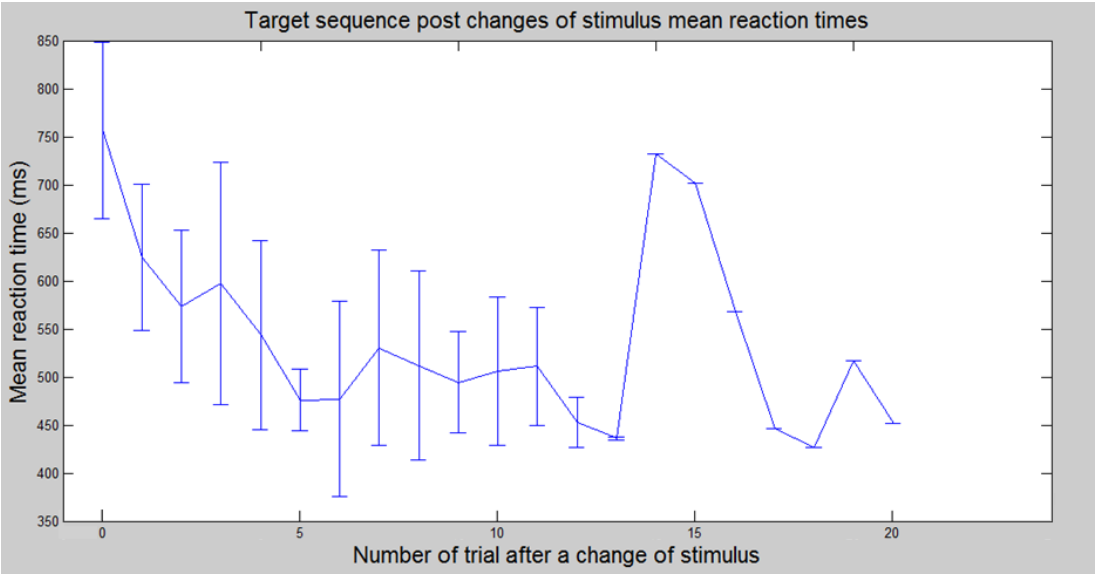

Figure 6. 5. The mean reaction time and standard deviation of repeated stimulus trials that follow a change of target stimulus.

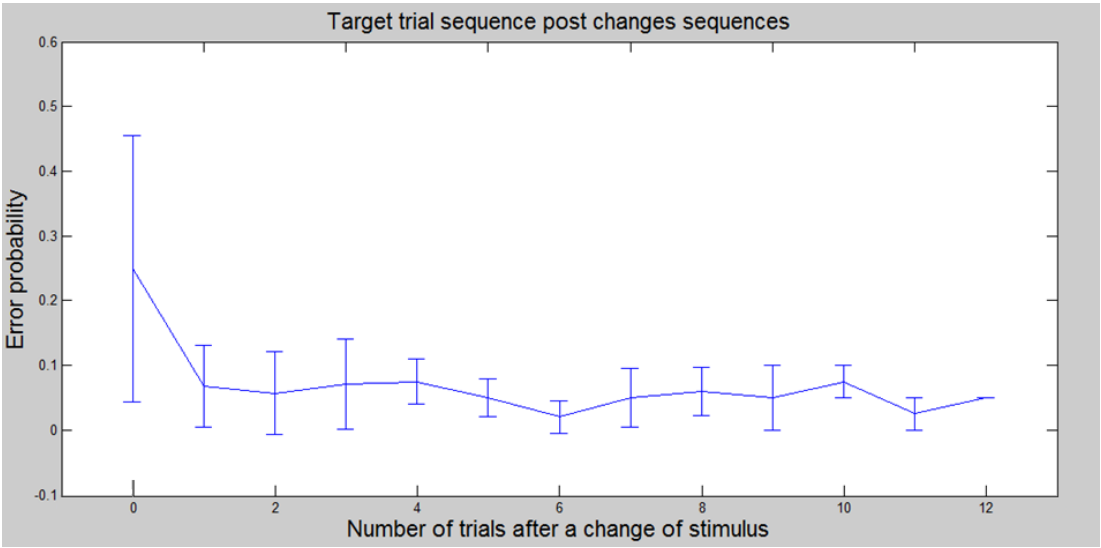

Figure 6. 6. The response error rate and standard deviation of repeated stimulus trials that follow a change of stimulus in the target sequence.

6.6.3 Distractor sequence

This section details the effect of the flanked distractor sequence on the subject's behavioural response.

The mean reaction time increases during the change of stimulus trial, then decreases by 100ms during the first four trials following the change of stimulus, as illustrated in figure 6.7. The effect in much weaker than that for the target sequences with no significant difference

between adjacent trials. The response error rate has no significant or observable during or following a change of stimulus trial, as illustrated in figure 6.8.

These results suggest there is a weak antipriming and repetition priming effect due to the distractor sequence in the mean reaction times, however the response error is not affected. This indicates that negative priming is successful inhibiting erroneous responses to the distractor [90, 95, 111, 118, 121]. The reaction time cycles may be due to the cognitive demands of negative priming combined with the changes of stimulus followed by repeated sequences.

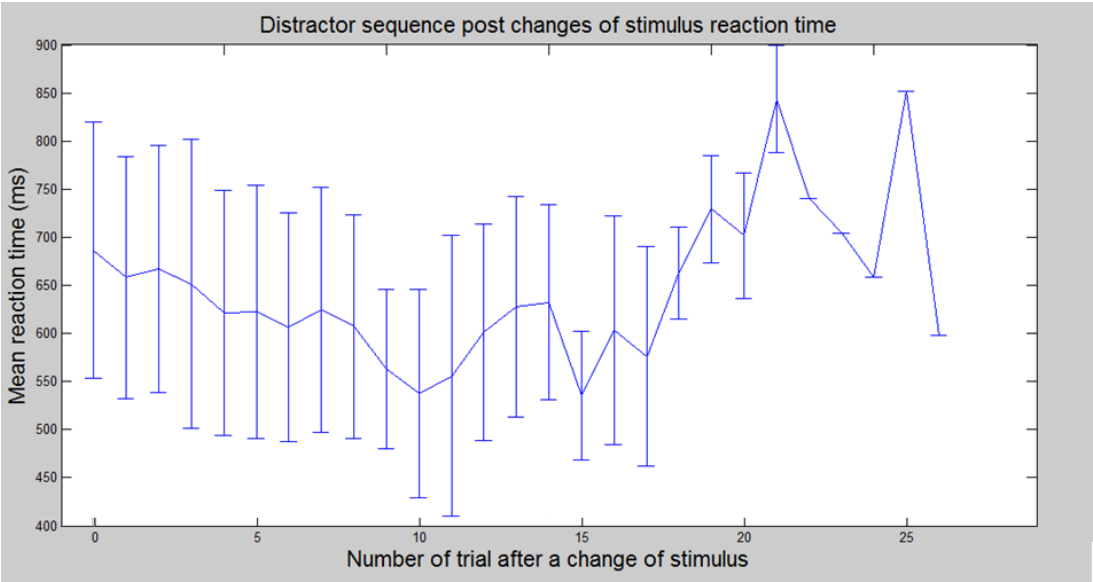

Figure 6. 7. The mean reaction times and standard deviation of repeated stimulus trials in the distractor sequence that follow a change of stimulus in the distractor sequence.

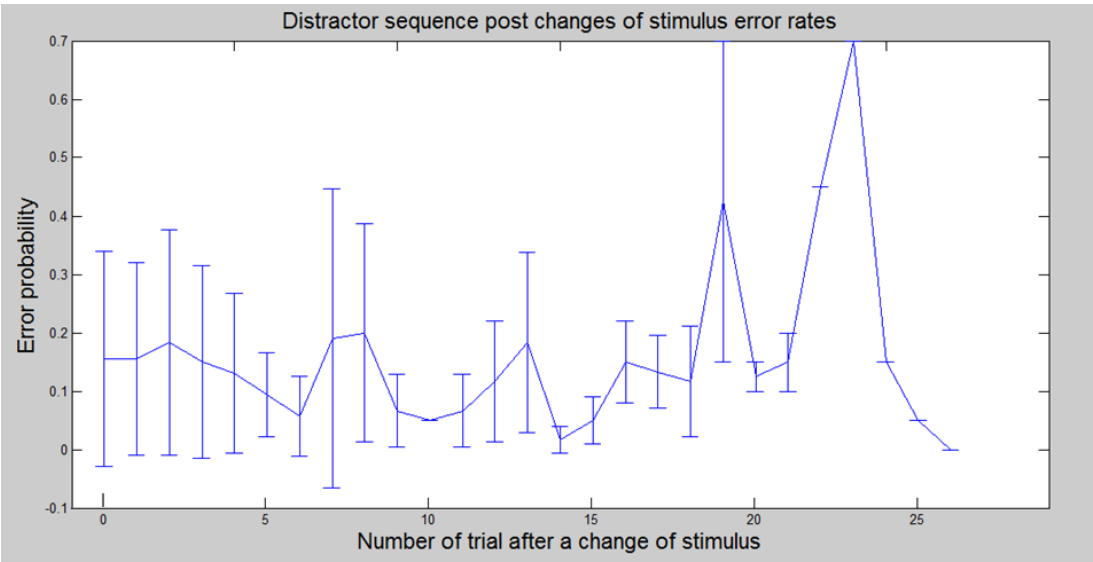

Figure 6. 8. The response error rates and standard deviations of repeated stimulus trials in the distractor sequence that follow a change of stimulus in the distractor sequence.

6.7 Sequence stimuli effects

These are the results of the analysis of response error rates at the end of specific sequences of four stimuli. Table 6.4 lists all the stimuli sequences that have significant response error rates. The significance is tested using the binomial test, alpha = 0.05. Binomial statistical analysis is described in chapter4 section 4.10. The results for sequences of length two and three trials are summarised in tables C.3 and C.5 in appendix C. Sequences of length two and three exhibit the pattern of results as those of length four.

Changes-of-stimulus immediately prior to the final trial in the sequence are more likely to cause significantly high response error rates. The greater the number of changes of stimuli within a sequence the more likely it is to have a significantly high response error rate. Table 6.5 lists the counts of significantly low and high response error rates and the number of within sequence changes of stimulus. The results are consistent with those found in experiment one, chapter 5.

Preceding sequence	**Final stimulus type**				**Final trial type**		
	Red	**Yellow**	**Double-yellow**	**Green**	**Change-of-stimuli**	**All response errors**	**Junctions**
R-R-R-R	-	-	-	H (55.56%)	-	H (24.64%)	-
Y-R-R-R	L (5.66%)	-	-	H (18.92%)	-	-	-
R-Y-R-R	L (5.66%)	-	-	-	-	-	-
Y-Y-R-R	-	-	-	H (29.41%)	-	-	-
D-Y-R-R	L (0.00%)	-	-	-	L (11.38%)	-	-
R-R-Y-R	L (5.56%)	H (70.59%)	-	-	-	H (22.22%)	-
Y-R-Y-R	L (7.35%)	-	-	-	L (8.26%)	-	-
R-D-Y-R	L (4.35%)	-	-	H (66.67%)	L (13.59%)	-	-
D-D-Y-R	-	H (43.75%)	H (42.31%)	H (21.59%)	-	H (26.04%)	-
G-D-Y-R	-	-	H (56.60%)	-	H (35.25%)	H (35.25%)	-
Y-R-R-Y	-	L (8.00%)	-	H (50.00%)	-	H (21.74%)	-
Y-Y-R-Y	-	L (0.00%)	-	-	-	-	-
D-Y-R-Y	H (35.29%)	L (7.84%)	-	-	-	H (21.57%)	-
R-R-Y-Y	H (81.25%)	-	H (44.12%)	-	H (46.97%)	H (46.97%)	H (75.00%)
Y-R-Y-Y	-	L (0.00%)	-	-	L (5.80%)	L (5.80%)	-
R-Y-Y-Y	-	L (0.00%)	-	-	L (0.00%)	-	L (0.00%)
Y-Y-Y-Y	-	-	-	H (51.43%)	H (51.43%)	H (51.43%)	H (100%)
Y-D-Y-Y	-	L (0.00%)	-	-	-	-	-
D-D-Y-Y	-	L (0.00%)	-	-	L (2.86%)	-	-
G-D-Y-Y	-	-	H (44.44%)	H (24.53%)	-	H (21.11%)	-
R-R-D-Y	-	-	-	-	L (6.25%)	-	-
Y-R-D-Y	H (32.39%)	-	-	-	H (32.39%)	H (32.39%)	-

Y-Y-D-Y	-	L (0.00%)	H (56.25%)	-	-	H (26.47%)	-
G-D-D-Y	H (47.67%)	-	H (40.00%)	H (72.22%)	H (40.80%)	H (40.80%)	-
Y-G-D-Y	-	-	-	H (46.67%)	-	-	-
G-G-D-Y	-	L (10.42%)	H (89.47%)	H (72.22%)	-	H (22.89%)	H (47.22%)
R-R-R-D	n/a	-	-	H (33.33%)	-	H (25.71%)	-
D-Y-R-D	n/a	H (33.80%)	-	-	-	H (25.71%)	H (94.44%)
R-Y-Y-D	n/a	H (58.82%)	-	H (27.78%)	H (48.08%)	H (48.08%)	-
Y-Y-Y-D	n/a	-	L (0.00%)	-	L (0.00%)	-	-
Y-D-Y-D	n/a	-	-	-	L (6.25%)	-	-
R-Y-D-D	n/a	-	-	H (23.53%)	-	-	-
G-D-D-D	n/a	-	-	-	L (9.33%)	-	-
G-G-D-D	n/a	H (27.59%)	L (0.00%)	H (13.70%)	-	H (19.14%)	-
Y-R-G-D	n/a	-	-	H (44.44%)	H (44.44%)	H (44.44%)	H (44.44%)
R-G-G-D	n/a	H (47.06%)	-	-	H (47.06%)	H (47.06%)	H (47.06%)
Y-G-G-D	n/a	-	-	-	L (9.80%)	-	-
D-G-G-D	n/a	-	-	H (52.63%)	-	H (25.00%)	-
G-G-G-D	n/a	H (40.28%)	L (5.95%)	H (41.82%)	-	H (23.75%)	-
R-R-R-G	n/a	n/a	-	L (0.00%)	L (0.00%)	L (0.00%)	-
Y-R-R-G	n/a	n/a	-	-	L (0.00%)	L (0.00%)	-
R-Y-R-G	n/a	n/a	-	L (1.39%)	L (1.39%)	L (1.39%)	-
D-Y-R-G	n/a	n/a	-	-	L (7.77%)	-	-
R-Y-Y-G	n/a	n/a	-	-	L (2.86%)	-	-
Y-Y-Y-G	n/a	n/a	-	-	L (3.03%)	-	-
D-Y-Y-G	n/a	n/a	-	-	L (7.04%)	-	-
D-D-Y-G	n/a	n/a	-	-	L (0.00%)	-	-
R-R-D-G	n/a	n/a	-	-	L (0.00%)	-	-
D-Y-D-G	n/a	n/a	H (61.11%)	-	H (61.11%)	H (61.11%)	H (61.11%)
D-D-D-G	n/a	n/a	-	-	L (0.00%)	-	-
G-D-D-G	n/a	n/a	H (94.44%)	-	-	H (27.40%)	-
R-G-D-G	n/a	n/a	H (66.67%)	-	H (66.67%)	H (66.67%)	-
G-G-D-G	n/a	n/a	-	-	L (8.70%)	-	-
R-R-G-G	n/a	n/a	-	L (1.11%)	L (1.11%)	L (1.11%)	-
Y-R-G-G	n/a	n/a	-	-	L (5.10%)	L (5.10%)	-
Y-Y-G-G	n/a	n/a	-	L (1.10%)	L (4.03%)	L (4.03%)	-
D-Y-G-G	n/a	n/a	-	-	L (6.06%)	-	-
R-D-G-G	n/a	n/a	-	-	L (2.78%)	-	-
Y-D-G-G	n/a	n/a	-	-	L (0.00%)	-	-
D-D-G-G	n/a	n/a	H (34.55%)	L (0.00%)	-	-	L (0.00%)
G-D-G-G	n/a	n/a	H (35.14%)	-	-	H (23.29%)	H (63.16%)
R-G-G-G	n/a	n/a	-	-	L (9.21%)	L (9.09%)	L (10.91%)
Y-G-G-G	n/a	n/a	L (2.94%)	-	L (4.96%)	L (4.92%)	-
D-G-G-G	n/a	n/a	L (5.41%)	-	L (6.94%)	L (6.94%)	-
G-G-G-G	n/a	n/a	L (14.91%)	L (1.46%)	L (3.86%)	L (3.86%)	L (16.77%)

Table 6. 4. This is a summary of the sequences of four stimuli that preceded significant error probabilities in the final stimuli or trial types. These are the symbols used in the table R = red stimulus, Y = yellow stimulus, D = double-yellow stimulus, G = green stimulus, L = lower than average significant results, H = higher than average significant result, and '–'means that this combination of stimuli did not occur or there is no significant difference in observed error rate. "n/a" means that the stimulus cannot occur in that combination. The sequence of stimuli in the first column is listed oldest to most recent.

Number of changes of stimulus within sequences	Significantly low response error probability	Significantly high response error probability
0	1	0
1	11	3
2	10	9
3	2	20
4	2	9

Table 6. 5. The count of the significantly high and low response error sequences based on the number of changes of stimulus. The red, yellow, double-yellow and green final stimuli cases are considered. The greater the number of changes of stimuli in a sequence the more likely it is to have a significantly high erroneous response probability.

6.8 Patterns of stimuli preceding zero and high error rate trials

This section details the investigation of the per trial response error rates which have zero or at least six out of 19. These trials have significantly low or high response error rates. The trials with at least six response errors out of 19 are the highest 5% of error rate trials. Figure 6.9 illustrates the response error rate for each trial. The trials that have high error counts are of particular interest because these are significantly different from the observed mean error rate.

The occurrence counts of the sequences of stimuli preceding zero and high error rate trials for sequence lengths two, three and four are summarised in tables C.2, C.4 and C.6 in appendix C. The preceding sequences containing only green stimuli are primarily associated with zero error rate trials. There are no clear overall patterns that segregate the stimuli sequences of either zero or high error rate trials. The only consistent feature of high error rate sequences of stimuli is that they all have a change of stimulus at the end. All the individual trials that are classed as high response error rates are change of stimulus trials.

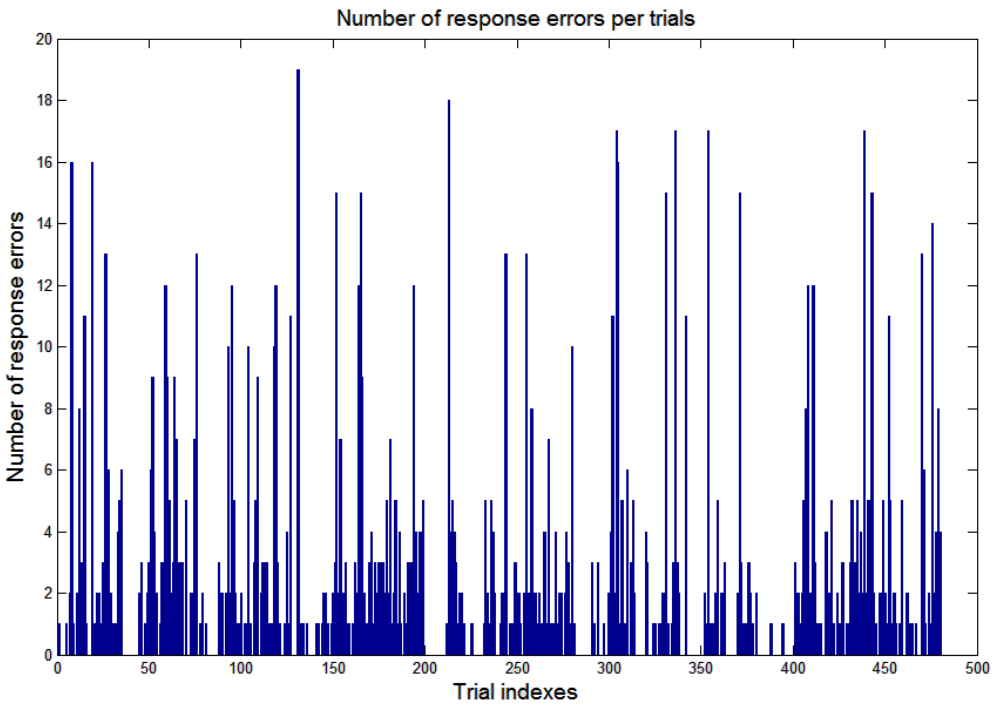

Figure 6. 9. The number of response errors of each trial for all subjects during experiment two. The range of error counts is limited to 0 to 19.

6.9 Junction sequences

In this section the effect that the junction stimulus have on the subject's reaction time and error rate are investigated. There is a greater attentional demand during experiment two because of the additional task of selecting the lateral position to attend and remembering this information. A number of factors relating to pre and post-junction stimuli sequences:

- The effect length of the prior repeated sequence upon junction trial response accuracy.
- The reaction times that follow a junction trial.
- The responses to the distractor stimuli.

6.9.1 Repeated sequence length between junctions

The length of the sequence between junction signals does not have a significant effect on the probability of a response error at the end of the sequence. The error rate for sequences of length one is significantly higher because of their frequent changing of stimuli. The

probability of a given number of errors occurring within an inter-junction sequence does not appear to be effected by the sequence length.

6.9.2 Post junction reaction times and response error rates

The effect of the junction stimulus on the following trial reaction times and response accuracy rates are considered in this section.

Figure 6.10 illustrates the mean reaction time per trial of the inter-junction target sequences. The mean reaction time decreases by 200ms during the first three post junction trials then stabilises. The error rate decreases in the first post junction response trial, then varies randomly as the sequence progresses as illustrated in figure 6.11. The variation in response error rate increases as the number of sequences of each length decreases.

These results show that repetition priming and antipriming are occurring in response to junction stimuli in the target sequence. The change of target spatial position following a junction has a shorter repetition priming and suppression phase than for single stimuli sequences which require five trials.

