Exploring the Mechanisms Underlying Conflict Adaptation

By

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Abstract

Human cognition is remarkedly flexible and can inhibit unwanted actions as well as alter behaviours to successfully navigate rapidly changing social environments. Laboratory tasks such as the Stroop test can gauge one's ability to suppress task-irrelevant information on a given trial. Yet the congruency-sequencing effect (Gratton et al., 1992) reveals that such performance is not constant throughout the task and fluctuates on a trial-by-trial basis. The reduced Stroop effect following an incongruent trial is considered an adaptative behaviour intended to minimise the experience of subsequent conflict and, therefore, is also known as conflict adaptation. Although well documented, the precise mechanisms underpinning conflict adaptation are unknown, although three key accounts emerge: Conflict Monitoring (Botnivick et al., 2001); Repetition Expectancy (Gratton et al., 1992; Egner, 2007), and Feature-Integration (Hommel, 1998; Hommel et al., 2004). The first two are top-down accounts that suggest the dorsolateral prefrontal cortex (DLPFC) is responsible for attentional adjustments to facilitate successful performance. They differ in that the Conflict-Monitoring model is a reactive account that proposes the DLPFC is recruited via conflict detection from the anterior cingulate cortex (ACC) and therefore, upregulation of attentional control towards either the task-relevant or task-irrelevant stimulus is determined by the conflict experienced on the previous trial. Whereas the Repetition Expectancy Model is a proactive account that proposes an anticipatory recruitment of the DLPFC via gated-dopamine release (Braver et al., 2007). Finally, the Feature-Integration account suggests that the task-relevant and task-irrelevant stimulus on each trial form an episodic memory file and it is the complete or partial repetition of one or both the stimulus features that produces the congruency-sequencing effect.

To isolate the top-down component of the congruency-sequencing effect, Chapter Three designed a feature-repetition free Stroop task and reported a reliable congruency-sequencing effect (although this was smaller than the Stroop task which included feature-repetitions). As such, it was concluded

that feature-repetitions can indeed produce and magnify congruency-sequencing effects, and once removed, a reliable top-down component remains. Due to known accelerated age-related cognitive decline in the DLPFC, it was predicted that older adults would exhibit impaired conflict adaptation. In contrast to predictions, no age-related differences in the congruency-sequencing effect were reported.

After establishing a top-down role in the congruency-sequencing effect, Chapter Four sought to use transcranial direct current stimulation (tDCS) to provide causal evidence for the involvement of the left DLFPC in producing conflict adaptation. In contrast to predictions, the magnitude of the congruency-sequencing effect did not differ between stimulation of the DLPFC or the primary motor cortex. Whilst various possibilities for this were discussed, it was concluded that tDCS did not modulate the functioning of the DLPFC, and future studies should return to behavioural paradigms to dissociate the mechanisms underlying conflict adaptation.

Next, Chapter Five used behavioural manipulations to dissociate between the two top-down accounts of conflict adaptation: proactive or reactive control. This involved the use of training and test phases to compare the magnitude of the congruency-sequencing effect during periods of high probability that the congruency of the previous trial would repeat against neutral test phases with equal probability of congruency-level repetitions. The results revealed that younger adults preferentially use proactive control processes during the Stroop task, consistent with findings from other cognitive paradigms.

Finally, this thesis introduced a novel classification system (first reported in Chapter Three) to try and differentiate how the congruency-sequencing effect is produced. In addition to providing more subtle measures of conflict adaptation, it suggests that whilst adaptation does occur following conflict (an incongruent trial), perhaps complementary stimulus (congruent trials) provides a more salient stimulus from which to adapt.

Acknowledgements

Little did I know that my undergraduate dissertation would be the start of a five-year journey with Dr. Craig McAllister ending here, with a 50,000-word thesis. Thank you for all your kindness and support, I am extremely grateful for all you have taught me along the way. Of course, the greatest lesson so far has been an understanding of rudimentary Scottish, a language I hope one day to master. That, and not to use apples and oranges when providing examples. I am glad there have been so many laughs along the way.

