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Samantha J. Broyd
University of Wollongong, sbroyd@uow.edu.au

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**ELECTROPHYSIOLOGICAL CORRELATES OF
INTERFERENCE CONTROL IN THE ERIKSEN TASK**

A thesis submitted in fulfilment of the requirements
for the award of the degree

DOCTOR OF PHILOSOPHY

from the

UNIVERSITY OF WOLLONGONG

by

SAMANTHA J. BROYD, BPsyc(Hons)

SCHOOL OF PSYCHOLOGY

2008

I, Samantha J. Broyd, declare that this thesis, submitted in fulfilment of the requirements of the award of Doctor of Philosophy, in the School of Psychology, University of Wollongong, is wholly my own work unless otherwise referenced or acknowledged. The document has not been submitted for qualifications at any other academic institution.

Samantha J. Broyd

21st July 2008

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Abstract

This thesis examined conflict monitoring in the Eriksen task in which participants must respond to a centrally positioned target arrow and ignore simultaneously presented distractors that flank the target. Distractors were either associated with a response congruent to the target, in conflict with the target, or, in a neutral condition, not associated with a response, instead producing only perceptual interference. This thesis extended on previous Eriksen research by systematically investigating the effect of varying the level of response conflict and task difficulty on stimulus processing in six studies and clarifying the functional role of ERP components elicited in the Eriksen task. Specifically, this was achieved by (a) varying the number of flanking distractors and, (b) the level of response conflict by using different permutations of incongruent distractors, (c) reducing target stimulus perceptibility through degradation, (d) utilising both valid and invalid information to increase response preparation and make conflict monitoring more difficult, and (e) providing feedback in a speeded version of the task. In all six studies, two N2 components were clearly delineated – the first of which was increased to stimuli requiring enhanced feature detection processes (N2a), while the second N2 component (N2b) was consistently observed to increase following the detection of response conflict. The P3 component, rarely considered in the Eriksen paradigm, was reduced at parietal sites and increased in latency as the discriminability of the target amongst the distractors became more difficult. The results suggest that the P3 component may reflect stimulus evaluation processes and equivocation related to the ease of target identification and concurrent response selection processes imperative for accurate task performance. This thesis also utilised digital filtering to clarify time-domain ERP results in terms of the relative contributions of activity in the alpha, theta and delta frequency ranges. Event-related theta oscillations contributed significantly to the morphology of the two N2 components reflecting allocation of focused attentional resources following the detection of perceptual (theta N2a) or response conflict (theta N2b). Activity in both theta and delta frequency ranges was robustly observed to contribute to the P3 component. An increased theta response at frontal sites was observed along with increases in task difficulty likely indexing the activation of anterior attentional resources. The results also suggest that the parietal delta P3 component reflects a refined form of equivocation, sensitive to the perceptibility of the target, and concomitant with the relative ease of accurate response selection. This thesis has clarified successful conflict monitoring and task performance in the Eriksen task, and the relationship with stimulus-locked ERP components in the time and frequency domains. The results suggest that the second frontally maximal N2

component reflects successful conflict monitoring, while the P3 component most probably reflects equivocation arising from difficult target identification and accurate response selection, rather than response conflict per se.