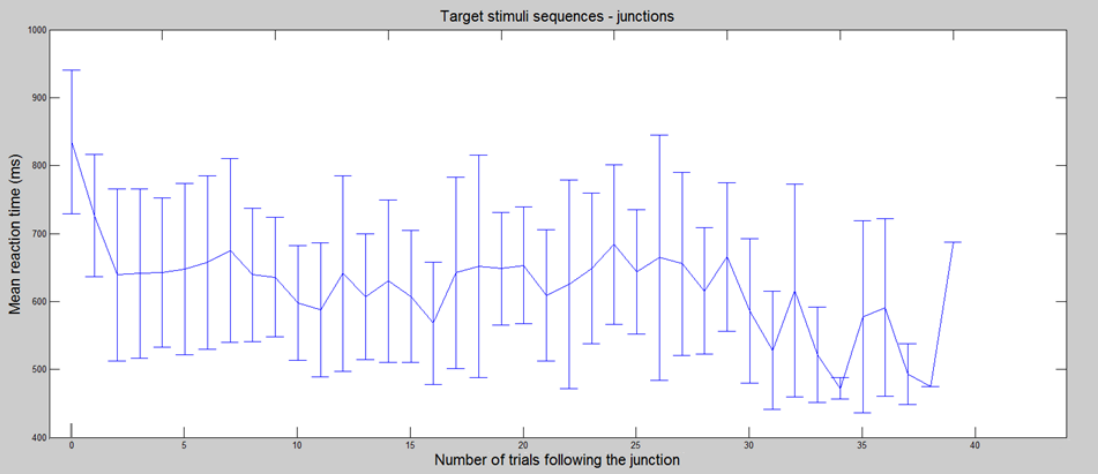

Figure 6. 10. This graph displays the mean reaction time of trials that follow junction trials in the target lateral position. The variation bars show one standard deviation. The first trial is the junction trial, the following trials are the non-junction trials.

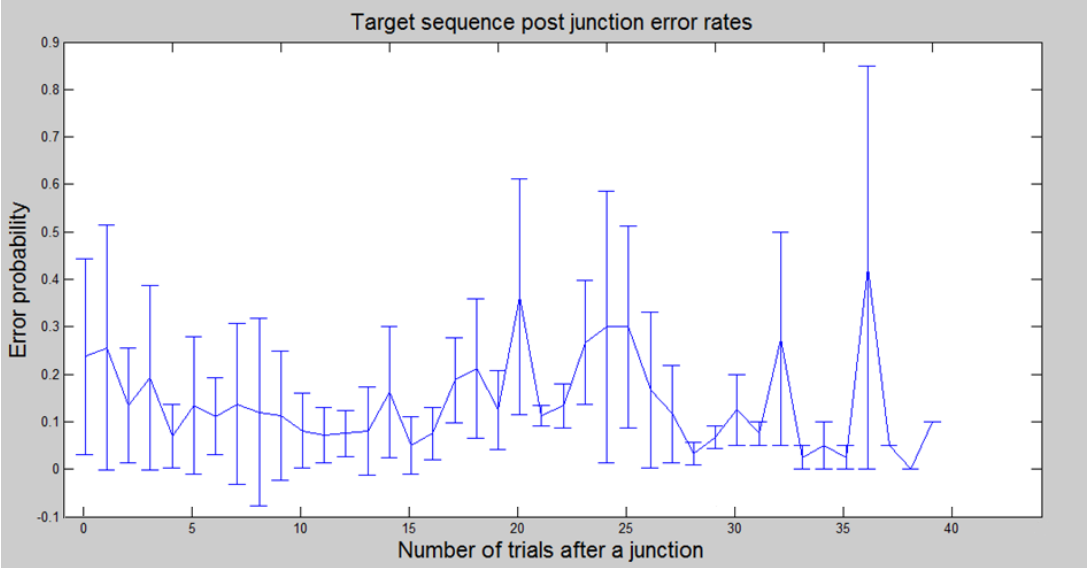

Figure 6. 11. This graph displays the response error probabilities of the trials that follow junction trials in the target lateral position. Trial index one is the junction trials. The variation bars show one standard deviation. The following trials are the non-junction trials that follow them.

6.9.3 Distractor stimuli sequence effects

The effect of the distractor stimuli sequence on the response accuracy and reaction time are examined in this section. The distractor sequence follows the same sequence grammar rules as the target stimuli. They are both displayed and hidden at the same time. The flanked distractors are having a detectable effect on the subject's cognitive response.

The effect of change of stimulus and repeated sequences in the distractor sequence on mean per trial reaction time are illustrated in figure 6.12. The post change of stimulus adaption rate is longer than for the target stimulus sequences where it requires eight trials instead of five repetitions for the reaction time to stabilise. The distractor sequences display the clear repetition priming-antipriming effect. The flanked distractors are clearly cognitively processed for response inhibition. The repetition priming effect in the reaction time suggests that negative priming is occurring [90, 95, 111, 118, 121].

The comparison of the response error probability against the distractor sequence lacks any significant trend as illustrated in figure 6.13. The error rate randomly varies throughout the sequences. The target stimulus is the primary influence on the subject's response accuracy.

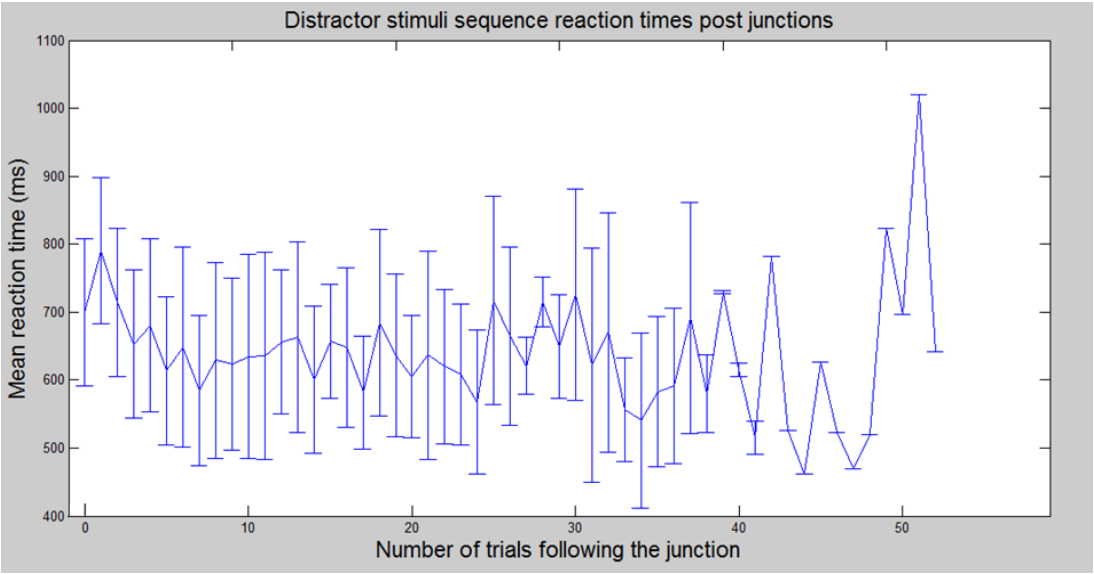

Figure 6. 12. The mean reaction time and standard deviation of trials that follow junction trials in the distractor sequence. The variation bars show one standard deviation. The following trials are the non-junction trials that follow them.

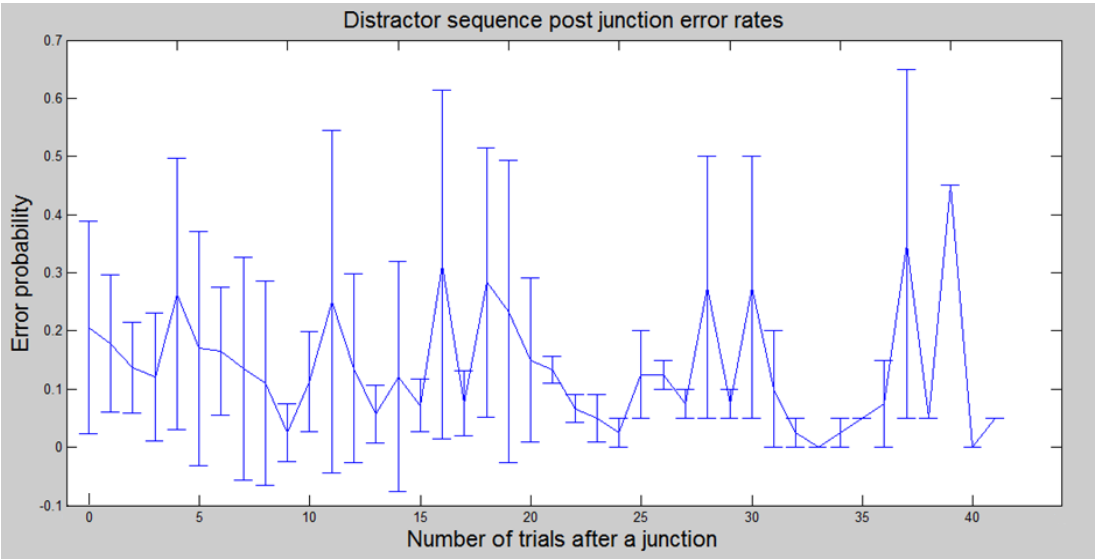

Figure 6. 13. The graph displays the per trial set error rate for trials that follow junctions in the distractor sequence. The The variance at the end of longer sequences is higher because of the smaller sample sizes. The variation bars show one standard deviation.

6.10 EEG results - Phase-locking analysis

This section details the significant results of the inter-channel phase-locking patterns measured using graph metrics. The phase-locking pattern variations reveals the characteristics of the cognitive activity associated with particular conditions. The details of

the analysis method are described in chapter 4, section 4.8. This permits complex patterns of functional-connectivity to be analysed. The methods and motivations are the same as for chapter 5, section 5.7.

The results of the EEG analysis of these effects are reveals:

- leading indicators of response errors
- repetition priming
- antipriming

A range of graph metrics where tested, only a sub-set of them lead to significant results. These are the graph metrics that where analysed:

- node degree, (ND)
- node phase locking value
- node nearest neighbour degree, (NNND)
- node nearest neighbour phase locking value, (NNNPLV)
- between centrality
- closeness centrality

6.10.1 Leading indicators of response errors

The graph metric and response type combinations are listed in table 6.6. There are many combinations where there are no significant results. The critical graph metric ranges for correct and erroneous responses are listed in table 6.7. The only frequency bands with significant marginal mean differences are 4-40Hz and alpha. The no-change of stimulus datasets have no significantly different features. The change of stimulus trial sets have significant differences in the left and right temporal regions for ND, NNND, NNNPLV and closeness centrality. There are additional regions in the closeness centrality and node degree graph metrics. The betweenness centrality graph metrics has significant features for zero vs high, all correct vs error, and junction correct vs error responses. These are fully listed in the right-hand column of table 6.6. The 4-40Hz frequency band is common to all grouping of datasets and the central, occipital and left temporal cortical regions have a key role. The junction trials have significant features in the alpha frequency band in addition to 4-40Hz.

The left and right temporal regions occur in most of the significant features, the central and occipital cognitive regions also appear frequently. This suggests the levels of connectivity in these cortical regions play a key role in response accuracy.

Frequency band and cortical region	Node degree	Node nearest neighbour degree	Node nearest neighbour PLV	Closeness centrality	Betweenness centrality
Zero vs high	-	-	-	-	4-40Hz in C and O
Change of stimulus	4-40Hz in F LT RT C and G	4-40Hz in LT and RT	4-40Hz in LT and RT	4-40Hz in all	-
All correct vs error	-	-	-	-	4-40Hz in LT
Junctions	-	-	-	-	4-40Hz and alpha in LT, C and O

Table 6. 6. A summary of the frequency band and region combination that are response error precursors for each graph metric. The cortical region codes are RT = right temporal, LT = left temporal, C = central, O = occipital and G = global.

Frequency band and cortical region	Node degree	Node nearest neighbour degree	Node nearest neighbour PLV	Closeness centrality	Betweenness centrality
Zero vs high	-	-	-	-	0.8 to 0.95
	-	-	-	-	0.88 to 0.93
Change of stimulus	1.45 to 1.57	13 to 15.5	12 to 13.5	6.3 to 6.8	-
	1.6 to 1.75	15.9 to 17.7	13.8 to 15.7	7 to 7.35	-
All correct vs error	-	-	-	-	0.8 to 0.85
	-	-	-	-	0.87 to 0.93
Junctions	-	-	-	-	0.8 to 0.9
	-	-	-	-	0.93 to 1

Table 6. 7. The range of response accuracy forecasting graph metrics for correct and erroneous responses.

The results of the 3 way ANOVA of (condition x frequency x cortical region) for the closeness centrality graph metric are shown in table 6.8. The full list of ANOVA results are listed in appendix F. The only significant interaction is between condition (response type), and

frequency band factors. The interaction between the condition and frequency band are shown in the marginal means graph in figure 6.14.

Source	Sum sq.	d.f.	Mean Sq.	F	p-value
condition	1.07E-05	1	1.07E-05	2.75E+01	1.79E-07
frequency	0.183	4	0.0457	1.18E+05	0
region	2.28E-06	6	3.79E-07	0.978	0.4386
condition*frequency	2.10E-05	4	5.24E-06	1.35E+01	8.20E-11
condition*region	1.24E-06	6	2.06E-07	0.5305	0.7854
frequency*region	6.81E-06	24	2.84E-07	0.7313	0.8229
condition*frequency*region	2.29E-06	24	9.54E-08	0.2458	0.9999
Error	5.43E-04	1400	3.88E-07		
Total	0.1836	1469			

Table 6. 8. The 3-way ANOVA (condition x frequency band x region) results for the closeness centrality graph metric, condition refers to correct and erroneous responses.

The significant marginal means difference between changes of stimulus trial sets for the closeness centrality graph metric are illustrated in figure 6.14. Comparison of the correct and erroneous responses for each region show differences between them for all the cortical regions. The NNND graph metric marginal means for response type and region are compared in figure 6.15. This exhibits the opposite effect compared to figure 6.14, there are no significant differences between response types for any cortical region. Figure 6.16 plots the closeness centrality graph metrics precursors for correct and erroneous responses, in the 4-40Hz frequency band. The growing difference in the closeness centrality prior to the response types is clear.

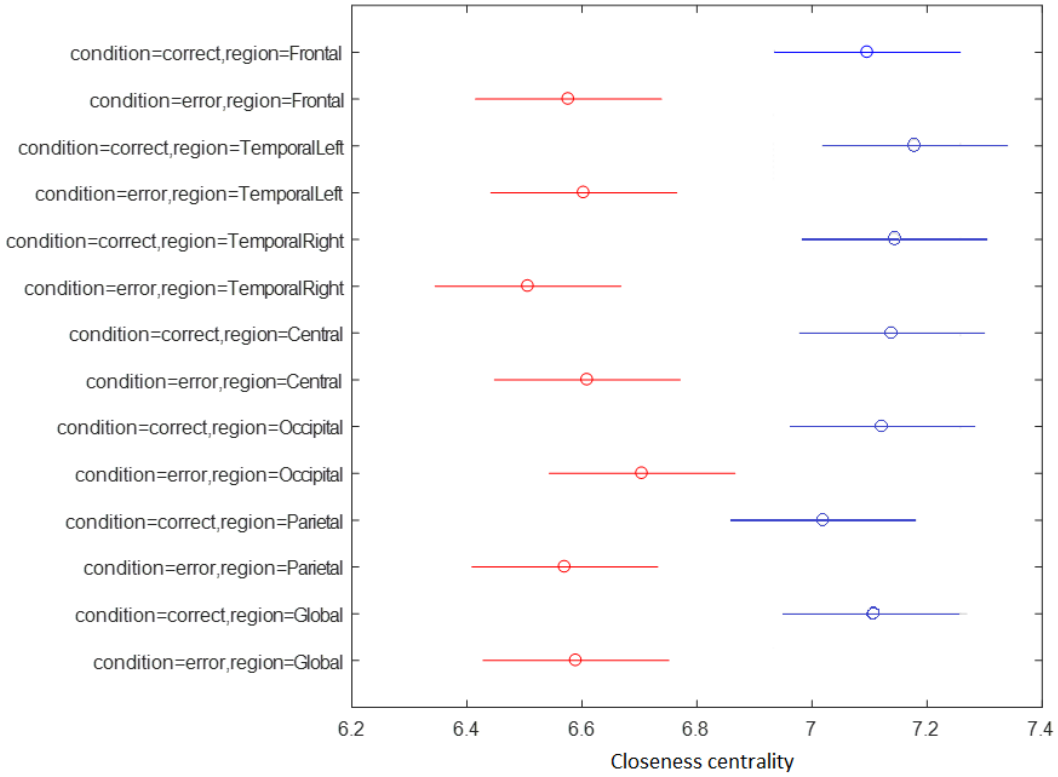

Figure 6. 14. The closeness centrality graph metric marginal means of response accuracies and cortical regions. The correct and erroneous marginal means significantly differ for all cortical regions. This is for change of stimulus response error rate trials. All the cortical regions have significantly different marginal means between the correct and erroneous response trial sets. The erroneous responses data is red and correct blue.

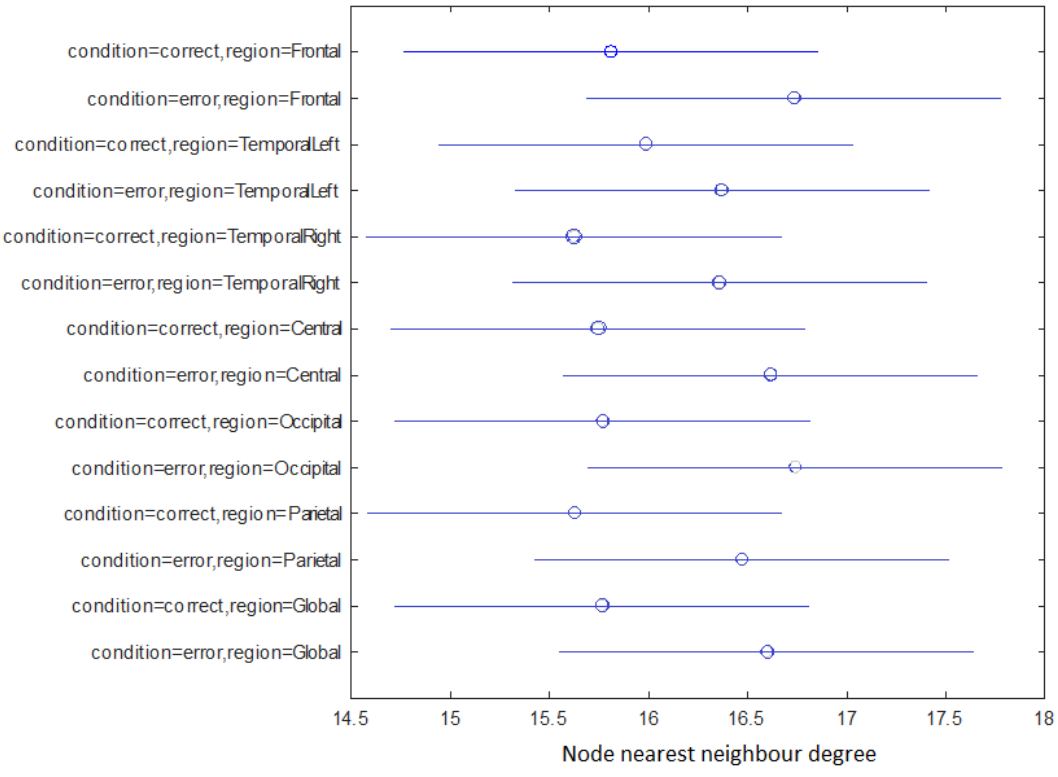

Figure 6. 15. The NNND graph metric marginal means of response accuracies and cortical regions. The correct and erroneous marginal means significantly differ for all cortical regions. This is for no-change of stimulus response rate trials. There are no significant difference between correct and erroneous responses for any cortical region.

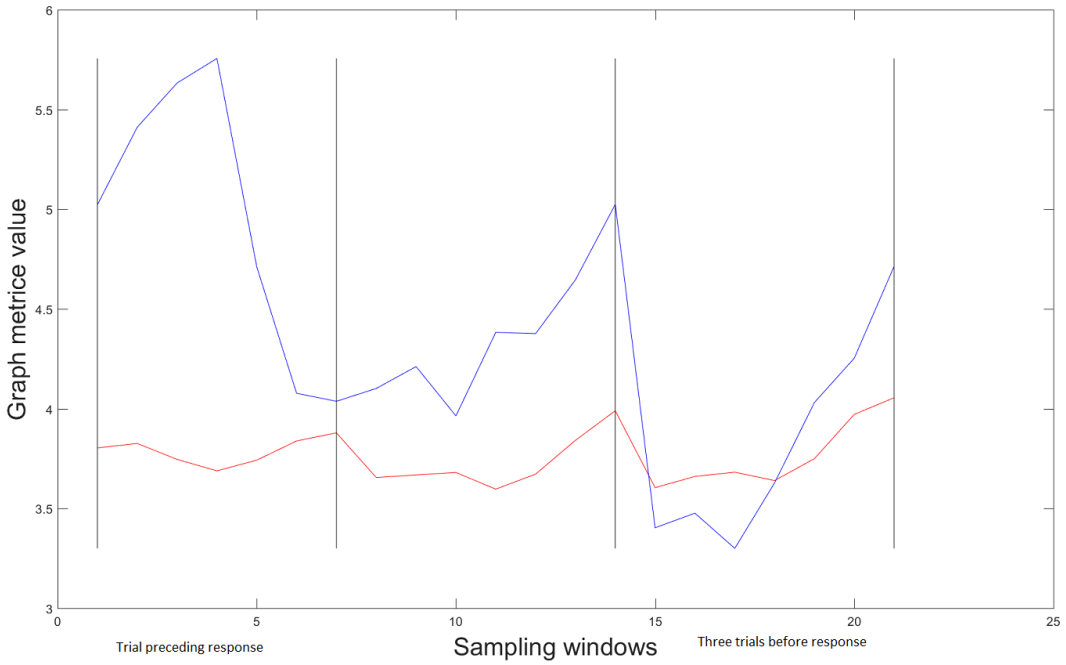

Figure 6. 16. The evolution of the betweenness centrality graph metric for junctions in the 4-40Hz frequency band and occipital cortical region. The time windows on the left are immediately before the response event. The red line is for the correct responses and the blue line for erroneous responses. There is a significant difference between the response accuracy precursors, particularly in the first two preceding trials.