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Chapter One: General Introduction

Human cognition is remarkedly flexible and can inhibit unwanted actions as well as alter behaviours to successfully navigate rapidly changing social environments. Such hallmarks of effective human behaviour are derivatives of cognitive control, specifically, cognitive inhibition and conflict adaptation (Botvinick et al., 2001, Miller and Cohen, 2001, Ridderinkhof et al., 2011) The exact mechanisms and processes that allow for successful behaviour following conflicting stimuli are unclear. Therefore, this thesis will use the congruency-sequencing effect (Gratton et al., 1992) as a behavioural index to investigate the precise mechanisms underpinning conflict adaptation. Specifically, Chapter Three will investigate the top-down component of the congruency-sequencing effect and Chapter Four will seek causal evidence for the involvement of a brain region (the left dorsolateral prefrontal cortex (DLFPC)) underlying conflict adaptation. Finally, Chapter Five will try to differentiate between two key strategies that could underpin conflict adaptation: proactive or reactive control.

1.1. Background

The earliest written reference to the brain was in the 17th century B.C. on an Egyptian medical papyrus that details the symptoms and diagnosis of skull fractures (Kandel et al., 2013). Despite their knowledge of the brain, the Ancient Egyptians believed the heart to be the site at which thoughts and feelings were instigated and it was considered the essence of a person's being (Santoro et al., 2009). They believed that upon death, the God of Mummification would weigh the heart against a feather to determine their afterlife in a ceremony called 'the weighing of the heart'. This cardiocentric view continued through to the times of Ancient Greece and was supported by the likes of Greek philosopher, Aristotle. However, it did not go unchallenged and Greek physician Hippocrates of Kos proposed an encephalocentric view that the brain was the key to intelligence and feelings. Observed changes in consciousness and sensation arising from head injuries drew support from Greek philosopher Plato

(Santoro et al., 2009). Galen (129-216 AD) solidified this view with his anatomical research which demonstrated that nerves originate in the brain and spinal cord (Kandel et al., 2013).

By the 19th century, Viennese physician Franz Joseph Gall reasoned that the cerebral cortex is not one single unit, but instead comprises of at least 27 separate units corresponding to specific functions, such as destructiveness, spirituality, and generosity. Although Gall's specific functional mapping was later discredited, Broca and Wernicke continued this line of research and localised regions for language which was furthered by the cellular work of Ramón y Cajal. In the early 20th century, Brodmann categorised the cerebral cortex into 52 functional areas based upon the structure, layering and connectivity of cells, a system which is still used today. This formed the basis and thinking behind an overwhelming wealth of evidence for the localisation of specific functions and is the central premise behind by the observation and manipulation of behaviour to infer the involvement and relative health of specific brain regions that underpins psychology and behavioural neuroscience.

In 1869, Franciscus Donders was the first to use reaction times to infer cognitive processing. He reported that the simple reaction times to a stimulus were longer when a decision was required to first select the appropriate response before execution (choice reaction time) (Donders, 1896). By subtracting choice reaction times from simple reaction times, he created an objective measure for decision making and thought processing. Reaction times continued to be used as a behavioural measure to study decision making under specific contexts such as in the presence of response conflict.

Response conflict arises from a situation or stimuli causing co-activation of two response pathways, of which only one can be executed (MacLeod, 1991, Stroop, 1935). In everyday life, imagine a driving scenario whereby you are stationary at the traffic lights and someone steps out to cross the road just as the lights turn green. There is activation of the 'go' response associated with the green light, whilst in parallel, there is also activation of the 'stop' response associated with the pedestrian. It is not

possible to execute both responses, and therefore, the competition between the 'go' and 'stop' response must be resolved. The automatic and more frequently executed 'green light, go' response must be overridden to avoid the undesirable outcome of hitting the pedestrian.

There are many behavioural tasks to explore conflict in a laboratory setting, most famous of which is the Stroop task (Stroop, 1935). Over a series of experiments, participants were presented with the word of a colour (red, blue, green, brown and purple) that was printed in either the same or different coloured ink, see Figure 1A. They were instructed to say the ink colour the word was printed in "as quickly as possible and to correct all errors" (Stroop, 1935). When presented with such stimuli, the natural tendency is to read the word, therefore, this creates conflict between the prepotent response and the task instruction.