Overview

The successful inhibition of distracting or task-irrelevant information and the selective attention to task-relevant information is pertinent for goal-directed activity, and more generally a requisite for socially appropriate, adaptive and efficacious behaviour in everyday life. For example, distracting and irrelevant sensory information must be inhibited when one is driving, attempting to cross a road, or even when one is attempting to learn in a classroom or lecture theatre. Interference control involves not only the suppression of task-irrelevant sensory/cognitive information, but also the inhibition of inappropriate and conflicting response tendencies. Surprisingly, the area of interference control and associated conflict monitoring has received rather limited scientific attention. It was, therefore, the primary aim of this thesis to systematically investigate brain electrical activity correlates of interference control. In particular, this thesis aimed to clarify the functional interpretations of the N2 and P3 event-related potential (ERP) components, with a lesser focus on the earlier, sensory N1 and P2 components. To accomplish this, this thesis employed the Eriksen flanker task as a measure of interference control and conflict monitoring, in which distracting sensory information is associated with a conflicting and task-irrelevant response that must be inhibited and replaced with the correct target response. Specifically, this thesis experimentally manipulated the perceptual characteristics of the stimuli to increase conflict monitoring and interference control requirements by (a) varying the number of distractors (Study 1, Chapter 4), (b) varying the level of response conflict created by the incongruent distractors (Study 2, Chapter 5), and (c) degrading the target stimulus (Study 3, Chapter 6; Study 4, Chapter 7). Study 5 (Chapter 8) investigated the relationship between response preparation and conflict monitoring by introducing informative cues that either correctly or incorrectly identified the target in the subsequent trial. Finally, task difficulty was increased in a speeded version of the Eriksen task in which an adaptive algorithm provided feedback about individual response times (Study 6, Chapter 9).

A secondary aim of this thesis was to investigate the contributions of event-related alpha (8-13 Hz), theta (4-8 Hz) and delta (0.1-4 Hz) oscillations to the time-domain N2 and P3 components. These underlying frequency are an important consideration for electrophysiological research, and provides an invaluable insight into the underlying neural and functional mechanisms that give rise to the ERP. Frequency-specific event-related oscillations are sensitive to experimental manipulations of cognitive processes, and underlie variations in the morphology of the time-domain ERP components.

Indeed, event-related oscillations highlight the heterogeneous nature and multi-frequency component structure of time-domain ERP components, particularly the P3. Event-related theta oscillations are thought to contribute primarily to the time-domain N2 component, while the morphology of the P3 component is primarily a function of event-related theta and delta components. In accord with the notion that ERPs reflect the superposition of time-locked EEG rhythms, and as part of a subsidiary investigation, this thesis explored the relative contribution of event-related alpha, theta and delta oscillations to the N2 and P3 components elicited in the Eriksen task.

The first three chapters of this thesis provide a comprehensive literature review on event-related potentials (Chapter 1), inhibition, interference control and conflict monitoring (Chapter 2), and ERP indices of these psychological processes (Chapter 3).

Study 1 (Chapter 4) investigated the effect of varying the number of distractors from zero, to two to four in a simple Eriksen task design in twenty-two adult participants. The inclusion of a neutral stimulus allowed independent comparison and topographic analysis of ERP components associated with the facilitatory effects of congruent distractors and the interference created by incongruent distractors. Target-alone (zero distractors) stimuli were included to ascertain the level of perceptual interference created by the distractors. ERP components measured in the first four studies of this thesis were the N1, P2a, P2b, N2a, N2b and P3, while all but the P2a component were also examined in the final two studies of this thesis. Congruent distractors were found to facilitate RT, while an interference effect of the incongruent distractors (incongruent > neutral) on task performance was evident both in reaction time (RT) data and error rate. In accord with previous research in the Eriksen task, two N2 components were elicited. The first, the N2a, was largest to neutral stimuli, thought to reflect the perceptual disparity of neutral distractors when compared with the prevailing arrow features that comprise the congruent and incongruent stimulus types. The second component, the N2b was enhanced to incongruent stimuli, and likely reflects the detection of response conflict. Both the N2a and N2b were clearly differentiated in the theta frequency. Theta N2b increased to incongruent stimuli signifying the activation of cognitive control mechanisms. The perceptual novelty of the neutral distractors relative to the arrows in congruent and incongruent stimuli was thought to have resulted in increased time-domain P3 amplitudes. Although, increased stimulus evaluation of incongruent stimuli was evidenced by longer P3 latencies. The morphology of the P3 component was largely a function of theta and delta oscillations, where delta P3 showed close correspondence with time-domain findings. In contrast,

increased frontal theta P3 amplitudes to incongruent stimuli suggested the activation of anterior attentional resources with increases in task difficulty to facilitate accurate responses.