6.10.2 Repetition priming and antipriming

The behavioural analysis in section 6.5 reveals repetition priming (RP) and antipriming (AP). This section describes the significant EEG analysis results related to those findings. There are two situations when RP and AP can occur, when a repeated sequence of stimuli starts and ends, and between junction stimuli.

6.10.2.1 Change of target stimulus

The graph metrics of the trials that surround the change of stimulus trials are analysed for significant differences. These cognitive response differences reflect the effect antipriming

and repetition priming have upon cognitive activity. The method of analysis is described in chapter 4, section 4.8. The 3-way ANOVA is performed for each graph metric type.

Figure 6.17 illustrates the significant increase in node PLV during the change of stimulus trials in the right temporal region in the 4-40Hz frequency band. The occipital and parietal cortical regions also exhibit the same pattern.

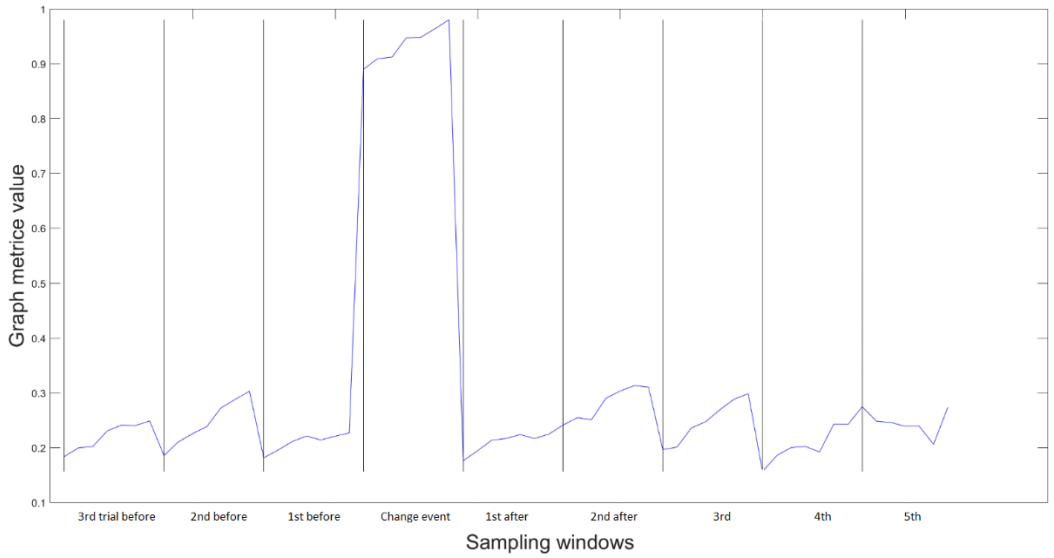

Figure 6. 17. The node PLV value increases significantly about the change of stimulus trials in the right temporal, 4-40Hz frequency band.

6.10.2.2 Junction trials sequences

There are no graph metrics that with detected a significant change focused upon the junction trials.

6.11 Conclusion

The key results are the effects of repetition priming and antipriming in the behavioural and EEG graph metric data. The behavioural responses observed in experiment two are consistent with those observed in experiment one. There are predictors of response accuracy in the EEG graph metrics that differ from those in chapter 5.

The patterns of behavioural response to the target stimulus exhibit RP and AP. Additionally, the flanked distractors also cause a small RP and AP in the mean reaction times. This shows that negative priming is occurring to inhibit responses to the flanked distractors. The flanked

distractors increase the response error probability for all types of trial which suggests that the cognitive work load is greater.

Junction trials have the highest response error. The RP and AP effect is present in the behavioural responses to junctions, though it only lasts for two trials post junction. No graph metric features where found relating the junction trial sequences.

The quantity of graph metrics that predict response accuracy in experiment two is lower than experiment one. The left and right temporal regions occur frequently in experiment two's EEG analysis. The junction trials betweenness centrality EEG markers may be the combination of zero vs high and all correct vs erroneous responses. The change of stimulus trials have unique graph metric EEG features.

The significant RP and AP related graph metrics are the node PLV graph metric in the 4-40Hz frequency band in the right temporal, occipital and parietal cortical regions. The cognitive responses to RP and AP appear to be distinct from those related to response accuracy.

Chapter

7. Discussion

7.1 Behavioural analysis – Repetition, negative priming, antipriming

The key finding of the behavioural analysis is the repetition priming and antipriming effects in the reaction times and response error rate. In experiment one repetition priming lasted five trials, which is consistent with previous experimental results [6, 12, 13, 15, and 16]. The observed antipriming effect in the behavioural data suggested that the cognitive work load of unlearning and relearning a new stimulus increased reaction times and decreased response accuracy.

Experiment two has a shorter repetition priming time of two trials that appears to be due to the dual stimuli. This suggests that information about the known extent of a sequence of events determines the duration of the associated repetition priming. The junction signals found before any change of target spatial position have some visual features unique to them. The unique features may reduce the overlap in cognitive resources, requiring less AP and RP effort. There are a number of factors that may influence the RP/AP effect, prior knowledge of the events and complexity of the visual scene.

The flanked distractors follow the same sequence grammar rules as the target stimuli. They also have a weak repetition priming-antipriming effect. This has a small but detectable effect upon the reaction times to target stimuli. This demonstrates that negative priming is actively inhibiting responses to the flanked distractors [64, 95 and 111]. These results show that the subjects are primarily attending the target stimulus.

The erroneous response rate is related to antipriming priming events and stimulus rarity. The rarer the stimulus and the more changes of stimulus present in the four trials before the

response trial the greater the probability of a response error. Experiment two has a higher overall response error rate, which indicates that the greater cognitive load increases the response errors.

The results from experiments one and two suggest that RP, and thus repetition suppression, are effected by spatial location [6, 12, 15, 16, 22, 24, 48 and 66]. Repetition suppression is the localisation and reduction of the cortical activity required to visually identify the stimulus. The more similar features the new stimulus have compared to the primed one the greater the disruptive effect it have on the pattern of cognitive activity. The change of target spatial location appears to reduce the level of cognitive resource sharing and thus antipriming effort required. The targets spatial location in the field of view may affect the exact location of the cognitive resource allocated to it. This may assist with the successful inhibiting of the flanked distractor. The distractor may be allocated cognitive resources that are independent of the target to a significant extent while still sharing the same target identification information.

7.2 Behavioural analysis and real train driving

It was not known if the RP and AP pattern of behaviour or cognitive response exists in real-life train driving. Data of this type is not available for either normal successful driving or SPAD situations. If the results match real-life situation, the experimental results suggest that busy areas, major stations and junctions are more inherently likely to exercise SPADs, with greater potential adverse consequences. The probability of a SPAD in these areas is not higher purely because of the greater volume of traffic thus number of signals observed by train drivers. The number of changes of signal indication and volume of flanked distractors further increase the probability of a SPAD. This may go some way to explain why some signals in the vicinity to busy stations have exceptionally high SPAD counts.

Modern multiple aspect signals of the type modelled in the experiments have very similar appearance. The only difference may be the colour of light displayed. The RP/AP and RS effects suggest that the change of coloured light displayed are competing for the same cognitive resources. This competition for resources may enhance the probability of a response error. Increasing the variation in the visual appearance of signals particularly in areas of busy or complex track layouts may significantly reduce the number of SPADs in those areas.

7.3 Functional-connectivity – graph metrics

The key findings of the functional connectivity analysis using graph metrics are the distinctive patterns of cognitive activity that predict response accuracy, and those surrounding change of stimulus trials. These provide insights into the nature of the cognitive activity that is important for these situations. There are EEG markers of repetition priming and antipriming.

7.3.1 Response accuracy precursors

The graph metrics that are response accuracy precursors in experiments one and two show that the level of cognitive connectivity in the two to three trials prior to a response has a significant effect. The analysis of experiments one and two produced different results.

In the results from experiment one the node degree, NNNPLV, betweenness centrality and closeness centrality graph metrics in the 4-40Hz and alpha frequency bands have significant predictive EEG markers in all the cortical regions measured. The NNND only has EEG markers in the 4-40Hz frequency band in all the cortical regions measured. The scope of the frequency bands and global spread of the results show the importance of the whole of the brain's activity in successful performance of the task [81]. Large scale network activity is shown to be important in [58 and 81]. When a graph metric value drops into its lower range a response error will occur within the next two or three trials. The node degree based graph metrics are a simple measure of the volume of immediate or secondary connections. The betweenness and closeness centrality are measures of a nodes contribution to the shortest path connectivity within the network. This suggests that efficient interactions within and between regions of the brain are important in addition to quantity.

The alpha frequency is associated with visual information processing [34, 40 and 50], cognitive alertness or arousal [65 and 68]. The alpha band phase locking is reported to increase during successful visual perception in [50]. Pre-stimulus alpha band activity is used to predict visual discrimination in [40], the alpha activity may be inhibiting competing cognitive activity to promote visual discrimination. Alpha band activity of short duration is reported to effect visual perception [34 and 55]. The importance of alpha phase-locking in the frontal regions of the brain for stimulus processing is demonstrated in [65 and 68].

Experiment two's results have fewer predictive graph metrics in more localised cortical regions. The betweenness centrality is important for response accuracy generally. Node degree, NNND, NNNPLV and closeness centrality are important for correct responses to changes of stimulus. Response errors during change of stimulus have phase locking reductions in the frontal [34, 40, 65 and 68], central [34 and 65], left temporal and right temporal regions [67]. The occipital network activity of the betweenness centrality graph metric [57].

Experiment two and one's results are likely to differ because of negative priming is occurring in parallel with target stimulus tracking. The effects of negative priming are assumed to be independent of the type of target trial. The EEG markers of junction trial response accuracy appear to be the combination of zero vs high and all correct vs error cases. This probably because junctions are have a high erroneous response rate, in addition to being included in the more general correct vs erroneous response trials.

The temporal lobe and left temporal region are associated with the visual recognition of objects [11] and memory [187]. A failure of the phase locking and thus communications within this region or with others could results the chain events needed for correct observation and response to the target stimulus.

The results indicate that the level of overall cortical connectivity is important for the effective engagement and response to the stimulus. The results in the 4-40Hz frequency suggest that phase locking in a broad range of frequency bands occur in parallel with the alpha phase locking. An explanation for the results is that there are many distinctive cognitive activities involved, some may not be easily detectable using current EEG recording and analysis technology.

7.3.2 Repetition priming and antipriming

The change of stimulus trials in experiments one and two have similar results. All the common significant results are in the 4-40Hz frequency band, in the right temporal region for the node PLV graph metric. Experiment two has significant results in the occipital and parietal regions as well. In experiment two the features in the occipital and parietal regions may be related to the flanked distractors and the negative priming. Negative priming takes place in parallel with the processing of the target stimulus. The junction trials have no graph metrics related to RP and AP effects.

The results show that the magnitude of phase locking surrounding nodes in these regions is effected by antipriming events in a broad range of frequencies. When antipriming is triggered by the change of visual stimulus an active process of unlearning or reallocating some of the cognitive resources is required. The temporal region plays a key role in antipriming and is reported to be involved in antipriming in [13, 15, 16 and 69]. The cortical region that is responsible for triggering the antipriming events may not be the same as the region that is being "antiprimed". This would further suggest that the function of the whole brain is important to successful performance of a complex task.

7.4 Applications for train driving ergonomics

The ability to predict driver perceptual and response errors objectively has clear railway system design safety benefits. Situations and locations where they are most likely to occur can be identified. This knowledge allows new signalling systems and driving cab layouts to be designed that capitalise on human strengths and minimise exposure to weaknesses.
The leading graph metric indicators of response accuracy suggest that the seeds of response error originate in the cognitive state that exists in two or three trials immediately beforehand. This is approximately 3 seconds in the experiments. It is not clear if it is the time or number of events that determine the range of the predictive effect.

The investigation of real SPADs may not always include the pre-SPAD signal sequences. The full details of the SPAD investigations are not always available to researchers or investigators of the wider factors across many SPADs. Gathering information about the correct day-to-day train driving patterns of activity would significantly assist with investigations of the type in these experiments. The data about the positive events gives contrasts to actions in the erroneous response situations. This in turn allows for better identification of the events and factors that are most relevant to any investigation. Factors that are not obvious or immediate may be making a significant contribution to the chain of events.

The leading indicators can act as an objective measure of cognitive effects of signalling and track layouts. When the graph metrics change from a higher level, into or towards the lower range it is a warning sign that a human error is pending. Investigation of multiple samples from many subjects may determine if the results are due to the design of the system. Being

able to objectively evaluate the cognitive effects of preceding events in addition to the signal or location of interest is a significant advancement. This has the potential to reveal significant cognitive effects of apparently innocuous sequences of events in a way that has not possible until now.

The different cognitive effects of spatial and light colour change triggered by antipriming are directly relevant to the train driving and signalling layout. The low read across error rate, and short duration of the adaption to post junction trials indicates that changing the spatial location has a shorter term effect then the light colour change. The light colour change results in more competition for cognitive resources that are already allocated. The maximum response or perceptual error risk is during the antipriming event. Designing signals that are simple to read but that reduce competition for cognitive resources have clear safety benefits.

Areas with three or more tracks usually have tracks that run parallel and signals facing the same direction near each other. The signal(s) on the other track(s) requires active suppression using NP. The type of workload and effect upon the driver's cognitive performance can be objectively measured using the graph metrics. This would allow signalling system designs of these higher risk areas to maximise safety in the face of human factors. The objective analysis of the multi-SPAD signals using methods based on those used in these experiments could provide new information and help to reduce them.

The safety benefits of objective measurement and prediction of the triggers of human perceptual and response errors are clear. Better systems can be designed and evaluated in advance, rather than attempting limited alterations to problems that become apparent over time.

Chapter

8. Conclusion

8.1 Introduction

This chapter includes the contribution to science that this thesis makes, a summary of the key findings, limitations of the project and future research ideas. The project investigated the effect that the signals used on the UKs national railway system have on the train driver's cognitive processes. The investigation focused on the normal operational conditions, rather than those linked to a particular incident or accident. The objective is to identify the behavioural and EEG patterns caused by the signal sequences under normal operational conditions. The EEG markers that preceded correct or erroneous responses are identified. The EEG correlates of repetition priming, antipriming and repetition suppression are identified. The project's research objectives are achieved.

8.2 Contribution to science

The contribution to science that this thesis makes is the investigation of the behavioural and cognitive affects associated with the train driver's cognitive processing of track side signals. The experiment is designed to bridge the gap between the complexities of train driving and simplified laboratory experiments. This project fulfils the challenge of satisfying the requirements of both industry and academic research.

The behavioural analysis reveals the following:

- Repetition priming and repetition suppression effects in the reaction times are caused by repetition of signal indications. Antipriming is triggered by changes of railway signal indication.

- Negative priming is caused by the flanked distractors (signals on the adjacent parallel track) in experiment two. This also increases the erroneous response rate for changes of signal indication, and junctions that warned of a change of track (target spatial position).
- The response error rate during changes of signal indication is related to the number of changes of signal indication in the four preceding trials. Rarer signal indications have higher response error rates.
- The different levels of response accuracy associated with different types of signal and operational situation.

The novel EEG functional connectivity phase-locking analysis findings are:

- The graph metric node PLV magnitude changes significantly during repetition priming and antipriming in 4-40Hz frequency band in the right temporal region.
- There are leading/predictive indicators of response accuracy. The magnitude of a range of functional connectivity graph metrics decrease significantly in the two or three trials immediately before response errors. The predictive indicators differ according to the number of signals visible and the situation.

8.3 Future work

The scope of this project limited the stimuli presented to the principle railway signals. The signals are drawn as stationary images and presented in a compressed time scale. This is to simplify the unknown paradigm sufficiently to identify the EEG markers, and obtain enough response samples. The results documented in this thesis could be used as a starting point for further investigations.

Future extensions to the experiments could study the effects of real-world inter-signal time intervals of 20 to 180 seconds. This could be combined with additional signage/information for the subjects. The additional time would give the subjects more time to correct an erroneous perception or to reinforce it. The additional effects of motion, judgement of speed and distance are another level of realism that could be added to a study. The cognitive effects of shift work patterns, times of day and season could be studied using the experiment designs documented in chapter 3. There is plenty of scope for extensions to the paradigms in this thesis and there practical applications within the rail transport industry.

The range of phase-locking functional-connectivity graph-metrics could be extended. Spectral analysis is an alternative method of analysing the phase-locking functional-connectivity patterns. This may reveal subsets or clusters of related cognitive activity that evolve over time. There are many other methods of EEG analysis too numerous to list here that could be applied to the EEG data.

Further work into the nature of repetition priming and antipriming using a range of EEG function connectivity analysis methods. This has the potential to reveal novel information about the nature of the overall patterns of cognitive connectivity.

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Appendix A - Subject's questionnaire form

University of Reading

EEG experiment for the purposes of measuring human cognitive performance

Subject Information

File number:

Date:

Have you consumed any caffeine in the last 12 hours? Yes / No

Age: 18-25 26-30 31-35 36-40 41-45 46-50 51-55 56-60 61-65

Gender: Male / Female

Handedness: Left / Right / Both

Train driving experience: No experience / qualified (if so how many years)

How alert to you feel?

(1=very alert, 3= alert, 5=neither alert nor sleepy, 7=sleepy, 9=very sleepy, difficulty staying awake, fighting fatigue)

1 2 3 4 5 6 7 8 9

How hungry are you?

(1=very hungry, 3=hungry, 5 = neither, 7=feed,9=fully fed)

1 2 3 4 5 6 7 8 9

How thirsty do you feel?

(1=very thirsty, 3=thirsty, 5=neither, 7=hydrated, 9= fully hydrated)

1 2 3 4 5 6 7 8 9

After block 1

How alert do you feel?

(1 = very alert, 3 = alert, 5= neither alert nor sleepy, 7 = sleepy, 9 = very sleepy, difficulty staying awake, fighting fatigue)

1 2 3 4 5 6 7 8 9

How difficult did you find the task?

(1 = very easy, 3 = easy, 5 = neither, 7 = difficult, 9 = very difficult)

1 2 3 4 5 6 7 8 9

After block 2

How alert do you feel?

(1 = very alert, 3 = alert, 5= neither alert nor sleepy, 7 = sleepy, 9 = very sleepy, difficulty staying awake, fighting fatigue)

1 2 3 4 5 6 7 8 9

How difficult did you find the task?

(1 = very easy, 3 = easy, 5 = neither, 7 = difficult, 9 = very difficult)

1 2 3 4 5 6 7 8 9

After block 3

How alert do you feel?

(1 = very alert, 3 = alert, 5= neither alert nor sleepy, 7 = sleepy, 9 = very sleepy, difficulty staying awake, fighting fatigue)

1 2 3 4 5 6 7 8 9

How difficult did you find the task?

(1 = very easy, 3 = easy, 5 = neither, 7 = difficult, 9 = very difficult)

1 2 3 4 5 6 7 8 9

General comments/feedback:

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Appendix B - Experiment one behavioural analysis data

This appendix contains the reference material that supports chapter 5 the behavioural analysis of experiment one. During experiment one a single sequence of stimulus is presented.

Table B.1 – The frequency of response type for each stimulus type for novice subjects

	Response type									
	Red		**Yellow**		**Double**		**Green**		**None**	
Stimuli type	**Count**	**Prob-ability**	**Count**	**Prob-ability**	**Count**	**Prob-ability**	**Count**	**Prob-ability**	**Count**	**Prob-ability**
Red	798	0.8526	82	0.0876	1	0.0011	6	0.0064	49	0.0524
Yellow	16	0.0128	1118	0.8958	54	0.0433	14	0.0112	46	0.0369
Double	17	0.0136	11	0.0088	1117	0.895	55	0.0441	48	0.0385
Green	24	0.0119	4	0.002	9	0.0045	1877	0.9315	101	0.0501

Table B.1. This table shows the response counts and error rates for novice subjects. The normalisation is row-wise so the probabilities for each stimuli type sum to 1.

Table B.2 – The frequency of response type for each stimulus type for expert subjects

	Response type									
	Red		**Yellow**		**Double**		**Green**		**None**	
Stimuli type	**Count**	**Prob-ability**	**Count**	**Prob-ability**	**Count**	**Prob-ability**	**Count**	**Prob-ability**	**Count**	**Prob-ability**
Red	438	0.869	47	0.0933	0	0	3	0.006	16	0.0317
Yellow	13	0.0193	591	0.8795	40	0.0595	5	0.0074	23	0.0342
Double	8	0.0119	11	0.0164	604	0.8988	24	0.0357	25	0.0372
Green	11	0.0101	0	0	13	0.012	1023	0.943	38	0.035

Table B.2. This table shows the response counts and error rates for expert subjects. The normalisation is row-wise so the probabilities for each stimuli type sum to 1.

Table B.3 – Individual red of stimulus trials preceding response errors for all subjects

	Binomial significance tests			
Number of preceding trials	**Number of a response errors**	**Total**	**Probability of a response error**	**Significantly high or low**
1	166	1420	0.1169	High
2	168	1420	0.1183	High
3	117	1420	0.0824	-
4	119	1420	0.0838	-
5	146	1420	0.1028	-
6	155	1420	0.1092	-
7	124	1420	0.0873	-

Table B.3. This table shows the number of individual red stimuli that precede response errors for all subjects. The binomial statistical significance tests results are shown for probability = 0.0971, alpha = 0.05 and two tails.

Table B.4 – Individual yellow of stimulus trials preceding response errors for all subjects

	Binomial significance tests			
Number of preceding trials	**Number of a response errors**	**Total**	**Probability of a response error**	**Significantly high or low**
1	234	1920	0.1219	High
2	219	1900	0.1153	High
3	230	1900	0.1211	High
4	238	1900	0.1253	High
5	199	1900	0.1047	-
6	182	1880	0.0968	-
7	196	1880	0.1043	-

Table B.4. This table shows the number of individual yellow stimuli that precede response errors for all subjects. The binomial statistical significance tests results are shown for probability = 0.0971, alpha = 0.05 and two tails.