There are two aspects to a Stroop stimulus: the task-relevant stimulus, which corresponds to the task instruction, in this instance, the ink colour; and the task-irrelevant stimulus which is the word itself. On some (congruent) trials there is agreement between the task-relevant and task-irrelevant stimuli such as when presented with the word red printed in red ink (RED_{red}), whereby both will lead to the same, correct response. Whereas on other (incongruent) trials, such as the word red printed in blue ink (RED_{blue}), conflict arises because the response associated with the task-relevant stimuli is different to that of the task-irrelevant stimuli, see Figure 1A. Therefore, the automatic reading response associated with the task-irrelevant stimulus must be overcome to produce the correct response associated only with the task-relevant stimulus. As such, the increased response times seen on incongruent compared to congruent trials, known as the 'congruency effect' or 'Stroop effect', is thought to represent the additional processing time required to resolve the response conflict (Stroop, 1935). This would have be considered by Donders (1869) to reflect the greater complexity and additional processing required for incongruent trials.

1.2. Dimensional Overlap Model

Processing of Stroop stimuli can most easily be explained through a parallel distributed processing (PDP) framework (Cohen et al., 1990). The general architecture consists of a fast and automatic response, which is activated due to the prepotency of the task-irrelevant stimulus (word-reading), whilst simultaneously and in parallel, the task-relevant stimulus activates the correct response via a slow and deliberate pathway based upon the task instructions. The response conflict must be resolved before a response is executed.

The Dimensional Overlap Model (Kornblum et al., 1990, Kornblum, 1994) categorises the extent to which the task-relevant stimuli, task-irrelevant stimuli and responses are perceptually, structurally or conceptually similar (that is, their degree of dimensional overlap) to predict the magnitude of the congruency effect. Stimuli with greater dimensional overlap induce a larger congruency effect. In a verbal Stroop task, there is overlap between the task-irrelevant stimulus (the word – red, blue etc…) and the verbal response (red, blue etc…). Additionally, there is also overlap between the task-relevant (the ink colour) and the task-irrelevant stimulus (the word). Finally, there is also overlap between the task-relevant stimulus (the ink colour) and the verbal response. Thus, a verbal Stroop task consists of three degrees of dimensional overlap and produces a larger Stroop effect.

Other conflict tasks do not elicit such high degrees of conflict. For example, during a Simon task (Simon, 1969) (see Figure 1B) participants are presented with a stimulus (e.g. a shape) that is presented on either the left or right of the screen. Participants may be asked to respond to a triangle stimulus with the left response button, and circle stimulus with the right response button. Responses are facilitated when presented in their congruent (the triangle stimuli presented on the left and the circle on the right) opposed to their incongruent locations, with the resultant time difference known as the Simon effect. Here, there is only one degree of overlap which arises between location of the task-irrelevant stimulus (left/right on screen) and the response (left/right button press).

Similarly, during a Flanker task (Eriksen and Eriksen, 1974) (see Figure 1C) participants are presented with a string of letters and asked to respond by pressing a button based upon the central letter (H = left button, S = left button). Responses are faster when the flanking letters are congruent with the central letter (HHHHH or SSSSS) than when they are not (SSHSS or HHSHH), resulting in the Flanker effect. Again, there is one degree of overlap, but this time arises as conceptual similarity (letters) between the task-relevant and task-irrelevant stimulus.

The Dimensional Overlap Model (Kornblum et al., 1990) precisely isolates the point of response conflict in an array of tasks and suggests that the way in which the conflict arises (the degree of overlap) will affect the time taken to resolve the conflict. Further, the greater the degrees of overlap, the more time required to resolve the conflict. More recently, other PDP models have been put forward to incorporate mechanisms for suppressing unwanted information.