Study 2 (Chapter 5) aimed to replicate and extend upon the findings of the first study, and to investigate the effect of varying the level of response conflict through permutations of the distractors to create two additional stimulus types of high and low incongruence. A topographic analysis of ERP data from twenty-two participants compared neutral stimuli with congruent stimuli and all three levels of incongruent stimuli, while an additional analysis compared completely incongruent with highly incongruent stimuli, which were in turn compared with stimuli of low incongruence. Increases in the level of response conflict were concomitant with increased RTs, error rates and N2b amplitude. The feature detection mechanism activated by perceptual deviance and reflected in the N2a as proposed in Study 1 was confirmed in Study 2. Increases in the allocation of attentional resources related to perceptual deviance was highlighted by a larger theta N2a response to neutral stimuli, while theta N2b was again increased to incongruent stimuli reflecting an increase in attentional control. Furthermore, P3 was reduced to all levels of incongruent stimuli, although larger to completely incongruent than highly incongruent stimuli. These findings, along with those of Study 1, suggest that P3 may reflect the ease with which the target may be identified amongst the simultaneously presented distractors. Similarly, delta P3 was reduced to all incongruent stimulus types, and may reflect a refined version of this equivocation. In contrast, theta P3 was again increased at frontal sites for completely incongruent and highly incongruent stimuli, reaffirming the activation of anterior attentional resources with increased task difficulty.

The effect of target degradation on conflict monitoring processes was investigated in Study 3 (Chapter 6), through the random removal of 50% of the pixels that made up the target and their relocation in the surrounding target space. ERP and behavioural data from twenty-five adults to equiprobable degraded and non-degraded trials were compared for target-alone, neutral, congruent and incongruent stimuli. Characteristic facilitation effects of the congruent distractors, and interference created by the incongruent distractors, were evident in error rate and RT data. Target degradation increased RTs and error rates, particularly for incongruent stimuli. However, despite strong behavioural findings there was little evidence of an effect of degradation on ERP components, and curiously, some of the seemingly robust effects of the distractors disappeared. Specifically, although the N2a component was increased to neutral

stimuli, it was not modulated by target degradation. Further, in contrast to predictions, the N2b and P3 components were not affected by target degradation nor did they show previously observed effects to the incongruent distractors, although P3 was increased at frontocentral sites to incongruent stimuli. Despite limited ERP differences between stimulus types in the time-domain, theta N2a was increased to neutral stimuli, while theta N2b was increased to incongruent stimuli reflecting attentional control following the detection of perceptual deviance (N2a) and response conflict (N2b). Further, theta P3 was increased at central sites, while a reduced delta P3 in the degraded condition suggests this component is sensitive to target perceptibility. The results of this study were rather curious, and were in contrast to several findings in Study 1 and 2. It is feasible that the random presentation of degraded trials amongst non-degraded trials may have required participants to alternate between two different task strategies resulting in a blurring of ERP effects. This possibility is examined in Study 4.

Accordingly, Study 4 (Chapter 7) aimed to elucidate potential effects of target degradation on response conflict processes by presenting equiprobable degraded stimuli in a blocked design. Forty adults took part in this study; the order of presentation of degraded stimulus blocks was counterbalanced across participants such that twenty participants first received two blocks of non-degraded stimuli, and twenty participants first received two blocks of degraded stimuli. As it was hypothesised that the order of presentation might influence task performance due to the perceptually demanding nature of the degraded condition, behavioural analyses and topographic analysis of ERP components compared each stimulus type in both degradation conditions, taking block order into consideration. Congruent distractors were again observed to facilitate task performance. In contrast, RT and error rates were greater to incongruent relative to neutral stimuli, and increased for degraded compared with non-degraded target-alone stimuli. Moreover RT was increased for degraded neutral stimuli when compared to degraded congruent and incongruent stimulus types. In this study, aside from the initial stimulus register, the N1, all other ERP components were sensitive to target degradation. On degraded trials, feature detection processes were delayed and conflict monitoring enhanced, evidenced by a delayed N2a and an increased N2b respectively. Further, reduced target perceptibility on degraded trials elicited smaller P3 amplitudes, including to target-alone stimuli, corroborating previous evidence suggesting this component is sensitive to the ease with which the target may be accurately identified. A delayed P3 peak to incongruent stimuli reflected augmented stimulus evaluation processes activated by the perceptual complexity of this stimulus type. Corroborating evidence of a perceptual deviance and