Table B.5 – Individual double-yellow of stimulus trials preceding response errors for all subjects

	Binomial significance tests			
Number of preceding trials	**Number of a response errors**	**Total**	**Probability of a response error**	**Significantly high or low**
1	199	1920	0.1037	-
2	195	1920	0.1016	-
3	183	1900	0.0963	-
4	177	1880	0.0941	-
5	173	1880	0.092	-
6	166	1880	0.0883	-
7	170	1860	0.0914	-

Table B.5. This table shows the number of individual double-yellow stimuli that precede response errors for all subjects. The binomial statistical significance tests results are shown for probability = 0.0971, alpha = 0.05 and two tails.

Table B.6 – Individual green of stimulus trials preceding response errors for all subjects

	Binomial significance tests			
Number of preceding trials	**Number of a response errors**	**Total**	**Probability of a response error**	**Significantly high or low**
1	213	3080	0.069156	Low
2	228	3060	0.07451	Low
3	274	3040	0.090132	-
4	268	3020	0.088742	-
5	282	3000	0.094	-
6	295	3000	0.098333	-
7	306	2980	0.10268	-

Table B.6. This table shows the number of individual green stimuli that precede response errors for all subjects. The binomial statistical significance tests results are shown for probability = 0.0971, alpha = 0.05 and two tails.

Table B.7 – Individual changes of stimulus trials preceding response errors for all subjects

	Binomial significance tests			
Number of preceding trials	**Number of a response errors**	**Total**	**Probability of a response error**	**Significantly high or low**
1	368	3360	0.1095	High
2	402	3340	0.1204	High
3	284	3340	0.0850	Low
4	323	3320	0.0973	-
5	310	3300	0.0939	-
6	346	3280	0.1055	-
7	309	3260	0.0948	-

Table B.7. This table shows the number of individual change of stimuli that precede response errors for all subjects. The binomial statistical significance tests results are shown for probability = 0.0971, alpha = 0.05 and two tails.

Table B.8 – Individual response error trials type preceding response errors for all subjects

	Binomial significance tests			
Number of preceding trials	**Number of a response errors**	**Total**	**Probability of a response error**	**Significantly high or low**
1	814	8360	0.0974	-
2	811	8320	0.0975	-
3	806	8280	0.0973	-
4	802	8240	0.0973	-
5	800	8200	0.0976	-
6	796	8160	0.0975	-
7	793	8120	0.0977	-

Table B.8. This table shows the number of individual response error trials that precede response errors for all subjects. The binomial statistical significance tests results are shown for probability = 0.0971, alpha = 0.05 and two tails.

Table B.9 - Individual trials preceding error response trials – summary of all significance test results for all subjects

Number of preceding trial	**Stimulus type**					
	Red	**Yellow**	**Double yellow**	**Green**	**Change**	**All**
1	High	High	-	High	Low	-
2	High	High	-	High	Low	-
3	-	High	-	Low	Low	-
4	-	High	-	-	-	-
5	-	-	-	-	-	-
6	-	-	-	-	-	-
7	-	-	-	-	-	-

Table B.9. This table summarises the results of the significance tests shown in tables B.1 to B.6. This is for all subjects.

Table B.10 – Trial sequences frequencies of length two that precede response error rates at red stimuli for all subjects

Trial history					
Trial type one step before	**Trial type two steps before**	**error count**	**total**	**error probability**	**Significantly high or low**
Red	Red	18	280	0.0643	Low
Red	yellow	30	420	0.0714	Low
yellow	Red	29	140	0.2071	High
yellow	double yellow	66	220	0.3000	High

Table B.10. This table shows the sequences of the two stimuli immediately prior to red stimuli response error trials. The binomial test for probability = 0.1417, two tails and alpha = 0.05 is used. The sequences listed have either significantly low or high probabilities of occurring. Sequences that occur but do not have significantly different error rates are excluded from this table.

Table B.11 - Trial sequences of significance tests length two that precede response error rates at yellow stimuli for all subjects

Trial history					
Trial type one step before	**Trial type two steps before**	**error count**	**total**	**error probability**	**Significantly high or low**
red	yellow	23	100	0.2300	High
yellow	yellow	22	380	0.0579	Low
yellow	double yellow	21	420	0.0500	Low
double yellow	Red	19	40	0.4750	High
double yellow	yellow	25	40	0.6250	High

Table B.11. This table shows the sequences of the two stimuli immediately prior to yellow stimuli response error trials. The binomial test for probability = 0.1099, two tails and alpha = 0.05 is used. The sequences listed have either significantly low or high probabilities of occurring. Sequences that occur but do not have significantly different error rates are excluded from this table.

Table B.12 – Trial sequences of length two that precede response error rates at double-yellow stimuli for all subjects

Trial history					
Trial type one step before	**Trial type two steps before**	**error count**	**total**	**error probability**	**Significantly high or low**
Red	Red	23	80	0.2875	High
Red	Yellow	20	60	0.3333	High
double yellow	double yellow	19	380	0.0500	Low
double yellow	Green	24	360	0.0667	Low

Table B.12. This table shows the sequences of the two stimuli immediately prior to double-yellow stimuli response error trials. The binomial test for probability = 0.1036, two tails and alpha = 0.05 is used. The sequences listed have either significantly low or high probabilities of occurring. Sequences that occur but do not have significantly different error rates are excluded from this table.

Table B.13 - Trial sequences of length two significance test results precede response error rates at green stimuli for all subjects

Trial history					
Trial type one step before	**Trial type two steps before**	**error count**	**total**	**error probability**	**Significantly high or low**
red	Red	32	200	0.1600	High
double yellow	green	4	20	0.2000	High

Table B.13. This table shows the sequences of the two stimuli immediately prior to green stimuli response error trials. The binomial test for probability = 0.0645, two tails and alpha = 0.05 is used. The sequences listed have either significantly low or high probabilities of occurring. Sequences that occur but do not have significantly different error rates are excluded from this table.

Table B.14 - Trial sequences frequencies of length two that precede response error rates at change of stimuli for all subjects

Trial history					
Trial type one step before	**Trial type two steps before**	**error count**	**total**	**error probability**	**Significantly high or low**
yellow	double yellow	77	360	0.2139	High
double yellow	Red	19	60	0.3167	High
double yellow	yellow	27	60	0.4500	High
double yellow	double yellow	65	560	0.1161	Low
double yellow	green	30	300	0.1000	Low

Table B.14. This table shows the sequences of the two stimuli immediately prior to change of stimuli response error trials. The binomial test for probability = 0.1538, two tails and alpha = 0.05 is used. The sequences listed have either significantly low or high probabilities of occurring. Sequences that occur but do not have significantly different error rates are excluded from this table.

Table B.15 - Trial sequences of length two significance test results precede response error rates at all error trials for all subjects

Trial history					
Trial type one step before	**Trial type two steps before**	**error count**	**total**	**error probability**	**Significantly high or low**
red	Red	86	700	0.1229	High
yellow	Red	38	240	0.1583	High
yellow	double yellow	98	780	0.1256	High
double yellow	Red	23	140	0.1643	High
double yellow	yellow	38	180	0.2111	High
green	Red	21	340	0.0618	Low
green	yellow	3	100	0.0300	Low
green	green	178	2460	0.0724	Low

Table B.15. This table shows the sequences of the two stimuli immediately prior to response error trials. The binomial test for probability = 0.0971, two tails and alpha = 0.05 is used. The sequences listed have either significantly low or high probabilities of occurring. Sequences that occur but do not have significantly different error rates are excluded from this table.

Table B.16 – Trial sequences of length two significance test results preceding trials with zero and high per trial error rates for all subjects

Prior trial stimuli		**Zero error rate trial**		**High error rate trials**	
Trial type one step before	**Trial type two steps before**	**Zero error rate trial count**	**Zero error rate trials probability**	**High error rate trial count**	**High error rate trials probability**
red	red	160	80	0.2286	0.1143
yellow	red	60	20	0.2500	0.0833
double yellow	red	60	20	0.4286	0.1429
green	red	80	0	0.2353	0.0000
red	yellow	120	40	0.1667	0.0556
yellow	yellow	200	80	0.2222	0.0889
double yellow	yellow	40	40	0.2222	0.2222
green	yellow	60	0	0.6000	0.0000
yellow	double yellow	160	100	0.2051	0.1282
double yellow	double yellow	240	40	0.2553	0.0426
green	double yellow	60	0	0.3000	0.0000
double yellow	green	140	0	0.2121	0.0000
green	green	500	40	0.2033	0.0163

Table B.16. This table shows the stimuli sequences of length two that precede high and zero error rated trials. The high error rate trials have an error rate of 6 out of 20 or higher.

Table B.17 – Summary of sequences of two trial preceding response errors for all subjects

Sequence	Stimulus type				Trial type	
	Red	Yellow	Double-yellow	Green	Change of stimuli	Response errors
R–R	L (6.43%)	-	H (28.75%)	H (16.00%)	-	H (12.29%)
Y-R	L (7.14%)	H (23.00%)	H (33.33%)	-	-	-
R-Y	H (20.71%)	-	-	-	-	H (15.83%)
Y-Y	-	L (5.79%)	-	-	-	-
D-Y	H (30.00%)	L (5.00%)	-	-	H (21.39%)	H (12.56%)
R-D	n/a	H (47.50%)	-	-	H (31.67%)	H (16.43%)
Y-D	n/a	H (62.50%)	-	-	H (45.00%)	H (21.11%)
D-D	n/a	-	L (5.00%)	-	L (11.61%)	-
G-D	n/a	-	L (6.67%)	H (20.00%)	L (10.00%)	-
R-G	n/a	n/a	-	-	-	L (6.18%)
Y-G	n/a	n/a	-	-	-	L (3.00%)
D-G	n/a	n/a	-	-	-	-
G-G	n/a	n/a	-	-	-	L (7.24%)

Table B.37. This table is a summary of the results of the significance tests for response error rates for preceding trial sequences of length two. R=red stimulus, Y = yellow stimulus, D = double-yellow stimulus and G = green stimulus. H = significantly higher, L = significantly lower, and "-"means that there is no significant difference in the response error probability. The "n/a" cells indicate sequences that cannot occur because of the sequence grammar rules. This is a summary of tables B.10 to B.16.

Table B.18 - Trial sequences of length three significance test results precede response errors at red stimuli for all subjects

Trial history			All			
Trial type one step before	**Trial type two steps before**	**Trial type three steps before**	**Error count**	**total**	**Observed error probability**	**Significantly high or low**
red	red	red	6	100	0.06	Low
red	red	yellow	12	180	0.066667	Low
red	yellow	yellow	11	240	0.045833	Low
yellow	red	red	0	40	0	Low
yellow	red	yellow	29	100	0.29	High
yellow	double yellow	red	13	20	0.65	High
yellow	double yellow	green	42	100	0.42	High

Table B.18. This table shows the sequences of the three stimuli immediately prior to red stimuli response error trials. The binomial test for probability = 0.1417, two tails and alpha = 0.05 is used. The sequences listed have either significantly low or high probabilities of occurring. Sequences that occur but do not have significantly different error rates are excluded from this table.

Table B.19 - Trial sequences of length three significance test results precede response errors at yellow stimuli for all subjects

Trial history			All			
Trial type one step before	**Trial type two steps before**	**Trial type three steps before**	**Error count**	**total**	**Observed error probability**	**Significantly high or low**
red	yellow	yellow	21	80	0.2625	High
yellow	yellow	yellow	7	140	0.05	Low
yellow	yellow	double yellow	10	180	0.055556	Low
yellow	double yellow	double yellow	12	280	0.042857	Low
double yellow	red	yellow	19	40	0.475	High
double yellow	yellow	double yellow	25	40	0.625	High

Table B.19. This table shows the sequences of the three stimuli immediately prior to yellow stimuli response error trials. The binomial test for probability = 0.1099, two tails and alpha = 0.05 is used. The sequences listed have either significantly low or high probabilities of occurring. Sequences that occur but do not have significantly different error rates are excluded from this table.

Table B.20 - Trial sequences of length three significance test results precede response errors at double-yellow stimuli for all subjects

Trial history			**All**			
Trial type one step before	**Trial type two steps before**	**Trial type three steps before**	**Error count**	**total**	**Observed error probability**	**Significantly high or low**
red	red	yellow	23	80	0.2875	High
red	yellow	yellow	15	20	0.75	High
double yellow	double yellow	double yellow	12	200	0.06	Low
double yellow	green	green	18	280	0.064286	Low
green	double yellow	double yellow	5	20	0.25	High

Table B.20. This table shows the sequences of the three stimuli immediately prior to double-yellow stimuli response error trials. The binomial test for probability = 0.1036, two tails and alpha = 0.05 is used. The sequences listed have either significantly low or high probabilities of occurring. Sequences that occur but do not have significantly different error rates are excluded from this table.

Table B.21 - Trial sequences of length three significance test results precede response errors at green stimuli for all subjects

Trial history			**All**			
Trial type one step before	**Trial type two steps before**	**Trial type three steps before**	**Error count**	**total**	**Observed error probability**	**Significantly high or low**
red	red	red	22	120	0.18333	High
red	red	yellow	10	80	0.125	High
double yellow	green	green	4	20	0.2	High

Table B.21. This table shows the sequences of the three stimuli immediately prior to green stimuli response error trials. The binomial test for probability = 0.0645, two tails and alpha = 0.05 is used. The sequences listed have either significantly low or high probabilities of occurring. Sequences that occur but do not have significantly different error rates are excluded from this table.

Table B.22 - Trial sequences of length three significance test results precede response errors at changes of stimuli for all subjects

Trial history			**All subjects**			
Trial type one step before	**Trial type two steps before**	**Trial type three steps before**	**Error count**	**total**	**Observed error probability**	**Significantly high or low**
red	yellow	yellow	37	140	0.26429	High
red	yellow	double yellow	3	60	0.05	Low
yellow	red	red	0	40	0	Low
yellow	red	yellow	29	100	0.29	High
yellow	double yellow	red	13	20	0.65	High
yellow	double yellow	green	46	160	0.2875	High
double yellow	red	yellow	19	40	0.475	High
double yellow	yellow	double yellow	25	40	0.625	High
double yellow	green	green	28	260	0.10769	Low

Table B.22. The sequences of the three stimuli immediately prior to change of stimuli response error trials. The binomial test for probability = 0.1538, two tails and alpha = 0.05 is used. The sequences listed have either significantly low or high probabilities of occurring. Sequences that occur but do not have significantly different error rates are excluded from this table.

Table B.23 - Trial sequences of length three significance test results precede all response error trials for all subjects

Trial history			All subjects			
Trial type one step before	**Trial type two steps before**	**Trial type three steps before**	**Error count**	**total**	**Observed error probability**	**Significantly high or low**
red	red	yellow	54	420	0.1286	High
yellow	red	yellow	29	100	0.29	High
yellow	double yellow	red	15	40	0.375	High
yellow	double yellow	double yellow	27	420	0.0643	Low
yellow	double yellow	green	53	280	0.1893	High
double yellow	red	red	2	80	0.025	Low
double yellow	red	yellow	21	60	0.35	High
double yellow	yellow	double yellow	28	80	0.35	High
green	red	red	9	200	0.045	Low
green	yellow	double yellow	1	60	0.0167	Low
green	green	double yellow	8	160	0.05	Low
green	green	green	143	1920	0.0745	Low

Table B.23. This table shows the sequences of the three stimuli immediately prior to response error trials. The binomial test for probability = 0.0971, two tails and alpha = 0.05 is used. The sequences listed have either significantly low or high probabilities of occurring. Sequences that occur but do not have significantly different error rates are excluded from this table.

Table B.24 - Trial sequences of length three preceding trials that have zero or high error rates for all subjects

Prior trial stimuli			**Occurrence counts**	
Trial type one step before	**Trial type two steps before**	**Trial type three steps before**	**Zero error rate trials count**	**High error rate trial count**
red	red	red	60	20
yellow	red	red	60	0
double yellow	red	red	40	0
green	red	red	80	0
yellow	yellow	red	20	0
yellow	double yellow	red	0	20
double yellow	double yellow	red	20	0
double yellow	green	red	20	0
green	green	red	20	0
red	red	yellow	100	60
yellow	red	yellow	0	20
double yellow	red	yellow	20	20
red	yellow	yellow	100	40
yellow	yellow	yellow	100	40
double yellow	yellow	yellow	20	0
green	yellow	yellow	20	0
yellow	double yellow	yellow	20	0
double yellow	double yellow	yellow	40	0
green	green	yellow	20	0
red	yellow	double yellow	20	0
yellow	yellow	double yellow	80	40
double yellow	yellow	double yellow	20	40
green	yellow	double yellow	40	0

yellow	double yellow	double yellow	100	0
double yellow	double yellow	double yellow	100	0
green	double yellow	double yellow	60	0
green	green	double yellow	60	0
yellow	double yellow	green	40	80
double yellow	double yellow	green	80	40
double yellow	green	green	120	0
green	green	green	400	40

Table B. 24. This table shows the stimuli sequences of length three that precede high and zero error rated trials. The high error rate trials have an error rate of 6 out of 20 or higher.

Table B.25 – Summary of trial sequences of length three preceding trials stimulus types for all subjects

Sequence	**Stimulus type**				**Trial types**	
	Red	**Yellow**	**Double-yellow**	**Green**	**Change of stimulus**	**Response error**
R-R-R	L (6%)	-	-	H (18.3%)	-	-
Y-R-R	L (6.7%)	-	H (28.75%)	H (12.5%)	-	H (12.9%)
Y-Y-R	L (4.5%)	H (26.75%)	H (75%)	-	H (26.49%)	-
D-Y-R	-	-	-	-	L (5%)	-
R-R-Y	L (0%)	-	-	-	L (0%)	-
Y-R-Y	-	-	-	-	H (29%)	H (29%)
Y-Y-Y	-	L (5%)	-	-	-	-
D-Y-Y	-	L (5.6%)	-	-	-	-
D-D-Y	-	L (4.3%)	-	-	-	L (6.4%)
G-D-Y	H (42%)	-	-	-	H (28.8%)	H (18.9%)
R-R-D	n/a	-	-	-	-	L (2.5%)

Y-R-D	n/a	H (47.5%)	-	-	H (47.5%)	H (35%)
D-Y-D	n/a	H (48.5%)	-	-	H (62.5%)	H (35%)
D-D-D	n/a	-	L (6%)	-	-	-
G-G-D	n/a	-	L (6.4%)	H (20%)	L (10.8%)	-
R-R-G	n/a	n/a	-	-	-	L (4.5%)
D-Y-G	n/a	n/a	-	-	-	L (1.67%)
D-D-G	n/a	n/a	H (25%)	-	-	-
D-G-G	n/a	n/a	-	-	-	L (5%)
G-G-G	n/a	n/a	-	-	-	L (7.4%)

Table B.25. This table summarises the results of the significance test results for the three stage trial histories. Not all of these prior stimuli sequences satisfy the grammatical rules applied. There is a maximum of 40 legal three trial stimuli patterns that can precede a trial. This is reduced for the red and yellow stimuli trials. These are the symbols used in the table R=red stimulus, Y = yellow stimulus, D = double-yellow stimulus, G = green stimulus, L = lower than average significant results, H = higher than average significant result, and '–'means that this combination of stimuli did not occur or there is no significant difference in observed error rate. "n/a" means that the stimulus cannot occur in that combination.

Table B.26 – Trial sequences of length four significance test results precede response errors at red stimuli for all subjects

Trial history				All subjects			
Trial type one step before	**Trial type two steps before**	**Trial type three steps before**	**Trial type four step before**	**Error count**	**total**	**Observed error probability**	**Significantly high or low**
red	red	Red	yellow	3	60	0.0500	Low
red	red	yellow	double yellow	2	80	0.0250	Low
red	yellow	yellow	yellow	2	80	0.0250	Low
red	yellow	yellow	double yellow	8	140	0.0571	Low
yellow	red	red	yellow	0	40	0.0000	Low
yellow	red	yellow	yellow	28	80	0.3500	High
yellow	yellow	double yellow	double yellow	24	100	0.2400	High
yellow	double yellow	red	yellow	13	20	0.6500	High
yellow	double yellow	green	green	42	100	0.4200	High

Table B.26. This table shows the sequences of the four stimuli immediately prior to red stimuli response error trials. The binomial test for probability = 0.1417, two tails and alpha = 0.05 is used. The sequences listed have either significantly low or high probabilities of occurring. Sequences that occur but do not have significantly different error rates are excluded from this table.

Table B.27 – Trial sequences of length four significance test results precede response errors at yellow stimuli for all subjects

Trial history				All subjects			
Trial type one step before	**Trial type two steps before**	**Trial type three steps before**	**Trial type four step before**	**Error count**	**total**	**Observed error probability**	**Significantly high or low**
red	yellow	yellow	yellow	18	40	0.4500	High
yellow	yellow	yellow	yellow	0	40	0.0000	Low
yellow	double yellow	double yellow	green	7	200	0.0350	Low
double yellow	red	yellow	yellow	19	20	0.9500	High
double yellow	yellow	double yellow	double yellow	18	20	0.9000	High
double yellow	yellow	double yellow	green	7	20	0.3500	High
double yellow	double yellow	double yellow	yellow	5	20	0.2500	High
double yellow	double yellow	green	red	7	20	0.3500	High
double yellow	double yellow	green	double yellow	5	20	0.2500	High

Table B.27. This table shows the sequences of the four stimuli immediately prior to yellow stimuli response error trials. The binomial test for probability = 0.1099, two tails and alpha = 0.05 is used. The sequences listed have either significantly low or high probabilities of occurring. Sequences that occur but do not have significantly different error rates are excluded from this table.