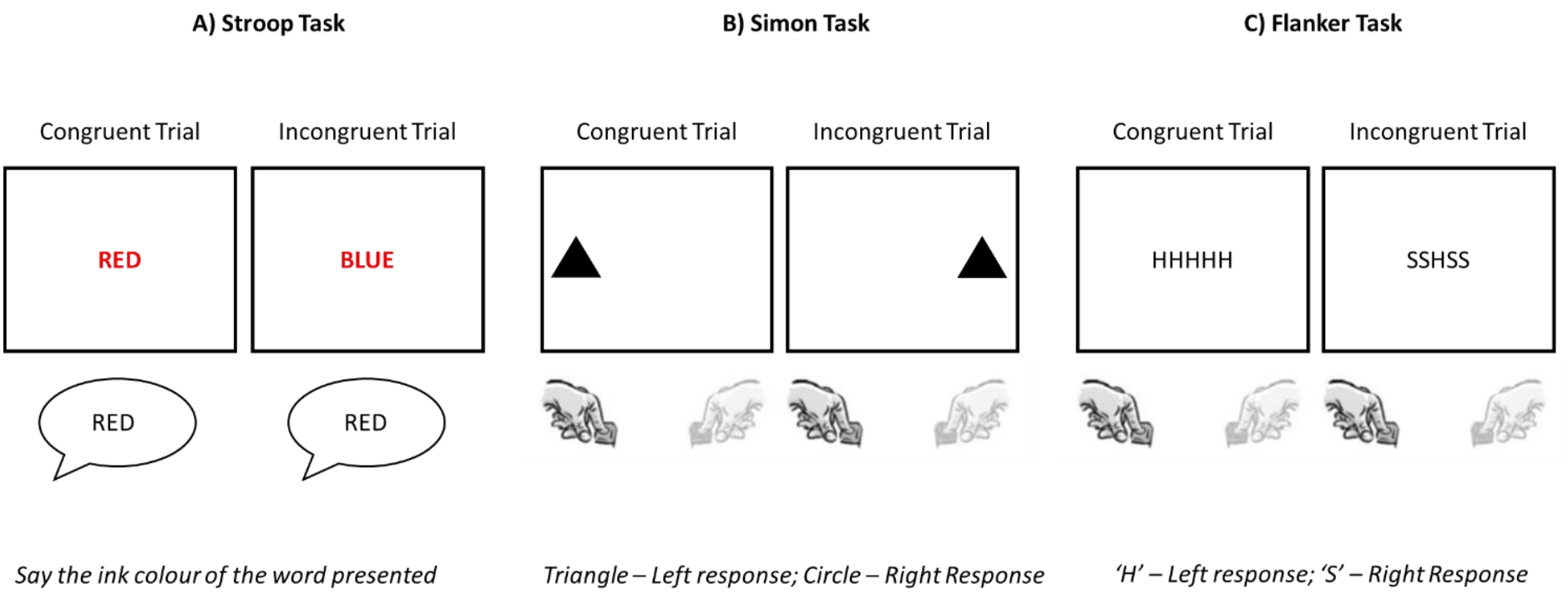


Figure 1. Examples stimuli from standard conflict tasks reported within the literature. ***Panel A)*** *shows a Stroop task - participants are instructed to respond to the ink colour of the stimulus.* ***Panel B)*** *shows a Simon task - participants are instructed to respond to a triangle with a left button response and a circle with a right response.* ***Panel C)*** *shows a Flanker task – participants are instructed to respond to the central letter by pressing the left button if the response is an H and the right button if it is an S. The correct response associated with each stimulus is shown on the bottom row of each panel. On all tasks, congruent trials are faster than incongruent trials with the resultant difference in response time known as a congruency effect.*

1.3 Activation-Suppression Model

The activation-suppression model (Ridderinkhof, 2002) is a PDP framework that introduces an external component to suppress the task-irrelevant stimulus to minimise the response conflict and enable response execution. Figure 2 demonstrates that the stimulus is processed, and its two dimensions (task-relevant and task-irrelevant) activate competing responses. The task-relevant stimulus is an arbitrary requirement unique to the Stroop task instructions and is processed through a slow and deliberate pathway, whereas the task-irrelevant stimulus is an automatic process reinforced through years of reading experience. Therefore, to achieve a correct response, there is an external input to suppress the task-irrelevant stimuli on trials when these pathways differ.