conflict monitoring interpretation of the N2a and N2b components respectively was also found in this study. A larger theta N2a highlighted increased attentional control for neutral stimuli, particularly in the degraded condition, while theta N2b was enhanced to incongruent stimuli signifying the activation of a cognitive control mechanism with response conflict. Further, larger time-domain P3 amplitudes at frontocentral sites to incongruent stimuli point to the activation of increased attentional control pertinent for accurate response selection. This frontocentral activation was correlated with similar increases in theta and delta P3, while delta P3 was also reduced to congruent and incongruent stimuli.

As the first four studies manipulate the perceptual characteristics of the Eriksen stimuli, it was the aim of Study 5 (Chapter 8) to investigate task difficulty in the context of varying levels of preparatory processing on subsequent conflict monitoring processes and interference control. In this study, thirty adult participants were presented with either a Specific cue, which correctly predicted the subsequent target stimulus on 80% of trials (Valid cue; and therefore incorrectly predicted the target on 20% of trials; Invalid cue), or a Non-specific cue that provided no information about the ensuing stimulus. It was hypothesised that Valid cues would facilitate preparation of the correct response and therefore reduce the level of conflict monitoring required on the subsequent trial. In contrast, preparatory processes associated with Invalid cues were expected to require suppression, increasing the level of response inhibition required on the subsequent trial, and influencing associated conflict monitoring processes. Non-specific cues were introduced as a control condition, and were presented on one third of the total number of trials. An enhanced CNV following Specific cues suggested that these cues effectively engaged preparatory processes. Invalid and Non-specific cues enhanced the N2a component to neutral stimuli, indicative of a feature detection mechanism activated by perceptual conflict between the cue and target. Theta N2a was similarly increased to neutral stimuli, and especially so following Invalid cues. Valid cues tended to reduce the N2b component, which again was largest to incongruent stimuli, while theta N2b was enhanced to incongruent stimuli, most likely reflecting the activation of cognitive control following the detection of response conflict. The time-domain P3 was reduced to incongruent stimuli and following Non-specific cues suggesting that this component does reflect uncertainty about accurate response selection. Interestingly, although theta P3 was larger at frontal sites to incongruent stimuli, a global reduction was observed to Invalidly cued incongruent stimuli. Further, delta P3 was reduced to incongruent stimuli, while a central increase was observed to

Invalidly cued neutral stimuli substantiating a perceptual rather than inhibitory interpretation of this component.