Table B.28 - Trial sequences of length four significance test results precede response errors at double-yellow stimuli for all subjects

Trial history				All subjects			
Trial type one step before	**Trial type two steps before**	**Trial type three steps before**	**Trial type four step before**	**Error count**	**total**	**Observed error probability**	**Significantly high or low**
red	red	yellow	yellow	21	60	0.3500	High
red	yellow	yellow	yellow	15	20	0.7500	High
green	double yellow	double yellow	green	5	20	0.2500	High
green	green	green	double yellow	9	20	0.4500	High

Table B.28. This table shows the sequences of the four stimuli immediately prior to double-yellow stimuli response error trials. The binomial test for probability = 0.1036, two tails and alpha = 0.05 is used. The sequences listed have either significantly low or high probabilities of occurring. Sequences that occur but do not have significantly different error rates are excluded from this table.

Table B.29 - Trial sequences of length four significance test results precede response errors at green stimuli for all subjects

Trial history				All subjects			
Trial type one step before	**Trial type two steps before**	**Trial type three steps before**	**Trial type four step before**	**Error count**	**total**	**Observed error probability**	**Significantly high or low**
red	red	red	red	11	60	0.1833	High
red	red	red	yellow	11	60	0.1833	High
red	red	yellow	double yellow	8	40	0.2000	High
double yellow	double yellow	double yellow	double yellow	5	20	0.2500	High
double yellow	green	green	green	4	20	0.2000	High

Table B.29. This table shows the sequences of the four stimuli immediately prior to green stimuli response error trials. The binomial test for probability = 0.0645, two tails and alpha =

0.05. The sequences listed have either significantly low or high probabilities of occurring. Sequences that occur but do not have significantly different error rates are excluded from this table.

Table B.30 - Trial sequences of length four significance test results precede response errors at changes of stimuli for all subjects

Trial history				**All subjects**			
Trial type one step before	**Trial type two steps before**	**Trial type three steps before**	**Trial type four step before**	**Error count**	**total**	**Observed error probability**	**Significantly high or low**
red	yellow	yellow	yellow	33	60	0.5500	High
red	yellow	yellow	double yellow	3	60	0.0500	Low
red	yellow	double yellow	green	1	40	0.0250	Low
yellow	red	red	yellow	0	40	0.0000	Low
yellow	red	yellow	yellow	28	80	0.3500	High
yellow	yellow	double yellow	double yellow	27	120	0.2250	High
yellow	double yellow	red	yellow	13	20	0.6500	High
yellow	double yellow	green	green	46	160	0.2875	High
double yellow	red	yellow	yellow	19	20	0.9500	High
double yellow	yellow	double yellow	double yellow	18	20	0.9000	High
double yellow	yellow	double yellow	green	7	20	0.3500	High
double yellow	double yellow	green	red	7	20	0.3500	High
double yellow	double yellow	green	green	22	240	0.0917	Low

double yellow	green	green	green	18	180	0.1000	Low
green	green	green	double yellow	9	20	0.4500	High

Table B.30. This table shows the sequences of the four stimuli immediately prior to change of stimuli response error trials. The binomial test for probability = 0.1538, two tails and alpha = 0.05. The sequences listed have either significantly low or high probabilities of occurring. Sequences that occur but do not have significantly different error rates are excluded from this table.

Table B.31 - Trial sequences of length four significance test results precede response error trials for all subjects

Trial history				**All subjects**			
Trial type one step before	**Trial type two steps before**	**Trial type three steps before**	**Trial type four step before**	**Error count**	**total**	**Observed error probability**	**Significantly high or low**
Red	red	yellow	yellow	38	240	0.1583	High
Red	yellow	yellow	yellow	35	140	0.2500	High
Red	yellow	yellow	double yellow	11	200	0.0550	Low
yellow	red	yellow	yellow	28	80	0.3500	High
yellow	yellow	yellow	red	13	60	0.2167	High
yellow	yellow	double yellow	double yellow	37	280	0.1321	High
yellow	double yellow	red	yellow	15	40	0.3750	High
yellow	double yellow	double yellow	green	14	260	0.0538	Low
yellow	double yellow	green	green	52	240	0.2167	High
double yellow	red	red	yellow	2	80	0.0250	Low

double yellow	red	yellow	yellow	19	20	0.9500	High
double yellow	yellow	double yellow	double yellow	18	20	0.9000	High
double yellow	yellow	double yellow	green	7	20	0.3500	High
double yellow	double yellow	green	red	7	20	0.3500	High
green	red	red	red	4	120	0.0333	Low
green	green	double yellow	double yellow	4	120	0.0333	Low
green	green	green	green	109	1500	0.0727	Low

Table B.31. The sequences of the four stimuli immediately prior to response error trials. The binomial test for probability = 0.0971, two tails and alpha = 0.05. The sequences listed have either significantly low or high probabilities of occurring. Sequences that occur but do not have significantly different error rates are excluded from this table.

Table B.32 – Trial sequences of length four preceding trials that have zero or high error rates for all subjects

Prior trial stimuli				**Occurrence counts**	
Trial type one step before	**Trial type two steps before**	**Trial type three steps before**	**Trial type four steps before**	**Zero error rate trials count**	**High error rate trial count**
yellow	red	red	red	20	0
green	red	red	red	60	0
yellow	yellow	red	red	20	0
double yellow	double yellow	red	red	20	0
double yellow	green	red	red	20	0

double yellow	red	yellow	red	20	0
yellow	yellow	yellow	red	0	20
yellow	double yellow	green	red	20	0
double yellow	double yellow	green	red	0	20
double yellow	green	green	red	20	0
green	green	green	red	40	0
red	red	red	yellow	60	20
yellow	red	red	yellow	40	0
double yellow	red	red	yellow	40	0
green	red	red	yellow	20	0
yellow	double yellow	red	yellow	0	20
green	green	red	yellow	20	0
red	red	yellow	yellow	40	40
yellow	red	yellow	yellow	0	20
double yellow	red	yellow	yellow	0	20
red	yellow	yellow	yellow	40	40
yellow	yellow	yellow	yellow	60	20
double yellow	yellow	yellow	yellow	20	0
green	yellow	yellow	yellow	20	0
double yellow	double yellow	yellow	yellow	40	0
double yellow	yellow	double yellow	yellow	20	0
yellow	double yellow	double yellow	yellow	20	0

double yellow	double yellow	double yellow	yellow	20	0
red	red	yellow	double yellow	60	20
red	yellow	yellow	double yellow	60	0
yellow	yellow	yellow	double yellow	40	0
yellow	double yellow	yellow	double yellow	20	0
green	green	yellow	double yellow	20	0
yellow	yellow	double yellow	double yellow	40	40
double yellow	yellow	double yellow	double yellow	0	20
green	yellow	double yellow	double yellow	20	0
double yellow	double yellow	double yellow	double yellow	60	0
green	double yellow	double yellow	double yellow	40	0
green	green	double yellow	double yellow	60	0
double yellow	double yellow	green	double yellow	20	0
double yellow	green	green	double yellow	20	0
green	green	green	double yellow	20	20
red	yellow	double yellow	green	20	0
yellow	yellow	double yellow	green	40	0
double yellow	yellow	double yellow	green	0	20

green	yellow	double yellow	green	20	0
yellow	double yellow	double yellow	green	80	0
double yellow	double yellow	double yellow	green	20	0
green	double yellow	double yellow	green	20	0
yellow	double yellow	green	green	20	80
double yellow	double yellow	green	green	60	20
double yellow	green	green	green	80	0
green	green	green	green	340	20

Table B.32. This table shows the high and zero error rated trial counts for sequences of four preceding stimuli. The high error rate trials have an error rate of 6/20 or higher.

Table B.33 – Summary of four stimuli sequences for all subjects

Sequence	**Red**	**Yellow**	**Double-yellow**	**Green**	**Change of stimuli**	**All response errors**
R-R-R-R	-	-	-	H (18.33%)	-	-
Y-R-R-R	L (5.00%)	-	-	H (18.33%)	-	-
Y-Y-R-R	-	-	H (35.00%)	-	-	H (15.83%)
D-Y-R-R	L (2.50%)	-	-	H (20.00%)	-	-
Y-Y-Y-R	L (2.50%)	H (45.00%)	H (75.00%)	-	H (55.00%)	H (25.00%)
D-Y-Y-R	L (5.71%)	-	-	-	L (5.00%)	L (5.50%)
G-D-Y-R	-	-	-	-	L (2.50%)	-
Y-R-R-Y	L (0.00%)	-	-	-	L (0.00%)	-
Y-Y-R-Y	H (35.00%)	-	-	-	H (35.00%)	H (35.00%)
R-Y-Y-Y	-	-	-	-	-	H (21.67%)
Y-Y-Y-Y	-	L (0.00%)	-	-	-	-

D-D-Y-Y	H (24.00%)	-	-	-	H (22.50%)	H (13.21%)
Y-R-D-Y	H (65.00%)	-	-	-	H (65.00%)	H (37.50%)
G-D-D-Y	-	L (3.50%)	-	-	-	L (5.38%)
G-G-D-Y	H (42.00%)	-	-	-	H (28.75%)	H (21.67%)
Y-R-R-D	n/a	-	-	-	-	L (2.50%)
Y-Y-R-D	n/a	H (95.00%)	-	-	H (95.00%)	H (95.00%)
D-D-Y-D	n/a	H (90.00%)	-	-	H (90.00%)	H (90.00%)
G-D-Y-D	n/a	H (35.00%)	-	-	H (35.00%)	H (35.00%)
Y-D-D-D	n/a	H (25.00%)	-	-	-	-
D-D-D-D	n/a	-	-	H (25.00%)	-	-
R-G-D-D	n/a	H (35.00%)	-	-	H (35.00%)	H (35.00%)
D-G-D-D	n/a	H (25.00%)	-	-	-	-
G-G-D-D	n/a	n/a	-	-	L (9.17%)	-
G-G-G-D	n/a	n/a	-	H (20.00%)	L (10.00%)	-
R-R-R-G	n/a	n/a	-	-	-	L (3.33%)
G-D-D-G	n/a	n/a	H (25.00%)	-	-	-
D-D-G-G	n/a	n/a	-	-	-	L (3.33%)
D-G-G-G	n/a	n/a	H (45.00%)	-	H (45.00%)	-
G-G-G-G	n/a	n/a	-	-	-	L (7.27%)

Table B.33. This table summaries tables B.26 to B.30. The sequences of four stimuli with significantly different error probabilities are listed for each stimulus or trial type. These are the symbols used in the table R=red stimulus, Y = yellow stimulus, D = double-yellow stimulus, G = green stimulus, L = lower than average significant results, H = higher than average significant result, and '–'means that this combination of stimuli did not occur or there is no significant difference in observed error rate. "n/a" means that the stimulus cannot occur in that combination.

Appendix C - Experiment two behavioural analysis

This appendix contains the dataset and tables that support chapter 6, the behavioural and EEG analysis of experiment two. Experiment two presents two stimuli simultaneously, one the target the other a flanked distractor.

Table C.1 – The subsets of 20 trials excluded from the analysis

Sub-block index	**Subject**																			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1		X								X	X						X			
2										X	X									
3										X	X									
4										X							X			
5										X										
6		X								X							X			
7										X										
8										X	X									
9										X	X						X		X	
10										X							X		X	
11										X										
12										X										
13										X	X						X	X		
14										X	X	X					X	X		
15										X										
16					X					X										
17										X	X									
18										X										

19										X										
20										X										
21										X	X									
22										X	X									
23										X	X									
24										X	X									

Table C.1. This table lists the subsets of 20 trials for each subject that have been excluded from the analysis process. These are excluded because it is believed that the subjects are unaware that they are tracking the distractor stimuli. "X" marks an excluded set of 20 trials for a subject.

Table C.2 – Trial sequences of length two significance test results preceding trials with zero and high per trial error rates for all subjects

Prior trial stimuli		**Occurrence counts**		
Trial type one step before	**Trial type two steps before**	**Zero error rate trials count**	**High error rate trial count**	**Total number of sequences**
red	red	6	2	27
yellow	red	3	4	20
double yellow	red	2	2	10
green	red	10	0	15
red	yellow	4	9	45
yellow	yellow	5	7	28
double yellow	yellow	2	1	10
green	yellow	5	1	12
yellow	double yellow	1	12	47
double yellow	double yellow	4	3	31
green	double yellow	5	3	17
double yellow	green	5	8	45

green	green	99	4	171

Table C.2. The stimuli sequences of length two that precede high and zero error rated trials. The high error rate trials have an error rate of 6/20 or higher. The values are the number of trials in that category and sequence of trial types.

Table C.3 - Summary of two stimuli sequences for all subjects

Sequence	**Red**	**Yellow**	**Double-yellow**	**Green**	**Change of stimuli**	**All response errors**	**Junctions**
R-R	L (6.21%)	-	-	H (27.78%)	L 15.92%)	-	-
Y-R	L (6.76%)	H (28.95%)	H (46.72%)	H 20.57%)	-	H (21.43%)	-
R-Y	H (27.46%)	L (7.41%)	-	H (50.00%)	-	H (20.64%)	-
Y-Y	-	L (1.90%)	H (29.55%)	H (26.24%)	-	H (20.98%)	H (35.29%)
D-Y	H (26.73%)	L (8.80%)	H (47.67%)	H (64.71%)	H (25.82%)	H (25.82%)	H (47.22%)
R-D	n/a	H (29.13%)	L (3.03%)	H (25.00%)	-	H (23.26%)	H (94.44%)
Y-D	n/a	H (35.29%)	L (1.89%)	H (16.67%)	-	H (21.26%)	-
D-D	n/a	-	L (4.05%)	H (14.17%)	L (15.32%)	-	-
G-D	n/a	H (31.81%)	L (6.21%)	H (39.09%)	-	H (22.54%)	-
R-G	n/a	n/a	-	L (1.61%)	L (3.38%)	L (3.38%)	-
Y-G	n/a	n/a	-	L (3.47%)	L (7.77%)	L (7.69%)	-
D-G	n/a	n/a	H (58.90%)	-	-	-	-
G-G	n/a	n/a	L (16.35%)	L (2.33%)	L (5.38%)	L (5.37%)	L (17.65%)

Table C.3. This is a summary of the sequences of two stimuli with significantly different error probabilities that precede the different final stimuli and trial types. These are the symbols used in the table R = red stimulus, Y = yellow stimulus, D = double-yellow stimulus, G = green stimulus, L = lower than average significant results, H = higher than average significant result, and '–'means that this combination of stimuli did not occur or there is no significant difference in observed error rate. "n/a" means that the stimulus cannot occur in that combination.

Table C.4 – Trial sequences of length three significance test results preceding trials with zero and high per trial error rates for all subjects

Prior trial stimuli			**Occurrence counts**		
Trial type one step before	**Trial type two steps before**	**Trial type three steps before**	**Zero error rate trials count**	**High error rate trial count**	**Total number of sequences**
red	red	red	2	1	10
yellow	red	red	1	2	9
double yellow	red	red	0	1	3
green	red	red	5	0	5
red	yellow	red	2	1	11
yellow	yellow	red	1	2	8
yellow	double yellow	red	0	1	6
green	double yellow	red	1	0	2
double yellow	green	red	0	1	1
green	green	red	9	0	14
red	red	yellow	4	1	17
yellow	red	yellow	2	2	11
double yellow	red	yellow	2	1	7
green	red	yellow	5	0	10
red	yellow	yellow	1	1	9
yellow	yellow	yellow	1	1	6
double yellow	yellow	yellow	1	1	5
green	yellow	yellow	4	0	8
yellow	double yellow	yellow	1	1	4
green	double yellow	yellow	0	1	2
green	green	yellow	3	0	10
red	yellow	double yellow	1	7	25
yellow	yellow	double yellow	3	4	14

double yellow	yellow	double yellow	1	0	5
green	yellow	double yellow	1	1	3
yellow	double yellow	double yellow	0	6	16
green	double yellow	double yellow	2	1	7
green	green	double yellow	5	2	13
yellow	double yellow	green	0	4	21
double yellow	double yellow	green	4	3	18
green	double yellow	green	2	1	6
double yellow	green	green	5	7	38
green	green	green	81	2	133

Table C.4. The stimuli sequences of length three that precede high and zero error rated trials. The high error rate trials have an error rate of 6/20 or higher. The values are the number of trials in that category and sequence of trial types.

Table C.5 – Summary of three stimuli sequences for all subjects

Sequence	**Red**	**Yellow**	**Double-yellow**	**Green**	**Change of stimuli**	**All response errors**	**Junctions**
R-R-R	L (5.80%)	-	-	H (30.91%)	-	-	-
Y-R-R	L (6.48%)	-	-	H (22.86%)	L (14.53%)	-	-
R-Y-R	L (6.73%)	H (70.59%)	-	-	L (13.47%)	-	-
Y-Y-R	-	-	-	-	-	-	-
D-Y-R	L (4.88%)	-	H (49.52%)	H (28.16%)	H (26.10%)	H (26.04%)	-
R-R-Y	-	L (9.09%)	-	H (50.00%)	-	H (20.78%)	-
Y-R-Y	H (28.93%)	L (5.80%)	-	-	-	H (20.53%)	-
R-Y-Y	H (43.75%)	L (0.00%)	H (30.77%)	-	-	H (25.93%)	H (75.00%)
Y-Y-Y	-	L (2.86%)	-	H (51.43%)	-	H (22.86%)	H (50.00%)
D-Y-Y	-	L (1.85%)	H (44.44%)	H (19.72%)	-	-	L (5.41%)
Y-D-R	-	-	-	-	-	H (24.27%)	-
Y-D-Y	-	L (5.71%)	-	-	-	-	-

D-D-Y	H (33.33%)	-	H (40.00%)	H (72.22%)	H (33.57%)	H (33.57%)	-
G-D-Y	-	L (9.44%)	H (89.47%)	H (60.61%)	-	H (21.83%)	H (47.22%)
R-R-D	n/a	-	-	H (33.33%)	-	H (24.00%)	-
Y-R-D	n/a	H (33.80%)	L (3.03%)	-	-	H (22.95%)	H (94.44%)
Y-Y-D	n/a	H (46.15%)	L (0.00%)	H (27.78%)	H (32.95%)	H (32.95%)	-
D-Y-D	n/a	-	L (2.86%)	-	L (9.30%)	-	-
R-D-D	n/a	-	-	H (23.53%)	-	-	-
Y-D-D	n/a	-	-	-	L (9.43%)	-	-
D-D-D	n/a	L (11.11%)	-	-	L (10.88%)	-	-
G-D-D	n/a	H (27.59%)	L (1.33%)	H (13.70%)	-	H (18.32%)	-
R-G-D	n/a	-	-	H (44.44%)	H (44.44%)	H (44.44%)	H (44.44%)
G-G-D	n/a	H (37.32%)	L (6.27%)	H (38.04%)	-	H (23.56%)	-
R-R-G	n/a	n/a	-	L (0.00%)	L (0.00%)	L (0.00%)	-
Y-R-G	n/a	n/a	-	L (2.55%)	L (5.14%)	L (5.14%)	-
Y-Y-G	n/a	n/a	-	L (2.42%)	L (5.04%)	L (4.96%)	-
R-D-G	n/a	n/a	-	-	L (2.78%)	-	-
Y-D-G	n/a	n/a	H (61.11%)	-	H (36.11%)	H (36.11%)	H (61.11%)
D-D-G	n/a	n/a	H (94.44%)	-	-	-	L (8.57%)
G-D-G	n/a	n/a	H (40.54%)	-	-	-	-
R-G-G	n/a	n/a	-	L (2.60%)	L (3.63%)	L (3.63%)	-
Y-G-G	n/a	n/a	-	-	L (5.20%)	L (5.20%)	-
D-G-G	n/a	-	H (34.78%)	-	L (15.68%)	-	-
G-G-G	n/a	-	L (13.71%)	L (2.14%)	L (4.60%)	L (4.58%)	L (16.24%)

Table C.5. This is a summary of the sequences of three stimuli with significantly different error probabilities that precede the different final stimuli and trial types. These are the symbols used in the table R = red stimulus, Y = yellow stimulus, D = double-yellow stimulus, G = green stimulus, L = lower than average significant results, H = higher than average significant result, and '–'means that this combination of stimuli did not occur or there is no significant difference in observed error rate. "n/a" means that the stimulus cannot occur in that combination.

Table C.6 – Trial sequences of length four significance test results preceding trials with zero and high per trial error rates for all subjects

Prior trial stimuli				**Occurrence counts**		
Trial type one step before	**Trial type two steps before**	**Trial type three steps before**	**Trial type four steps before**	**Zero error rate trials count**	**High error rate trial count**	**Total number of sequences**
red	red	red	red	0	1	4
double yellow	red	red	red	0	1	2
green	red	red	red	3	0	3
red	yellow	red	red	0	1	4
yellow	yellow	red	red	0	2	4
green	double yellow	red	red	1	0	1
green	green	red	red	4	0	5
red	red	yellow	red	1	1	6
green	red	yellow	red	3	0	4
yellow	yellow	yellow	red	1	0	1
double yellow	yellow	yellow	red	0	1	3
green	yellow	yellow	red	1	0	2
red	yellow	double yellow	red	1	1	6
green	green	double yellow	red	1	0	2
green	double yellow	green	red	0	1	1
double yellow	green	green	red	0	1	1
green	green	green	red	4	1	13
red	red	red	yellow	2	0	6
yellow	red	red	yellow	1	2	8
green	red	red	yellow	2	0	2
red	yellow	red	yellow	2	0	7
yellow	yellow	red	yellow	1	0	4

yellow	double yellow	red	yellow	0	1	4
double yellow	green	red	yellow	0	1	1
green	green	red	yellow	5	0	9
yellow	red	yellow	yellow	1	1	4
yellow	yellow	yellow	yellow	0	1	2
double yellow	yellow	yellow	yellow	1	0	1
green	yellow	yellow	yellow	1	0	2
yellow	double yellow	yellow	yellow	1	1	2
green	green	yellow	yellow	3	0	7
yellow	yellow	double yellow	yellow	1	0	2
double yellow	yellow	double yellow	yellow	1	0	2
green	green	double yellow	yellow	1	0	1
yellow	double yellow	green	yellow	0	1	2
green	green	green	yellow	2	0	7
red	red	yellow	double yellow	3	0	7
yellow	red	yellow	double yellow	1	1	6
double yellow	red	yellow	double yellow	2	1	6
green	red	yellow	double yellow	2	0	6
red	yellow	yellow	double yellow	1	1	6
green	yellow	yellow	double yellow	2	0	4
green	double yellow	yellow	double yellow	0	1	1
red	yellow	double yellow	double yellow	0	3	11
yellow	yellow	double yellow	double yellow	1	0	2

green	yellow	double yellow	double yellow	1	0	1
yellow	double yellow	double yellow	double yellow	0	1	5
green	double yellow	double yellow	double yellow	1	0	1
green	green	double yellow	double yellow	3	1	6
double yellow	green	green	double yellow	0	1	5
green	green	green	double yellow	3	0	8
red	yellow	double yellow	green	0	3	8
yellow	yellow	double yellow	green	1	4	10
green	yellow	double yellow	green	0	1	2
yellow	double yellow	double yellow	green	0	5	10
green	double yellow	double yellow	green	1	1	4
green	green	double yellow	green	0	1	4
yellow	double yellow	green	green	0	3	16
double yellow	double yellow	green	green	4	3	17
green	double yellow	green	green	2	0	5
double yellow	green	green	green	5	5	29
green	green	green	green	71	1	104

Table C.6. The stimuli sequences of length four that precede high and zero error rated trials. The high error rate trials have an error rate of 6/20 or higher. The values are the number of trials in that category and sequence of trial types.