For congruent trials, the correct response can be achieved via the task-relevant or task-irrelevant stimulus pathways. The lack of competition between these two pathways signals that the processing of the direct pathway does not need to be suppressed and an overt response is achieved more quickly. Conversely, on incongruent trials, the correct response can only be achieved via the deliberate, task-relevant stimulus pathway. In Figure 2, at the response activation process, the potential responses from both these pathways are compared against one another and if they match, then the response will be implemented. Conversely, if they do not match (such as on an incongruent trial), then this conflict will lead to additional processing time to achieve the correct response. Whilst acknowledging there is decay in the of the direct response pathway over time, Ridderinkhof et al. suggest there is also selective suppression externally imposed to inhibit this pathway so to resolve the conflict. Therefore, the activation of the task-irrelevant stimuli must be suppressed for the correct response to be activated. This accounts for the slower response times on incongruent trials and that any errors on incongruent trials are more likely to be fast due to the time required for sufficient suppression to accumulate before the response occurs (Ridderinkhof et al., 2005). Trials on which the automatic response is overly strong, the response threshold may be reached before sufficient selective suppression is accumulated resulting in an incorrect response (Ridderinkhof et al., 2005).

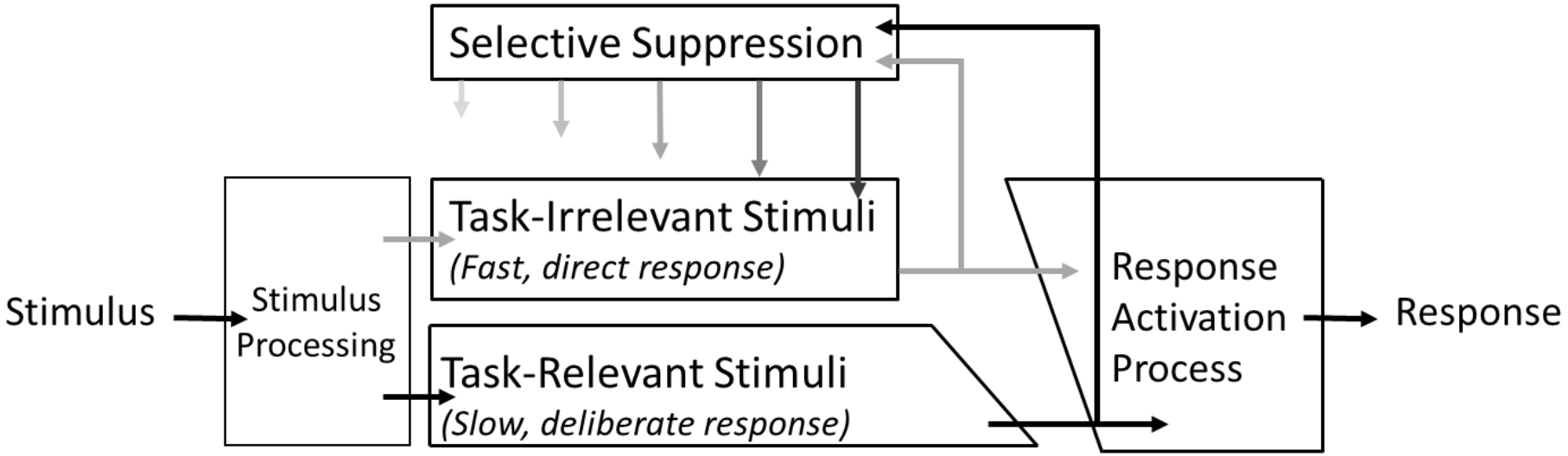


Figure 2.The architecture of the dual-processing activation-suppression mode. The visual stimuli are initially processed. From here, there are two parallel pathways activated by the stimulus dimensions: The task-irrelevant stimulus activates a fast-acting response, whereas the task-relevant stimulus is a slower acting response based upon the task instruction. The latter also serves to suppress the direct response but takes time to accumulate, as denoted by increasing size and contrast of the suppression arrows. On trials where there is no competition between the task-relevant and task-irrelevant stimuli (i.e., a congruent trial) there is no cause for involvement of the selective suppression because both will lead to the correct response.