The final study of this thesis (Chapter 9) aimed to increase task difficulty through the introduction of a speeded response requirement, and to investigate successful and unsuccessful conflict monitoring on correct and incorrect trials respectively. In this study, an adaptive algorithm dynamically adjusted the performance of twenty-one adult participants so that the speeded response requirement was upheld, and a 20% error rate achieved. In fact, this error rate was only achieved for incongruent stimuli, and subsequent ERP analysis compared the effect of trial accuracy on the processing of this stimulus type. RTs were longer on incorrect trials, while typical effects of facilitation and interference of the congruent and incongruent distractors were observed, although the interference effect (incongruent > neutral RT) was reduced on incorrect trials. The N2a component was the first temporally to demonstrate sensitivity to response accuracy, reduced in amplitude on incorrect trials. This component was also enhanced to neutral stimuli, illustrating the activation of a feature detection mechanism with perceptual conflict. Further, N2b amplitude increased with the detection of response conflict, reflecting the activation of conflict monitoring processes. The aforementioned time-domain N2a and N2b effects were also evident in event-related theta oscillations (theta N2a and theta N2b respectively). Moreover, the time-domain N2b component was enhanced at frontal sites and increased in latency on incorrect trials. Theta N2b was also increased to incongruent stimuli, and incorrect compared with correct trials. As mean RT preceded the N2b peak on incorrect trials, this suggested that conflict monitoring processes were engaged neither sufficiently nor with enough speed, thus failing to ensure accurate response selection. Similarly subsequent stimulus evaluation processes were belated on incorrect trials concomitant with a delayed P3, the peak of which also fell after mean RT. On correct trials, P3 amplitudes were increased to congruent and target-alone relative to neutral stimuli, reflecting an association between the magnitude of this components and the ease of target identification. Importantly, although P3 latency was increased to correct incongruent stimuli, it peaked before the mean RT, reflecting efficacious stimulus evaluation. On correct incongruent trials, theta P3 was increased at frontal sites while delta P3 was reduced, highlighting the multicomponent structure of the P3 component. Frontal theta P3 likely reflects an anterior attentional system activated by task difficulty, while delta P3 reflects equivocation dependent on the difficulty of target identification.

An overall summary of the findings of this thesis, and suggestions for future research, are delimited in Chapter 10. Functional interpretations of ERP components elicited in the Eriksen task are discussed, with particular focus given to the N2a, N2b and P3 components. Further, the contribution of event-related alpha, theta and delta oscillations to the time-domain N2a, N2b and P3 components are also considered with reference to the functional interpretations of event-related oscillations in each activity band. It is concluded that the N2a component reflects feature detection processes activated by perceptual conflict, while the N2b component is an index of conflict monitoring on successful trials. Importantly, each study of this thesis aimed to illuminate a functional interpretation of the P3 component in the context of an Eriksen task. The results suggest that P3 reflects the careful identification and considered evaluation of the target, amongst competing and contemporaneous distractors, influencing accurate response selection and modulated by target perceptibility and task difficulty.

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Abbreviations used in the text

ACC	Anterior cingulate cortex
A/D	Analog to Digital
AD/HD	Attention-deficit/Hyperactivity Disorder
ANOVA	Analysis of Variance
BOLD	Blood oxygen level dependent
CNS	Central Nervous System
CNV	Contingent Negative Variation
CRN	Correction-related Negativity
CSD	Current Source Density
dB	Decibels
DC	Direct Current
Df	Degrees of Freedom
DLPFC	Dorsolateral prefrontal cortex
EEG	Electroencephalogram
EMG	Electromyogram
EOG	Electrooculogram
ERN	Error-related Negativity
ERP	Event-related Potential
fMRI	Functional Magnetic Resonance Imaging
FT	Fourier Transform
Hz	Hertz in cycles per second
ICA	Independent Component Analysis
ISI	Inter-stimulus Interval
LPC	Late Positive Complex
LRP	Lateralised Readiness Potential
MMN	Mismatch Negativity
MPN	Movement preceding Negativity
Ne	Error Negativity
OCD	Obsessive Compulsive Disorder
OR	Orienting Response
PCA	Principal Component Analysis
Pe	Error Positivity
PN	Processing Negativity
RT	Reaction time
S1	Stimulus 1
S2	Stimulus 2
SD	Standard Deviation
SOA	Stimulus Onset Asynchrony
SPN	Stimulus-preceding Negativity
SSRT	Stop-signal Reaction time
STFT	Short-time Fourier Transform
SW	Slow wave
TTI	Target-to-target Interval
WT	Wavelet Transform