Appendix D - EEG Analysis data

This appendix contains the data tables that support chapters 5 and 6, EEG analysis sections. The trial sets listed in tables D.1 to D.14 are used to select subsets of the EEG data for comparison of experimental conditions.

Table D.1 – Trial set size for repetition priming sequences

Trial set	Experiment one	Experiment two
All change of stimuli	3380	4351
Post-change 1	1896	1004
Post-change 2	891	507
Post-change 3	476	286
Post-change 4	241	179
Post-change 5	210	150
Post-change 6	113	148
Post-change 7	77	107
Post-change 8	47	90
Post-change 9	46	73

Table D. 1. The trial set sizes for post-change of stimulus trials that are used for analysis of repetition priming. The values for experiments one and two are listed. The first trial set is the change of stimulus trials. The following sets are no change of stimulus and correct response trial sets that are a subset of the adjacent set.

Table D.2 – Trial set size for antipriming sequences

Trial set	Experiment one	Experiment two
All change of stimuli	3380	4351
Pre-change 1	1917	1025
Pre-change 2	910	495
Pre-change 3	503	292

Table D. 2. The trial set sizes for pre-change of stimulus trials that are used for analysis of antipriming. The values for experiments one and two are listed. The first trial set is the change of stimulus trials. The preceding sets are no change of stimulus and correct response trials.

Table D.3 – Trial set size for trials in correct response sequences

Trial set	Experiment one	Experiment two
Correct response trials	7566	5561
Pre correct 1	4307	2986
Pre correct 2	2435	2016
Pre correct 3	1531	1453
Post correct 1	4292	2970

Table D. 3. The trial set sizes for post and pre-correct response trials that are used for analysis of response accuracy. The values for experiments one and two are listed. The first trial set is the correct response trials. The preceding sets are correct response trials that are a subset of the adjacent set. The post correct trials are the trials that have correct responses that follow the initial correct response. A minimum trial spacing of four is imposed between the initial set of trials to prevent any trial being selected more than once.

Table D.4 – Trial set size for trials in erroneous response sequences

Trial set	Experiment one	Experiment two
Erroneous response trials	814	3540
Pre error 1	419	504
Pre error 2	221	263
Pre error 3	121	263
Post error 1	394	478

Table D. 4. The trial set sizes for post and pre-erroneous response trials that are used for analysis of response accuracy. The values for experiments one and two are listed. The first trial set is the erroneous response trials. The preceding sets are correct response trials that are a subset of the adjacent set. The post correct trials are the trials that have correct responses that follow the initial erroneous response.

Table D.5 – Trial set size for trials in correct response to change of stimulus sequences

Trial set	Experiment one	Experiment two
Correct response to change of stimulus trials	2860	2087
Pre correct 1	1651	707
Pre correct 2	783	372
Pre correct 3	435	193
Post correct 1	1656	716
Post correct 2	772	354
Post correct 3	427	205

Table D. 5. The trial set sizes for pre and post-change of stimulus correct response trials that are used for analysis of response accuracy. The values for experiments one and two are listed. The first trial set is the change of stimulus correct response trials. The preceding sets are no change of stimulus correct response

trials that are a subset of the adjacent set. The post correct trials are the trials that have no change of stimulus correct responses that follow the initial correct response. A minimum trial spacing of four is imposed between the initial set of trials to prevent any trial being selected more than once.

Table D.6 – Trial set size for trials in erroneous response to change of stimulus sequences

Trial set	Experiment one	Experiment two
Erroneous response to change of stimulus trials	520	756
Pre error 1	266	318
Pre error 2	127	123
Pre error 3	68	99
Post error 1	240	288
Post error 2	119	153
Post error 3	287	81

Table D. 6. The trial set sizes for pre and post-change of stimulus erroneous response trials that are used for analysis of response accuracy. The values for experiments one and two are listed. The first trial set is the change of stimulus erroneous response trials. The preceding sets are no change of stimulus correct response trials that are a subset of the adjacent set. The post correct trials that have no change of stimulus correct responses and follow the initial erroneous response.

Table D.7 – Trial set size for trials sequences for zero error rate trials

Trial set	Experiment one	Experiment two
Zero error rate trials	1900	2128
Pre zero trials 1	1048	1738
Pre zero trials 2	588	1134
Pre zero trials 3	388	1079
Post zero trials 1	1133	1610

Table D. 7. The trial set sizes for pre and post zero error rate trials that are used for analysis of response accuracy. The values for experiments one and two are listed. The first trial set is the zero error rate trials. The preceding sets are correct response trials that are a subset of the adjacent set. The post correct trials are the trials that have correct responses that follow the initial zero error rate set. A minimum trial spacing of four is imposed between the initial set of trials to prevent any trial being selected more than once.

Table D.8 – Trial set size for trials sequences for high error rate trials

Trial set	Experiment one	Experiment two
High error rate trials	420	3477
Pre high trials 1	266	490
Pre high trials 2	87	250
Pre high trials 3	36	197
Post high trials 1	167	498

Table D. 8. The trial set sizes for pre and post high error rate trials that are used for analysis of response accuracy. The values for experiments one and two are listed. The first trial set is the high error rate trials. The preceding sets are correct response trials that are a subset of the adjacent set. The post event trials are the trials that have correct responses.

Table D.9 – Trial set size for no change of stimulus correct response trials

Trial set	Experiment one	Experiment two
No change of stimulus correct response trials	2189	1594
Pre no change correct 1	752	669
Pre no change correct 2	461	508
Pre no change correct 3	461	508
Post no change correct 1	1169	914

Table D. 9. The trial set sizes for pre and post no change of stimulus correct response trials that are used for analysis of response accuracy. The values for experiments one and two are listed. The first trial set is the no change of stimulus correct response trials. The preceding sets are no change of stimulus correct response trials that are a subset of the adjacent set. The post no change of stimulus correct trials are the trials that have no change of stimulus correct responses that follow the initial event. A minimum trial spacing of four is imposed between the initial set of trials to prevent any trial being selected more than once.

Table D.10 – Trial set size for no change of stimulus erroneous response trials

Trial set	Experiment one	Experiment two
No change of stimulus erroneous response trials	294	1276
Pre no change error 1	153	186
Pre no change error 2	94	140
Pre no change error 3	53	92
Post no change error 1	154	190

Table D. 10. The trial set sizes for pre and post no change of stimulus erroneous response trials that are used for analysis of response accuracy. The values for experiments one and two are listed. The first trial set is the no change of stimulus erroneous response trials. The preceding sets are no change of stimulus

correct response trials that are a subset of the adjacent set. The post no change of stimulus erroneous response trials have no change of stimulus correct responses that follow the initial event.

Table D.11 – Trial set size for junction correct response trials

Trial set	Experiment two
Junction correct response trials	405
Pre junction correct 1	46
Pre junction correct 2	30
Pre junction correct 3	10
Post junction correct 1	217

Table D. 11. The trial set sizes for pre and post junction correct response trials that are used for analysis of response accuracy. The values for experiment two are listed. The first trial set are the junction correct response trials. The preceding sets are no-junction correct response trials that are a subset of the adjacent set. The post correct trials are no-junction correct responses that follow the initial correct response.

Table D.12 – Trial set size for junction erroneous response trials

Trial set	Experiment two
Junction erroneous response trials	507
Pre junction error 1	215
Pre junction error 2	157
Pre junction error 3	144
Post junction error 1	121

Table D. 12. The trial set sizes for pre and post junction erroneous response trials that are used for analysis of response accuracy. The values for experiment two are listed. The first trial set is the junction erroneous response trials. The preceding sets are no-junction correct response trials that are a subset of the adjacent set. The post correct trials are the no-junction correct responses that follow the initial junction erroneous response.

Table D.13 – Trial set size for junction repetition priming trials

Trial set	Experiment two
Junction trials	912
Post junction 1	654
Post junction 2	373
Post junction 3	266
Post junction 4	207
Post junction 5	157
Post junction 6	140

Table D. 13. The trial set sizes for post junction trials that are used for analysis of repetition priming. The values for experiment two are listed. The first trial set is the junction trials. The following set are no-junction and correct response trial sets that are a subset of the adjacent set.

Table D.14 – Trial set size for junction antipriming trials

Trial set	**Experiment two**
Junction trials	912
Pre junction 1	337
Pre junction 2	273
Pre junction 3	270

Table D. 14. The trial set sizes for pre junction trials that are used for analysis of antipriming. The values for experiments one and two are listed. The first trial set is the junction trials. The following set are no-junction and correct response trial sets that are a subset of the adjacent set.

Appendix E – ANOVA results of experiment one

This appendix contains the 3 way ANOVA results tables that support chapter 5, graph metric response accuracy precursor and repetition priming-antipriming analysis.

Source	Sum sq.	d.f.	Mean Sq.	F	p-value
condition	41.5111	1	41.5111	881.0308	1.36E-150
frequency	2,910	4	727.8304	1.54E+04	0
region	0.2834	6	0.0472	1.0024	0.4221
condition*frequency	88.1613	4	22.0403	467.7837	4.02E-256
condition*region	0.2525	6	0.0421	0.8933	0.4989
frequency*region	0.5656	24	0.0236	0.5001	0.9794
condition*frequency*region	0.4677	24	0.0195	0.4136	0.9947
Error	65.9631	1400	0.0471		
Total	3,110	1469			

Table E. 1. The 3-way ANOVA (condition x frequency band x region) results for the node degree graph metric for zero vs high response error rate trials, condition refers to zero and high error rate.

Source	Sum sq.	d.f.	Mean Sq.	F	p-value
condition	0.1307	1	0.1307	111.3237	4.32E-25
frequency	27.4837	4	6.8709	5.85E+03	0
region	0.0311	6	0.0052	4.4177	1.96E-04
condition*frequency	0.0563	4	0.0141	11.9811	1.42E-09
condition*region	0.0174	6	0.0029	2.4669	0.0223
frequency*region	0.0925	24	0.0039	3.2826	1.67E-07
condition*frequency*region	0.0334	24	0.0014	1.1859	0.2437
Error	1.6352	1393	0.0012		
Total	29.507	1462			

Table E. 2. The 3-way ANOVA (condition x frequency band x region) results for the node phase locking values graph metric for zero vs high response error rate trials, condition refers to zero and high error rate.

Source	Sum sq.	d.f.	Mean Sq.	F	p-value
condition	6.28E+03	1	6.28E+03	637.7033	2.96E-116
frequency	3.69E+05	4	9.22E+04	9.37E+03	0
region	5.7097	6	0.9516	0.0967	0.9967
condition*frequency	1.80E+04	4	4.49E+03	456.2731	8.11E-252
condition*region	3.3836	6	0.5639	0.0573	0.9993
frequency*region	21.8577	24	0.9107	0.0925	1
condition*frequency*region	12.1854	24	0.5077	0.0516	1
Error	1.38E+04	1400	9.8438		
Total	4.07E+05	1469			

Table E. 3. The 3-way ANOVA (condition x frequency band x region) results for the node nearest degree graph metric for zero vs high response error rate trials, condition refers to zero and high error rate.

Source	Sum sq.	d.f.	Mean Sq.	F	p-value
condition	4.26E+03	1	4.26E+03	545.8922	3.24E-102
frequency	2.96E+05	4	7.40E+04	9.48E+03	0
region	3.9109	6	0.6518	0.0835	0.9978
condition*frequency	1.40E+04	4	3.49E+03	447.3694	1.91E-248
condition*region	2.3537	6	0.3923	0.0502	0.9995
frequency*region	16.4454	24	0.6852	0.0877	1
condition*frequency*region	10.3479	24	0.4312	0.0552	1
Error	1.09E+04	1400	7.809		
Total	3.25E+05	1469			

Table E. 4. The 3-way ANOVA (condition x frequency band x region) results for the node nearest PLV graph metric for zero vs high response error rate trials, condition refers to zero and high error rate.

Source	Sum sq.	d.f.	Mean Sq.	F	p-value
condition	5.5053	1	5.5053	248.8714	9.92E-52
frequency	886.2491	4	221.5623	10000	0
region	0.5934	6	0.0989	4.4706	17100
condition*frequency	5.8413	4	1.4603	66.0145	3.32E-51
condition*region	0.9189	6	0.1532	6.9235	2.90E-07
frequency*region	1.7757	24	0.074	3.3447	9.91E-08
condition*frequency*region	3.0287	24	0.1262	5.7048	7.81E-17
Error	30.9697	1400	0.0221		
Total	934.8822	1469			

Table E. 5. The 3-way ANOVA (condition x frequency band x region) results for the betweenness centrality graph metric for zero vs high response error rate trials, condition refers to zero and high error rate.

Source	Sum sq.	d.f.	Mean Sq.	F	p-value
condition	59200	1	59200	1200	5.70E-191
frequency	0.0568	4	0.0142	28900	0
region	1.17E-06	6	1.95E-07	0.3973	0.8811
condition*frequency	0.0012	4	29000	588.8222	4.82E-298
condition*region	1.27E-06	6	2.11E-07	0.4288	0.8601
frequency*region	3.84E-06	24	1.60E-07	0.3251	0.9992
condition*frequency*region	3.10E-06	24	1.29E-07	0.2627	0.9999
Error	68800	1400	4.92E-07		
Total	0.0593	1469			

Table E. 6. The 3-way ANOVA (condition x frequency band x region) results for the closeness centrality graph metric for zero vs high response error rate trials, condition refers to zero and high error rate.

Source	Sum sq.	d.f.	Mean Sq.	F	p-value
condition	28.9528	1	28.9528	716.0536	9.65E-128
frequency	2810	4	702.4216	17400	0
region	0.3123	6	0.052	1.2871	0.2599
condition*frequency	60.279	4	15.0698	372.7016	1.36E-218
condition*region	0.1245	6	0.0207	0.5131	0.7988
frequency*region	0.598	24	0.0249	0.6163	0.9257
condition*frequency*region	0.2632	24	0.011	0.2712	0.9998
Error	56.6074	1400	0.0404		
Total	2960	1469			

Table E. 7. The 3-way ANOVA (condition x frequency band x region) results for the node degree graph metric for change of stimulus correct and erroneous response error rate trials, condition refers to correct and erroneous responses.

Source	Sum sq.	d.f.	Mean Sq.	F	p-value
condition	0.0123	1	0.0123	12.8839	34300
frequency	29.3154	4	7.3289	7690	0
region	0.0062	6	0.001	1.0871	0.3678
condition*frequency	0.031	4	0.0077	8.1239	1.79E-06
condition*region	0.0077	6	0.0013	1.3462	0.2333
frequency*region	0.0426	24	0.0018	1.8646	0.0069
condition*frequency*region	0.0277	24	0.0012	1.2124	0.2192
Error	1.3322	1398	9.53E-04		
Total	30.7631	1467			

Table E. 8. The 3-way ANOVA (condition x frequency band x region) results for the node PLV graph metric for change of stimulus correct and erroneous response error rate trials, condition refers to correct and erroneous responses.

Source	Sum sq.	d.f.	Mean Sq.	F	p-value
condition	3040	1	3040	369.2267	3.23E-73
frequency	3.56E+05	4	89000	10800	0
region	6.8515	6	1.1419	0.1387	0.9912
condition*frequency	9450	4	2360	286.9344	3.03E-180
condition*region	1.7426	6	0.2904	0.0353	0.9998
frequency*region	18.5862	24	0.7744	0.0941	1
condition*frequency*region	4.7827	24	0.1993	0.0242	1
Error	11,500	1400	8.2315		
Total	380,000	1469			

Table E. 9. The 3-way ANOVA (condition x frequency band x region) results for the NNND graph metric for change of stimulus correct and erroneous response error rate trials, condition refers to correct and erroneous responses.

Source	Sum sq.	d.f.	Mean Sq.	F	p-value
condition	2270	1	2270	341.7409	1.92E-68
frequency	2.84E+05	4	71,100	10700	0
region	5.9608	6	0.9935	0.1496	0.9892
condition*frequency	7440	4	1860	279.9851	6.47E-177
condition*region	1.6539	6	0.2756	0.0415	0.9997
frequency*region	18.1317	24	0.7555	0.1138	1
condition*frequency*region	4.969	24	0.207	0.0312	1
Error	9300	1400	6.6393		
Total	303,000	1469			

Table E. 10. The 3-way ANOVA (condition x frequency band x region) results for the NNNPLV graph metric for change of stimulus correct and erroneous response error rate trials, condition refers to correct and erroneous responses.

Source	Sum sq.	d.f.	Mean Sq.	F	p-value
condition	7.5754	1	7.5754	520.7865	2.92E-98
frequency	842.7818	4	210.6955	14500	0
region	0.5784	6	0.0964	6.6275	6.35E-07
condition*frequency	12.587	4	3.1468	216.3314	1.34E-144
condition*region	0.2686	6	0.0448	3.0777	0.0054
frequency*region	1.6628	24	0.0693	4.7631	4.18E-13
condition*frequency*region	1.0663	24	0.0444	3.0544	1.08E-06
Error	20.3644	1400	0.0145		
Total	886.8847	1469			

Table E. 11. The 3-way ANOVA (condition x frequency band x region) results for the betweenness centrality graph metric for change of stimulus correct and erroneous response error rate trials, condition refers to correct and erroneous responses.

Source	Sum sq.	d.f.	Mean Sq.	F	p-value
condition	50,900	1	5.09E-04	1,410	2.78E-214
frequency	0.0543	4	0.0136	37,700	0
region	1.63E-06	6	2.72E-07	0.7541	0.6061
condition*frequency	0.0011	4	26,500	736.4949	0
condition*region	3.64E-07	6	6.06E-08	0.1682	0.9852
frequency*region	3.39E-06	24	1.41E-07	0.3917	0.9965
condition*frequency*region	5.73E-07	24	2.39E-08	0.0663	1
Error	50,400	1400	3.60E-07		
Total	0.0564	1469			

Table E. 12. The 3-way ANOVA (condition x frequency band x region) results for the closeness centrality graph metric for change of stimulus correct and erroneous response error rate trials, condition refers to correct and erroneous responses.

Source	Sum sq.	d.f.	Mean Sq.	F	p-value
condition	97.9577	1	97.9577	2,060	6.07E-277
frequency	7,300	4	1,830	38,300	0
region	0.3926	6	0.0654	1.3731	0.222
condition*frequency	237.2655	4	59.3164	1,240	0
condition*region	0.4247	6	0.0708	1.4854	0.1795
frequency*region	0.6712	24	0.028	0.5868	0.9439
condition*frequency*region	0.8165	24	0.034	0.7138	0.8417
Error	66.7227	1400	0.0477		
Total	7,700	1469			

Table E. 13. The 3-way ANOVA (condition x frequency band x region) results for the node degree graph metric for no-change of stimulus correct and erroneous response error rate trials, condition refers to correct and erroneous responses.

Source	Sum sq.	d.f.	Mean Sq.	F	p-value
condition	0.0529	1	0.0529	840.8784	3.45E-145
frequency	28.978	4	7.2445	1.15E+05	0
region	0.0141	6	0.0023	37.2802	4.13E-42
condition*frequency	0.0191	4	0.0048	75.9952	2.31E-58
condition*region	5.85E-04	6	9.74E-05	1.5493	0.1585
frequency*region	0.0379	24	0.0016	25.1323	1.27E-91
condition*frequency*region	0.0043	24	18,100	2.8762	4.52E-06
Error	0.0881	1400	6.29E-05		
Total	29.195	1469			

Table E. 14. The 3-way ANOVA (condition x frequency band x region) results for the node PLV graph metric for no-change of stimulus correct and erroneous response error rate trials, condition refers to correct and erroneous responses.

Source	Sum sq.	d.f.	Mean Sq.	F	p-value
condition	9.16E+03	1	9,160	768.8002	3.09E-135
frequency	1.03E+06	4	2.57E+05	21,600	0
region	12.1455	6	2.0243	0.1699	0.9848
condition*frequency	32,800	4	8,200	688.1884	0
condition*region	16.5657	6	2.761	0.2318	0.9664
frequency*region	44.3526	24	1.848	0.1551	1
condition*frequency*region	39.0231	24	1.626	0.1365	1
Error	16,700	1400	11.9131		
Total	1.09E+06	1469			

Table E. 15. The 3-way ANOVA (condition x frequency band x region) results for the NNND graph metric for no-change of stimulus correct and erroneous response error rate trials, condition refers to correct and erroneous responses.

Source	Sum sq.	d.f.	Mean Sq.	F	p-value
condition	7,630	1	7,630	785.4406	1.45E-137
frequency	8.24E+05	4	2.06E+05	21,200	0
region	10.9839	6	1.8307	0.1885	0.9801
condition*frequency	26,700	4	6,670	686.8691	0
condition*region	14.0471	6	2.3412	0.2411	0.9629
frequency*region	39.5602	24	1.6483	0.1697	1
condition*frequency*region	37.9192	24	1.58	0.1627	1
Error	13,600	1400	9.7115		
Total	8.72E+05	1469			

Table E. 16. The 3-way ANOVA (condition x frequency band x region) results for the NNNPLV graph metric for no-change of stimulus correct and erroneous response error rate trials, condition refers to correct and erroneous responses.