1.3.1 Time-Course Distribution

In their seminal paper, De Jong et al. (1994) introduced delta plots to explore the time course distribution of congruency effects. These plot the magnitude of the congruency effect along the *y*-axis as a function of response time across the *x*-axis (for an example, see Figure 3). The Activation-Suppression Model can predict the basic congruency effects from the Stroop, Simon, and Flanker conflicts tasks. However, it does not support the time-course distributional analyses of all three. This suggests that just as each task has a different degree of dimensional overlap (Kornblum, 1994), different mechanisms must underlie each congruency effect (Pratte et al., 2010).

The architecture of the Activation-Suppression Model would predict negative-going delta plots due to the selective suppression reducing the influence of the task-irrelevant stimuli on response selection as the trial time progressed. Thus, slower responses should have reduced congruency effects. Delta plots resulting from Simon task are consistent with such predictions from the Activation-Suppression Model (Pratte et al., 2010, Ridderinkhof et al., 2005, van den Wildenberg et al., 2010, Wylie et al., 2009a), including the reversed Simon effect that is sometimes reported with the slowest response times (Pratte et al., 2010, Ridderinkhof et al., 2011). Conversely, delta plots produced from Stroop tasks demonstrate a positive-going delta (Pratte et al., 2010, Spieler et al., 1996). This represents a positive relationship between the mean and standard deviation of response times (Wagenmakers and Brown, 2007) and indicates increasing congruency effect with slower responses. Flanker tasks produce inconsistently shaped deltas that are either flat or an inverted-U (Ulrich et al., 2015). As such, it is clear the Activation-Suppression Model cannot fully explain the results arising from the Stroop nor Flanker tasks.

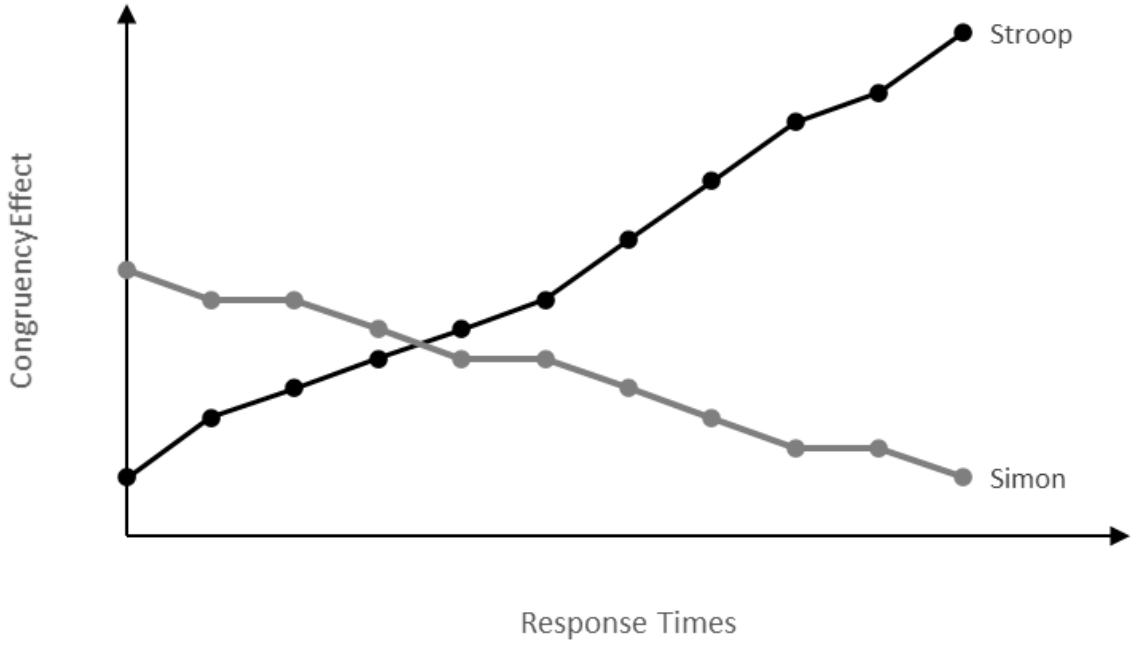


Figure 3. An example delta plot: the magnitude of the congruency effect is plotted against the response speed for both the Stroop (black) and Simon (grey) tasks.