Source	Sum sq.	d.f.	Mean Sq.	F	p-value
condition	19.7718	1	19.7718	1.66E+03	3.73E-240
frequency	1.61E+03	4	403.1293	3.39E+04	0
region	0.808	6	0.1347	11.318	2.23E-12
condition*frequency	43.0839	4	10.771	905.2677	0
condition*region	0.8193	6	0.1366	11.4766	1.45E-12
frequency*region	1.9249	24	0.0802	6.741	5.26E-21
condition*frequency*region	1.978	24	0.0824	6.9268	9.31E-22
Error	16.6574	1400	0.0119		
Total	1.70E+03	1469			

Table E. 17. The 3-way ANOVA (condition x frequency band x region) results for the betweenness centrality graph metric for no-change of stimulus correct and erroneous response error rate trials, condition refers to correct and erroneous responses.

Source	Sum sq.	d.f.	Mean Sq.	F	p-value
condition	0.0016	1	0.0016	3.82E+03	0
frequency	0.1287	4	0.0322	7.75E+04	0
region	2.77E-06	6	4.61E-07	1.1098	0.3542
condition*frequency	0.0038	4	9.55E-04	2.30E+03	0
condition*region	2.67E-06	6	4.46E-07	1.0731	0.3764
frequency*region	4.48E-06	24	1.87E-07	0.4498	0.9901
condition*frequency*region	3.58E-06	24	1.49E-07	0.3592	0.9982
Error	5.81E-04	1400	4.15E-07		
Total	0.1347	1469			

Table E. 18. The 3-way ANOVA (condition x frequency band x region) results for the closeness centrality graph metric for no-change of stimulus correct and erroneous response error rate trials, condition refers to correct and erroneous responses.

Source	Sum sq.	d.f.	Mean Sq.	F	p-value
condition	26.8728	1	26.8728	599.5456	1.69E-110
frequency	3.71E+03	4	927.4708	2.07E+04	0
region	0.1645	6	0.0274	0.6119	0.721
condition*frequency	39.3801	4	9.845	219.6476	2.27E-146
condition*region	0.1912	6	0.0319	0.7109	0.6409
frequency*region	0.4656	24	0.0194	0.4329	0.9925
condition*frequency*region	0.5497	24	0.0229	0.511	0.9762
Error	62.7506	1400	0.0448		
Total	3.84E+03	1469			

Table E. 19. The 3-way ANOVA (condition x frequency band x region) results for the node degree graph metric, condition refers to correct and erroneous responses.

Source	Sum sq.	d.f.	Mean Sq.	F	p-value
condition	26.8728	1	26.8728	599.5456	1.69E-110
frequency	3.71E+03	4	927.4708	2.07E+04	0
region	0.1645	6	0.0274	0.6119	0.721
condition*frequency	39.3801	4	9.845	219.6476	2.27E-146
condition*region	0.1912	6	0.0319	0.7109	0.6409
frequency*region	0.4656	24	0.0194	0.4329	0.9925
condition*frequency*region	0.5497	24	0.0229	0.511	0.9762
Error	62.7506	1400	0.0448		
Total	3.84E+03	1469			

Table E. 20. The 3-way ANOVA (condition x frequency band x region) results for the node PLV graph metric, condition refers to correct and erroneous responses.

Source	Sum sq.	d.f.	Mean Sq.	F	p-value
condition	3.28E+03	1	3.28E+03	354.3127	1.23E-70
frequency	4.93E+05	4	1.23E+05	1.33E+04	0
region	4.95	6	0.825	0.0891	0.9974
condition*frequency	7.72E+03	4	1.93E+03	208.3556	2.68E-140
condition*region	4.5745	6	0.7624	0.0823	0.9979
frequency*region	22.1031	24	0.921	0.0994	1
condition*frequency*region	13.5094	24	0.5629	0.0608	1
Error	1.30E+04	1400	9.2631		
Total	5.17E+05	1469			

Table E. 21. The 3-way ANOVA (condition x frequency band x region) results for the NNND graph metric, condition refers to correct and erroneous responses.

Source	Sum sq.	d.f.	Mean Sq.	F	p-value
condition	2.20E+03	1	2.20E+03	301.0287	3.13E-61
frequency	3.93E+05	4	9.82E+04	1.34E+04	0
region	4.6771	6	0.7795	0.1064	0.9957
condition*frequency	6.18E+03	4	1.54E+03	210.9243	1.09E-141
condition*region	3.8265	6	0.6377	0.0871	0.9975
frequency*region	19.5567	24	0.8149	0.1113	1
condition*frequency*region	12.8859	24	0.5369	0.0733	1
Error	1.03E+04	1400	7.3244		
Total	4.12E+05	1469			

Table E. 22. The 3-way ANOVA (condition x frequency band x region) results for the NNNPLV graph metric, condition refers to correct and erroneous responses.

Source	Sum sq.	d.f.	Mean Sq.	F	p-value
condition	5.1498	1	5.1498	442.3295	1.48E-85
frequency	996.1101	4	249.0275	2.14E+04	0
region	0.1988	6	0.0331	2.8464	0.0093
condition*frequency	3.3208	4	0.8302	71.3087	5.07E-55
condition*region	0.4456	6	0.0743	6.3795	1.22E-06
frequency*region	1.005	24	0.0419	3.5967	1.18E-08
condition*frequency*region	2.5677	24	0.107	9.1895	6.01E-31
Error	16.2995	1400	0.0116		
Total	1.03E+03	1469			

Table E. 23. The 3-way ANOVA (condition x frequency band x region) results for the betweenness centrality graph metric, condition refers to correct and erroneous responses.

Source	Sum sq.	d.f.	Mean Sq.	F	p-value
condition	4.24E-04	1	4.24E-04	999.1543	5.85E-166
frequency	0.0693	4	0.0173	4.08E+04	0
region	8.66E-07	6	1.44E-07	0.34	0.9159
condition*frequency	5.87E-04	4	1.47E-04	345.52	5.93E-207
condition*region	7.49E-07	6	1.25E-07	0.2939	0.94
frequency*region	3.36E-06	24	1.40E-07	0.3294	0.9991
condition*frequency*region	1.89E-06	24	7.86E-08	0.1852	1
Error	5.94E-04	1400	4.25E-07		
Total	0.0709	1469			

Table E. 24. The 3-way ANOVA (condition x frequency band x region) results for the closeness centrality graph metric, condition refers to correct and erroneous responses.

Source	Sum sq	d.f.	Mean sq	F	p-value
trials	1.0996	2	0.5498	38.3142	1.98E-16
frequency	0.0953	6	0.0159	1.1065	0.3569
region	1.77E+03	4	441.8192	3.08E+04	0
trials*frequency	0.0191	12	1.60E-03	0.1107	0.9999
trials*region	0.631	8	0.0789	5.4968	9.97E-07
frequency*region	0.1462	24	0.0061	0.4244	0.9933
trials*frequency*region	0.0539	48	0.0011	0.0782	1
Error	9.0401	630	0.0143		
Total	1.78E+03	734			

Table E. 25. The 3-way ANOVA (trials x frequency band x region) results for the node degree graph metric for trials immediately surrounding change of stimulus trials.

Source	Sum sq	d.f.	Mean sq	F	p-value
trials	0.0031	2	0.0015	46.6485	1.28E-19
frequency	6.51E-04	6	1.08E-04	3.3101	0.0032
region	14.6185	4	3.6546	1.12E+05	0
trials*frequency	7.30E-04	12	6.09E-05	1.8581	0.0366
trials*region	0.003	8	3.80E-04	11.5871	1.99E-15
frequency*region	0.0024	24	1.01E-04	3.0893	1.39E-06
trials*frequency*region	0.0026	48	5.45E-05	1.6625	0.0041
Error	0.0206	630	3.28E-05		
Total	14.6516	734			

Table E. 26. The 3-way ANOVA (trials x frequency band x region) results for the node PLV graph metric for trials immediately surrounding change of stimulus trials.

Source	Sum sq	d.f.	Mean sq	F	p-value
trials	274.1441	2	137.072	36.0256	1.54E-15
frequency	2.1384	6	0.3564	0.0937	0.997
region	2.29E+05	4	5.72E+04	1.50E+04	0
trials*frequency	0.7019	12	0.0585	0.0154	1
trials*region	215.2793	8	26.9099	7.0725	5.68E-09
frequency*region	5.0316	24	0.2096	0.0551	1
trials*frequency*region	2.6215	48	0.0546	0.0144	1
Error	2.40E+03	630	3.8048		
Total	2.32E+05	734			

Table E. 27. The 3-way ANOVA (trials x frequency band x region) results for the NNNPLV degree graph metric for trials immediately surrounding change of stimulus trials.

Source	Sum sq	d.f.	Mean sq	F	p-value
trials	183.7037	2	91.8519	28.602	1.29E-12
frequency	1.9486	6	0.3248	0.1011	0.9963
region	1.84E+05	4	4.59E+04	1.43E+04	0
trials*frequency	0.6311	12	0.0526	0.0164	1
trials*region	193.5199	8	24.19	7.5326	1.24E-09
frequency*region	5.1681	24	0.2153	0.0671	1
trials*frequency*region	2.5946	48	0.0541	0.0168	1
Error	2.02E+03	630	3.2114		
Total	1.86E+05	734			

Table E. 28. The 3-way ANOVA (trials x frequency band x region) results for the NNNPLV graph metric for trials immediately surrounding change of stimulus trials.

Source	Sum sq	d.f.	Mean sq	F	p-value
trials	0.0019	2	9.55E-04	0.6777	0.5081
frequency	0.2181	6	0.0363	25.7938	1.78E-27
region	506.3966	4	126.5992	8.98E+04	0
trials*frequency	0.0799	12	0.0067	4.7275	2.01E-07
trials*region	0.0372	8	0.0046	3.2994	0.0011
frequency*region	0.5303	24	0.0221	15.6815	1.67E-49
trials*frequency*region	0.3057	48	0.0064	4.5199	2.72E-19
Error	0.8878	630	0.0014		
Total	508.4576	734			

Table E. 29. The 3-way ANOVA (trials x frequency band x region) results for the betweenness centrality graph metric for trials immediately surrounding change of stimulus trials.

Source	Sum sq	d.f.	Mean sq	F	p-value
trials	1.05E-05	2	5.25E-06	47.524	5.98E-20
frequency	6.10E-07	6	1.02E-07	0.9206	0.4794
region	0.0338	4	0.0084	7.65E+04	0
trials*frequency	1.52E-07	12	1.27E-08	0.1151	0.9999
trials*region	4.84E-06	8	6.05E-07	5.4774	1.06E-06
frequency*region	7.61E-07	24	3.17E-08	0.2871	0.9997
trials*frequency*region	4.36E-07	48	9.08E-09	0.0822	1
Error	6.95E-05	630	1.10E-07		
Total	0.0338	734			

Table E. 30. The 3-way ANOVA (trials x frequency band x region) results for the closeness centrality graph metric for trials immediately surrounding change of stimulus trials.

Appendix F – ANOVA results of experiment two

This appendix contains the 3 way ANOVA results tables that support chapter 6, graph metric response accuracy precursor and repetition priming-antipriming analysis.

Source	Sum sq.	d.f.	Mean Sq.	F	p-value
condition	0.0332	1	0.0332	0.521	0.4704
frequency	9.48E+03	4	2.37E+03	3.72E+04	0
region	0.2278	6	0.038	0.5962	0.7336
condition*frequency	0.4571	4	1.14E-01	1.79	0.1274
condition*region	0.0744	6	0.0124	0.1947	0.9784
frequency*region	0.5364	24	0.0223	0.351	0.9985
condition*frequency*region	0.1875	24	0.0078	0.1227	1
Error	89.136	1400	0.0637		
Total	9.57E+03	1469			

Table F. 1. The 3-way ANOVA (condition x frequency band x region) results for the node degree graph metric for zero vs high response error rate trials, condition refers to zero and high error rate.

Source	Sum sq.	d.f.	Mean Sq.	F	p-value
condition	0.0036	1	3.60E-03	2.11E+01	4.69E-06
frequency	27.5466	4	6.8867	4.00E+04	0
region	0.0026	6	4.33E-04	2.51	0.0201
condition*frequency	0.0028	4	7.11E-04	4.13	0.0025
condition*region	0.0023	6	3.89E-04	2.2582	0.0357
frequency*region	0.0087	24	3.62E-04	2.10	0.0014
condition*frequency*region	0.0149	24	6.20E-04	3.6033	1.12E-08
Error	0.241	1400	1.72E-04		
Total	27.8226	1469			

Table F. 2. The 3-way ANOVA (condition x frequency band x region) results for the node PLV graph metric for zero vs high response error rate trials, condition refers to zero and high error rate.

Source	Sum sq.	d.f.	Mean Sq.	F	p-value
condition	24	1	24	1.48	0.2233
frequency	1.20E+06	4	301000	1.86E+04	0
region	5.9398	6	0.99	0.0612	0.9991
condition*frequency	108	4	26.9	1.67	0.1553
condition*region	6.3666	6	1.0611	0.0656	0.9989
frequency*region	22.7491	24	0.9479	0.0586	1
condition*frequency*region	17.8262	24	0.7428	0.0459	1
Error	2.26E+04	1400	16.1663		
Total	1.23E+06	1469			

Table F. 3. The 3-way ANOVA (condition x frequency band x region) results for the NNND graph metric for zero vs high response error rate trials, condition refers to zero and high error rate.

Source	Sum sq.	d.f.	Mean Sq.	F	p-value
condition	13.7	1	13.7	1.05	0.3064
frequency	9.59E+05	4	2.40E+05	1.83E+04	0
region	4.5482	6	0.758	0.0578	0.9992
condition*frequency	60.7	4	15.2	1.16	0.3276
condition*region	4.5427	6	0.7571	0.0577	0.9992
frequency*region	15.3276	24	0.6386	0.0487	1
condition*frequency*region	13.9695	24	0.5821	0.0444	1
Error	1.84E+04	1400	13.1119		
Total	9.77E+05	1469			

Table F. 4. The 3-way ANOVA (condition x frequency band x region) results for the NNNPLV graph metric for zero vs high response error rate trials, condition refers to zero and high error rate.

Source	Sum sq.	d.f.	Mean Sq.	F	p-value
condition	0.007	1	7.00E-03	0.673	0.4123
frequency	2780	4	694.4161	66900	0
region	0.6402	6	0.107	10.3	3.71E-11
condition*frequency	0.2729	4	0.0682	6.57	3.08E-05
condition*region	0.2968	6	0.0495	4.76	8.12E-05
frequency*region	2.2471	24	0.0936	9.02	3.06E-30
condition*frequency*region	1.4698	24	0.0612	5.90	1.32E-17
Error	14.5391	1400	0.0104		
Total	2800	1469			

Table F. 5. The 3-way ANOVA (condition x frequency band x region) results for the betweenness centrality graph metric for zero vs high response error rate trials, condition refers to zero and high error rate.

Source	Sum sq.	d.f.	Mean Sq.	F	p-value
condition	1.62E-06	1	1.62E-06	3.41	0.065
frequency	0.1808	4	0.0452	9.52E+04	0
region	2.43E-06	6	4.05E-07	0.8524	0.5295
condition*frequency	1.69E-05	4	4.23E-06	8.92	4.14E-07
condition*region	5.27E-07	6	8.79E-08	0.1851	0.981
frequency*region	3.71E-06	24	1.55E-07	0.3257	0.9992
condition*frequency*region	1.44E-06	24	6.01E-08	0.1265	1
Error	6.65E-04	1400	4.75E-07		
Total	0.1815	1469			

Table F. 6. The 3-way ANOVA (condition x frequency band x region) results for the closeness centrality graph metric for zero vs high response error rate trials, condition refers to zero and high error rate.

Source	Sum sq.	d.f.	Mean Sq.	F	p-value
condition	6.9105	1	6.91	8.97E+01	1.14E-20
frequency	9.67E+03	4	2.42E+03	3.14E+04	0
region	0.3235	6	0.0539	0.6997	0.6499
condition*frequency	15.7819	4	3.95	5.12E+01	2.80E-40
condition*region	0.3602	6	0.06	0.779	0.5864
frequency*region	1.4071	24	0.0586	0.7609	0.7889
condition*frequency*region	1.2757	24	0.0532	0.6899	0.8657
Error	107.8721	1400	0.0771		
Total	9.80E+03	1469			

Table F. 7. The 3-way ANOVA (condition x frequency band x region) results for the node degree graph metric for change of stimulus correct and erroneous response error rate trials, condition refers to correct and erroneous responses.

Source	Sum sq.	d.f.	Mean Sq.	F	p-value
condition	0.0018	1	1.80E-03	4.74	0.0296
frequency	27.9692	4	6.9923	1.82E+04	0
region	0.0038	6	6.28E-04	1.6348	0.1338
condition*frequency	0.013	4	3.20E-03	8.44	9.94E-07
condition*region	0.0081	6	0.0013	3.5067	0.0019
frequency*region	0.0142	24	5.91E-04	1.5397	0.0462
condition*frequency*region	0.0219	24	9.10E-04	2.3708	2.15E-04
Error	5.38E-01	1400	3.84E-04		
Total	28.5695	1469			

Table F. 8. The 3-way ANOVA (condition x frequency band x region) results for the node PLV graph metric for change of stimulus correct and erroneous response error rate trials, condition refers to correct and erroneous responses.

Source	Sum sq.	d.f.	Mean Sq.	F	p-value
condition	1.31E+03	1	1.31E+03	7.04E+01	1.20E-16
frequency	1.25E+06	4	3.11E+05	1.67E+04	0
region	19.9619	6	3.327	0.1782	0.9828
condition*frequency	4.25E+03	4	1.06E+03	5.69E+01	1.48E-44
condition*region	16.1285	6	2.6881	0.144	0.9902
frequency*region	91.9648	24	3.8319	0.2053	1
condition*frequency*region	64.7322	24	2.6972	0.1445	1
Error	2.61E+04	1400	18.6687		
Total	1.28E+06	1469			

Table F. 9. The 3-way ANOVA (condition x frequency band x region) results for the NNND graph metric for change of stimulus correct and erroneous response error rate trials, condition refers to correct and erroneous responses.

Source	Sum sq.	d.f.	Mean Sq.	F	p-value
condition	9.89E+02	1	9.89E+02	6.52E+01	1.47E-15
frequency	9.94E+05	4	2.49E+05	1.64E+04	0
region	18.1426	6	3.0238	0.1991	0.9771
condition*frequency	3.36E+03	4	8.39E+02	5.52E+01	2.68E-43
condition*region	11.6731	6	1.9455	0.1281	0.9929
frequency*region	80.0464	24	3.3353	0.2196	1
condition*frequency*region	48.9467	24	2.0394	0.1343	1
Error	2.13E+04	1400	15.1849		
Total	1.02E+06	1469			

Table F. 10. The 3-way ANOVA (condition x frequency band x region) results for the NNNPLV graph metric for change of stimulus correct and erroneous response error rate trials, condition refers to correct and erroneous responses.

Source	Sum sq.	d.f.	Mean Sq.	F	p-value
condition	0.3192	1	3.19E-01	9.09	0.0026
frequency	2.74E+03	4	684.0694	1.95E+04	0
region	0.9448	6	1.58E-01	4.48	1.66E-04
condition*frequency	0.1416	4	3.54E-02	1.01	0.402
condition*region	0.6756	6	0.1126	3.2069	0.0039
frequency*region	4.5307	24	1.89E-01	5.38	1.59E-15
condition*frequency*region	2.7533	24	1.15E-01	3.27	1.89E-07
Error	49.1586	1400	0.0351		
Total	2.79E+03	1469			

Table F. 11. The 3-way ANOVA (condition x frequency band x region) results for the betweenness centrality graph metric for change of stimulus correct and erroneous response error rate trials, condition refers to correct and erroneous responses.

Source	Sum sq.	d.f.	Mean Sq.	F	p-value
condition	9.98E-05	1	9.98E-05	2.04E+02	2.24E-43
frequency	0.1818	4	0.0454	9.31E+04	0
region	2.09E-06	6	3.48E-07	0.7125	0.6395
condition*frequency	2.19E-04	4	5.48E-05	112.2238	4.83E-83
condition*region	1.70E-06	6	2.83E-07	0.5794	0.747
frequency*region	1.17E-05	24	4.89E-07	1.001	0.4613
condition*frequency*region	6.88E-06	24	2.87E-07	0.587	0.9437
Error	6.84E-04	1400	4.88E-07		
Total	0.1828	1469			

Table F. 12. The 3-way ANOVA (condition x frequency band x region) results for the closeness centrality graph metric for change of stimulus correct and erroneous response error rate trials, condition refers to correct and erroneous responses.

Source	Sum sq.	d.f.	Mean Sq.	F	p-value
condition	0.8093	1	8.09E-01	9.48	0.0021
frequency	1.01E+04	4	2.52E+03	2.95E+04	0
region	0.2737	6	0.0456	0.5342	0.7826
condition*frequency	3.2921	4	0.823	9.6383	1.09E-07
condition*region	0.3606	6	0.0601	0.7039	0.6465
frequency*region	1.0539	24	0.0439	0.5143	0.9752
condition*frequency*region	1.0105	24	0.0421	0.4931	0.9813
Error	119.5478	1400	0.0854		
Total	1.02E+04	1469			

Table F. 13. The 3-way ANOVA (condition x frequency band x region) results for the node degree graph metric for no-change of stimulus correct and erroneous response error rate trials, condition refers to correct and erroneous responses.

Source	Sum sq.	d.f.	Mean Sq.	F	p-value
condition	0.0024	1	2.40E-03	7.56	0.0061
frequency	26.962	4	6.7405	2.09E+04	0
region	0.0115	6	1.90E-03	5.97	3.61E-06
condition*frequency	0.0076	4	1.90E-03	5.87	1.11E-04
condition*region	4.40E-03	6	7.41E-04	2.3014	0.0324
frequency*region	0.0332	24	1.40E-03	4.29	2.84E-11
condition*frequency*region	3.71E-02	24	1.50E-03	4.80	3.00E-13
Error	4.51E-01	1400	3.22E-04		
Total	27.509	1469			

Table F. 14. The 3-way ANOVA (condition x frequency band x region) results for the node PLV graph metric for no-change of stimulus correct and erroneous response error rate trials, condition refers to correct and erroneous responses.

Source	Sum sq.	d.f.	Mean Sq.	F	p-value
condition	2.32E+02	1	2.32E+02	1.13E+01	7.76E-04
frequency	1.32E+06	4	3.30E+05	1.61E+04	0
region	13.3099	6	2.2183	0.1084	0.9955
condition*frequency	9.67E+02	4	241.6483	11.8124	1.94E-09
condition*region	12.2354	6	2.0392	0.0997	0.9964
frequency*region	60.5904	24	2.5246	0.1234	1
condition*frequency*region	41.6948	24	1.7373	0.0849	1
Error	2.86E+04	1400	20.4571		
Total	1.35E+06	1469			

Table F. 15. The 3-way ANOVA (condition x frequency band x region) results for the NNND graph metric for no-change of stimulus correct and erroneous response error rate trials, condition refers to correct and erroneous responses.

Source	Sum sq.	d.f.	Mean Sq.	F	p-value
condition	1.94E+02	1	1.94E+02	1.16E+01	6.70E-04
frequency	1.05E+06	4	2.62E+05	1.57E+04	0
region	9.6288	6	1.6048	0.0964	0.9967
condition*frequency	8.08E+02	4	202.0436	12.1343	1.06E-09
condition*region	7.7375	6	1.2896	0.0774	0.9982
frequency*region	42.5592	24	1.7733	0.1065	1
condition*frequency*region	29.3921	24	1.2247	0.0736	1
Error	2.33E+04	1400	16.6506		
Total	1.07E+06	1469			

Table F. 16. The 3-way ANOVA (condition x frequency band x region) results for the NNNPLV graph metric for no-change of stimulus correct and erroneous response error rate trials, condition refers to correct and erroneous responses.

Source	Sum sq.	d.f.	Mean Sq.	F	p-value
condition	0.013	1	1.30E-02	7.20E-01	0.3962
frequency	2.74E+03	4	685.2103	3.78E+04	0
region	0.3684	6	6.14E-02	3.39	0.0025
condition*frequency	0.2105	4	0.0526	2.9067	0.0207
condition*region	0.6398	6	1.07E-01	5.89	4.41E-06
frequency*region	2.4922	24	1.04E-01	5.74	5.91E-17
condition*frequency*region	2.4567	24	1.02E-01	5.65	1.25E-16
Error	25.349	1400	0.0181		
Total	2.77E+03	1469			

Table F. 17. The 3-way ANOVA (condition x frequency band x region) results for the betweenness centrality graph metric for no-change of stimulus correct and erroneous response error rate trials, condition refers to correct and erroneous responses.

Source	Sum sq.	d.f.	Mean Sq.	F	p-value
condition	7.83E-06	1	7.83E-06	10.7142	0.0011
frequency	0.1897	4	0.0474	6.49E+04	0
region	3.19E-06	6	5.31E-07	0.7269	0.628
condition*frequency	3.16E-05	4	7.90E-06	10.8055	1.25E-08
condition*region	2.01E-06	6	3.34E-07	0.4577	0.8398
frequency*region	6.40E-06	24	2.67E-07	0.3651	0.998
condition*frequency*region	3.74E-06	24	1.56E-07	0.2133	1
Error	1.00E-03	1400	7.31E-07		
Total	0.1908	1469			

Table F. 18. The 3-way ANOVA (condition x frequency band x region) results for the closeness centrality graph metric for no-change of stimulus correct and erroneous response error rate trials, condition refers to correct and erroneous responses.

Source	Sum sq.	d.f.	Mean Sq.	F	p-value
condition	0.6101	1	6.10E-01	1.14E+01	7.59E-04
frequency	9.67E+03	4	2.42E+03	4.51E+04	0
region	0.2588	6	0.0431	0.8053	0.5658
condition*frequency	1.1804	4	2.95E-01	5.51	2.12E-04
condition*region	0.2148	6	0.0358	0.6683	0.6753
frequency*region	0.9465	24	0.0394	0.7362	0.8175
condition*frequency*region	0.5433	24	0.0226	0.4226	0.9937
Error	74.9949	1400	0.0536		
Total	9.75E+03	1469			

Table F. 19. The 3-way ANOVA (condition x frequency band x region) results for the node degree graph metric, condition refers to correct and erroneous responses.

Source	Sum sq.	d.f.	Mean Sq.	F	p-value
condition	8.49E-04	1	8.49E-04	6.43	0.0113
frequency	27.5086	4	6.8772	5.21E+04	0
region	0.0035	6	5.91E-04	4.4801	1.67E-04
condition*frequency	6.33E-04	4	1.58E-04	1.20	0.3097
condition*region	0.0014	6	2.39E-04	1.8073	0.0942
frequency*region	0.0134	24	5.57E-04	4.2182	5.39E-11
condition*frequency*region	0.0136	24	5.67E-04	4.2948	2.74E-11
Error	0.1848	1400	1.32E-04		
Total	27.7269	1469			

Table F. 20. The 3-way ANOVA (condition x frequency band x region) results for the node PLV graph metric, condition refers to correct and erroneous responses.

Source	Sum sq.	d.f.	Mean Sq.	F	p-value
condition	9.49E+01	1	9.49E+01	7.03	0.0081
frequency	1.24E+06	4	3.11E+05	2.30E+04	0
region	13.9302	6	2.3217	0.1721	0.9843
condition*frequency	2.71E+02	4	6.77E+01	5.02	5.13E-04
condition*region	8.9649	6	1.4941	0.1108	0.9952
frequency*region	65.8636	24	2.7443	0.2035	1
condition*frequency*region	28.4926	24	1.1872	0.088	1
Error	1.89E+04	1400	13.4884		
Total	1.26E+06	1469			

Table F. 21. The 3-way ANOVA (condition x frequency band x region) results for the NNND graph metric, condition refers to correct and erroneous responses.

Source	Sum sq.	d.f.	Mean Sq.	F	p-value
condition	6.35E+01	1	63.5	5.74	0.0167
frequency	9.89E+05	4	2.47E+05	2.23E+04	0
region	10.7185	6	1.7864	0.1614	0.9867
condition*frequency	190	4	47.6	4.30	0.0019
condition*region	5.6731	6	0.9455	0.0854	0.9977
frequency*region	48.8898	24	2.0371	0.184	1
condition*frequency*region	20.0769	24	0.8365	0.0756	1
Error	1.55E+04	1400	11.0697		
Total	1.01E+06	1469			

Table F. 22. The 3-way ANOVA (condition x frequency band x region) results for the NNNPLV graph metric, condition refers to correct and erroneous responses.

Source	Sum sq.	d.f.	Mean Sq.	F	p-value
condition	0.0834	1	0.0834	6.17	0.0131
frequency	2,750	4	686.411	5.07E+04	0
region	0.5696	6	0.0949	7.0146	2.28E-07
condition*frequency	0.1101	4	275	2.03	0.0875
condition*region	0.3653	6	609	4.50	1.60E-04
frequency*region	2.8073	24	0.117	8.64	1.00E-28
condition*frequency*region	0.9353	24	0.039	2.88	4.40E-06
Error	18.9487	1400	0.0135		
Total	2.77E+03	1469			

Table F. 23. The 3-way ANOVA (condition x frequency band x region) results for the betweenness centrality graph metric, condition refers to correct and erroneous responses.

Source	Sum sq.	d.f.	Mean Sq.	F	p-value
condition	1.07E-05	1	1.07E-05	2.75E+01	1.79E-07
frequency	0.183	4	0.0457	1.18E+05	0
region	2.28E-06	6	3.79E-07	0.978	0.4386
condition*frequency	2.10E-05	4	5.24E-06	1.35E+01	8.20E-11
condition*region	1.24E-06	6	2.06E-07	0.5305	0.7854
frequency*region	6.81E-06	24	2.84E-07	0.7313	0.8229
condition*frequency*region	2.29E-06	24	9.54E-08	0.2458	0.9999
Error	5.43E-04	1400	3.88E-07		
Total	0.1836	1469			

Table F. 24. The 3-way ANOVA (condition x frequency band x region) results for the closeness centrality graph metric, condition refers to correct and erroneous responses.

Source	Sum sq.	d.f.	Mean Sq.	F	p-value
condition	1.1621	1	1.1621	11.8137	6.05E-04
frequency	9.600	4	2,400	24,400	0
region	1.0716	6	0.1786	1.8156	0.0926
condition*frequency	5.4062	4	1.3516	13.7402	5.40E-11
condition*region	0.5836	6	0.0973	0.9888	0.4312
frequency*region	2.619	24	0.1091	1.1094	0.3243
condition*frequency*region	1.5044	24	0.0627	0.6372	0.9107
Error	137.7113	1400	0.0984		
Total	9,750	1469			

Table F. 25. The 3-way ANOVA (condition x frequency band x region) results for the node degree graph metric for junction trial correct and erroneous response error rate trials. Condition refers to correct and erroneous responses.

Source	Sum sq.	d.f.	Mean Sq.	F	p-value
condition	4.93E-04	1	4.93E-04	0.974	0.3239
frequency	28.171	4	7.0427	1.39E+04	0
region	0.0044	6	7.34E-04	1.4484	0.1927
condition*frequency	0.0117	4	0.0029	5.7713	1.32E-04
condition*region	0.0017	6	2.91E-04	0.5736	0.7516
frequency*region	0.0269	24	0.0011	2.2128	6.67E-04
condition*frequency*region	0.0144	24	5.99E-04	1.1815	0.2479
Error	0.7087	1399	5.07E-04		
Total	28.9397	1468			

Table F. 26. The 3-way ANOVA (condition x frequency band x region) results for the node PLV graph metric for junction trial correct and erroneous response error rate trials. Condition refers to correct and erroneous responses.

Source	Sum sq.	d.f.	Mean Sq.	F	p-value
condition	4.41E+02	1	440.8183	19.1575	1.29E-05
frequency	1.22E+06	4	3.05E+05	1.32E+04	0
region	31.0254	6	5.1709	0.2247	0.9689
condition*frequency	1.74E+03	4	435.8797	18.9428	3.50E-15
condition*region	16.1907	6	2.6985	0.1173	0.9944
frequency*region	123.4775	24	5.1449	0.2236	1
condition*frequency*region	55.2919	24	2.3038	0.1001	1
Error	3.22E+04	1400	23.0103		
Total	1.25E+06	1469			

Table F. 27. The 3-way ANOVA (condition x frequency band x region) results for the NNND graph metric for junction trial correct and erroneous response error rate trials. Condition refers to correct and erroneous responses.

Source	Sum sq.	d.f.	Mean Sq.	F	p-value
condition	3.00E+02	1	300.1235	16.4157	5.37E-05
frequency	9.76E+05	4	2.44E+05	1.33E+04	0
region	26.1901	6	4.365	0.2388	0.9638
condition*frequency	1.20E+03	4	301.1199	16.4702	3.40E-13
condition*region	13.1522	6	2.192	0.1199	0.994
frequency*region	103.7007	24	4.3209	0.2363	1
condition*frequency*region	45.5397	24	1.8975	0.1038	1
Error	2.56E+04	1400	18.2828		
Total	1.00E+06	1469			

Table F. 28. The 3-way ANOVA (condition x frequency band x region) results for the NNNPLV graph metric for junction trial correct and erroneous response error rate trials. Condition refers to correct and erroneous responses.

Source	Sum sq.	d.f.	Mean Sq.	F	p-value
condition	0.5999	1	0.5999	25.1099	6.11E-07
frequency	2.87E+03	4	718.2371	3.01E+04	0
region	3.3988	6	0.5665	23.7105	8.16E-27
condition*frequency	1.4952	4	0.3738	15.6462	1.57E-12
condition*region	2.1925	6	0.3654	15.2948	4.86E-17
frequency*region	8.9532	24	0.373	15.6144	1.68E-56
condition*frequency*region	6.4804	24	0.27	11.3019	1.77E-39
Error	33.4477	1400	0.0239		
Total	2.93E+03	1469			

Table F. 29. The 3-way ANOVA (condition x frequency band x region) results for the betweenness centrality graph metric for junction trial correct and erroneous response error rate trials. Condition refers to correct and erroneous responses.

Source	Sum sq.	d.f.	Mean Sq.	F	p-value
condition	7.38E-06	1	7.38E-06	8.5973	0.0034
frequency	0.1833	4	0.0458	5.34E+04	0
region	7.94E-06	6	1.32E-06	1.5415	0.161
condition*frequency	4.74E-05	4	1.18E-05	13.8006	4.82E-11
condition*region	3.70E-06	6	6.16E-07	0.7182	0.635
frequency*region	2.15E-05	24	8.97E-07	1.0454	0.4024
condition*frequency*region	1.15E-05	24	4.81E-07	0.5607	0.9572
Error	1.20E-03	1400	8.58E-07		
Total	0.1846	1469			

Table F. 30. The 3-way ANOVA (condition x frequency band x region) results for the closeness centrality graph metric for junction trial correct and erroneous response error rate trials. Condition refers to correct and erroneous responses.

Source	Sum sq	d.f.	Mean sq	F	p-value
trials	0.3117	2	0.1558	3.4345	0.0328
frequency	0.1901	6	0.0317	0.6984	0.651
region	5.12E+03	4	1.28E+03	2.82E+04	0
trials*frequency	0.0594	12	0.005	0.1091	0.9999
trials*region	0.8275	8	0.1034	2.2798	0.0207
frequency*region	0.2837	24	0.0118	0.2606	0.9999
trials*frequency*region	0.2474	48	0.0052	0.1136	1
Error	28.5839	630	0.0454		
Total	5.15E+03	734			

Table F. 31. The 3-way ANOVA (trials x frequency band x region) results for the node degree graph metric for trials immediately surrounding change of stimulus trials.

Source	Sum sq	d.f.	Mean sq	F	p-value
trials	0.0071	2	0.0035	91.0446	1.85E-35
frequency	0.0014	6	2.37E-04	6.0799	3.34E-06
region	13.9046	4	3.4762	8.92E+04	0
trials*frequency	8.41E-04	12	7.01E-05	1.7989	0.0449
trials*region	0.0126	8	0.0016	40.5391	3.29E-52
frequency*region	0.0061	24	2.56E-04	6.5624	6.59E-19
trials*frequency*region	0.0036	48	7.57E-05	1.9423	2.26E-04
Error	0.0246	630	3.90E-05		
Total	13.961	734			

Table F. 32. The 3-way ANOVA (trials x frequency band x region) results for the node PLV graph metric for trials immediately surrounding change of stimulus trials.

Source	Sum sq	d.f.	Mean sq	F	p-value
trials	53.5032	2	26.7516	2.2451	0.1068
frequency	4.8398	6	0.8066	0.0677	0.9988
region	6.70E+05	4	1.67E+05	1.41E+04	0
trials*frequency	2.225	12	0.1854	0.0156	1
trials*region	200.8925	8	25.1116	2.1075	0.0332
frequency*region	13.4469	24	0.5603	0.047	1
trials*frequency*region	10.5337	48	0.2195	0.0184	1
Error	7.51E+03	630	11.9155		
Total	6.77E+05	734			

Table F. 33. The 3-way ANOVA (trials x frequency band x region) results for the NNND graph metric for trials immediately surrounding change of stimulus trials.

Source	Sum sq	d.f.	Mean sq	F	p-value
trials	37.294	2	18.647	1.8661	0.1556
frequency	4.3253	6	0.7209	0.0721	0.9986
region	5.35E+05	4	1.34E+05	1.34E+04	0
trials*frequency	1.9136	12	0.1595	0.016	1
trials*region	144.046	8	18.0057	1.8019	0.0738
frequency*region	13.795	24	0.5748	0.0575	1
trials*frequency*region	8.7471	48	0.1822	0.0182	1
Error	6.30E+03	630	9.9927		
Total	5.42E+05	734			

Table F. 34. The 3-way ANOVA (trials x frequency band x region) results for the NNNPLV graph metric for trials immediately surrounding change of stimulus trials.

Source	Sum sq	d.f.	Mean sq	F	p-value
trials	0.0166	2	0.0083	1.6883	0.1857
frequency	0.3813	6	0.0635	12.9475	7.86E-14
region	1.39E+03	4	346.4068	7.06E+04	0
trials*frequency	0.1296	12	0.0108	2.2	0.0105
trials*region	0.0599	8	0.0075	1.5254	0.1449
frequency*region	0.9481	24	0.0395	8.0485	3.24E-24
trials*frequency*region	0.5939	48	0.0124	2.5209	2.24E-07
Error	3.0922	630	0.0049		
Total	1.39E+03	734			

Table F. 35. The 3-way ANOVA (trials x frequency band x region) results for the betweenness centrality graph metric for trials immediately surrounding change of stimulus trials.

Source	Sum sq	d.f.	Mean sq	F	p-value
trials	4.09E-06	2	2.04E-06	6.2652	0.002
frequency	1.44E-06	6	2.40E-07	0.7354	0.6213
region	0.0956	4	0.0239	7.33E+04	0
trials*frequency	3.76E-07	12	3.14E-08	0.0962	1
trials*region	9.85E-06	8	1.23E-06	3.7752	2.45E-04
frequency*region	2.02E-06	24	8.43E-08	0.2585	0.9999
trials*frequency*region	1.72E-06	48	3.58E-08	0.1098	1
Error	2.05E-04	630	3.26E-07		
Total	0.0958	734			

Table F. 36. The 3-way ANOVA (trials x frequency band x region) results for the closeness centrality graph metric for trials immediately surrounding change of stimulus trials.

Source	Sum sq	d.f.	Mean sq	F	p-value
trials	25.7128	2	12.8564	343.2672	1.48E-101
frequency	1.0829	6	0.1805	4.819	8.04E-05
region	4.57E+03	4	1.14E+03	3.05E+04	0
trials*frequency	1.1569	12	0.0964	2.5742	0.0024
trials*region	56.8696	8	7.1087	189.8035	2.81E-162
frequency*region	2.4714	24	0.103	2.7494	1.80E-05
trials*frequency*region	2.8065	48	0.0585	1.5611	0.0107
Error	23.5954	630	0.0375		
Total	4.69E+03	734			

Table F. 37. The 3-way ANOVA (trials x frequency band x region) results for the node degree graph metric for trials immediately surrounding junction trials.

Source	Sum sq	d.f.	Mean sq	F	p-value
trials	0.0337	2	0.0169	36.147	1.38E-15
frequency	0.0067	6	0.0011	2.3966	0.0268
region	13.6453	4	3.4113	7.32E+03	0
trials*frequency	0.0111	12	9.24E-04	1.9826	0.0235
trials*region	0.0816	8	0.0102	21.8768	1.67E-29
frequency*region	0.0459	24	0.0019	4.1056	4.37E-10
trials*frequency*region	0.0429	48	8.95E-04	1.9189	2.93E-04
Error	0.2933	629	4.66E-04		
Total	14.176	733			

Table F. 38. The 3-way ANOVA (trials x frequency band x region) results for the node PLV graph metric for trials immediately surrounding junction trials.

Source	Sum sq	d.f.	Mean sq	F	p-value
trials	4.67E+03	2	2.33E+03	269.9818	2.08E-85
frequency	35.2516	6	5.8753	0.6797	0.6662
region	5.63E+05	4	1.41E+05	1.63E+04	0
trials*frequency	39.7242	12	3.3103	0.3829	0.9696
trials*region	1.49E+04	8	1.87E+03	215.8976	6.45E-175
frequency*region	113.1302	24	4.7138	0.5453	0.9631
trials*frequency*region	123.1238	48	2.5651	0.2967	1
Error	5.45E+03	630	8.6444		
Total	5.88E+05	734			

Table F. 39. The 3-way ANOVA (trials x frequency band x region) results for the NNND graph metric for trials immediately surrounding junction trials.

Source	Sum sq	d.f.	Mean sq	F	p-value
trials	3.42E+03	2	1.71E+03	226.4783	7.76E-75
frequency	29.9781	6	4.9964	0.6614	0.6809
region	4.51E+05	4	1.13E+05	1.49E+04	0
trials*frequency	31.3927	12	2.6161	0.3463	0.9801
trials*region	1.14E+04	8	1.43E+03	188.8057	9.04E-162
frequency*region	101.1515	24	4.2146	0.5579	0.9575
trials*frequency*region	103.412	48	2.1544	0.2852	1
Error	4.76E+03	630	7.5543		
Total	4.71E+05	734			

Table F. 40. The 3-way ANOVA (trials x frequency band x region) results for the NNNPLV graph metric for trials immediately surrounding junction trials.

Source	Sum sq	d.f.	Mean sq	F	p-value
trials	0.0056	2	0.0028	0.1347	0.874
frequency	2.2841	6	0.3807	18.4365	8.59E-20
region	1.47E+03	4	367.1034	1.78E+04	0
trials*frequency	2.7375	12	0.2281	11.0483	3.47E-20
trials*region	4.9273	8	0.6159	29.8287	1.29E-39
frequency*region	7.0978	24	0.2957	14.3227	2.86E-45
trials*frequency*region	9.1147	48	0.1899	9.1964	9.21E-47
Error	13.0085	630	0.0206		
Total	1.51E+03	734			

Table F. 41. The 3-way ANOVA (trials x frequency band x region) results for the betweenness centrality graph metric for trials immediately surrounding junction trials.

Source	Sum sq	d.f.	Mean sq	F	p-value
trials	2.59E-04	2	1.29E-04	450.3852	3.51E-122
frequency	8.54E-06	6	1.42E-06	4.9522	5.76E-05
region	0.0884	4	0.0221	7.70E+04	0
trials*frequency	1.03E-05	12	8.55E-07	2.9764	4.66E-04
trials*region	4.59E-04	8	5.73E-05	199.6249	3.58E-167
frequency*region	1.66E-05	24	6.92E-07	2.409	2.11E-04
trials*frequency*region	2.22E-05	48	4.63E-07	1.6107	0.0068
Error	1.81E-04	630	2.87E-07		
Total	0.0894	734			

Table F. 42. The 3-way ANOVA (trials x frequency band x region) results for the closeness centrality graph metric for trials immediately surrounding junction trial.