1.4. Diffusion Model for Conflict Tasks

Like the Activation-Suppression Model, the Diffusion Model for Conflict Tasks (DMC; Ulrich et al., 2015) supports the principle of dual-route processing but from a drift-diffusion perspective. As with other dual-route processing models, diffusion models operate on the general principle that conflict elicits both fast, automatic processes driven by the task-irrelevant stimuli and deliberate, controlled processes driven by the task-relevant, both represented by response boundaries (see Figure 4). Evidence accumulates towards these boundaries over time, until a response threshold is surpassed, at which point the associated overt response is executed. As shown in Figure 4, it is the combined influence (accumulated drift rate) of these processes towards the response boundaries (which remain fixed) that determines the response time. The starting point of evidence accumulation towards either response boundary is in the middle (at zero). The distance between the two boundaries indicates either a cautious (large) or impulsive (small) response strategy that may vary across individuals. Other factors

influencing the distance from either boundary (such as previous exposure to stimuli) will be discussed later in the introduction in Section 1.6.1.3. Note, the key difference is that the DMC does not involve selective suppression of the task-irrelevant stimuli that is fundamental in producing the negative-going delta plots of the Activation-Suppression Model.

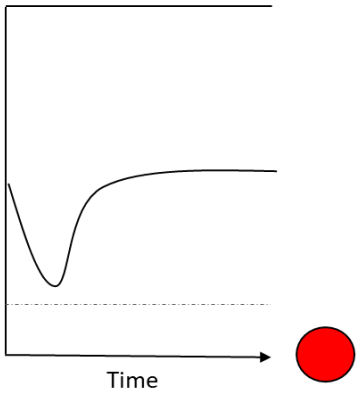
First note, that Figure 4A depicts a congruent trial, which, for the simplicity of this thesis, is represented by only one response boundary because both the automatic and controlled process lead to the same response. Conversely, panel B depicts an incongruent trial on which there are two competing responses arising from the task-relevant stimulus (represented by the response boundary at the top) and the task-irrelevant stimulus (represented by the response boundary at the bottom). See next that the rate of evidence accumulation differs between the automatic and controlled processes. The middle panels of Figure 4 show the slow and controlled process elicited by the task instruction. This occurs at the same rate for both congruent and incongruent trials (compare panel A and B of Figure 4). The left-hand panels of Figure 4 shows that the automatic response process reaches its maximal output and is then subject to spontaneous decay, as seen by returning to zero. For both congruent and incongruent trials, the strength and maximal output of both the automatic process and controlled process is the same, however, on congruent trials their direction is the same, whereas for incongruent trials, they accumulate evidence in opposite directions and hence create a source of conflict. Finally, the right-hand panels of Figure 4 shows the accumulated drift rate towards the response boundaries which constitutes the combined influence of both pathways. On congruent trials, the evidence accumulation is linear towards the correct response boundary and as such, the threshold is surpassed much sooner than on incongruent trials. The accumulated drift rate on an incongruent trial is first directed towards the incorrect response due to rapid activation of the automatic pathway, but as this response decays, there is greater influence from the controlled process, and subsequently the correct response is executed, but at the cost of slower response times. Thus, providing an explanation for basic congruency effects.

The DMC predicts that the shape of the observed delta plot (positive- or negative-going) is due to the peak amplitude of the automatic response. A smaller peak amplitude generates a congruency effect that decreases with response time (negative-going delta) whereas a larger peak latency generates congruency effects that increase with response time (positive-going deltas). Perhaps this relates back to the dimensional overlap taxonomy of Kornblum et al. (1990) whereby the task-irrelevant stimulus in a Stroop task elicits a prepotent and automatic response with a large peak amplitude and hence a positive-going delta. Conversely, the task-irrelevant stimulus in a Simon task may elicit only a small automatic response (due to the minimal degrees of dimensional overlap). As such, with time, there is greater variance between the mean and standard deviation of the responses on incongruent compared to congruent trial, thus producing a negative-going delta (Wagnemarkers and Brown, 2007). Whilst the Activation-Suppression Model (Ridderinkhof, 2002, Ridderinkhof et al., 2005) can explain the results of the Simon task, the Diffusion Model for Conflict Tasks (Ulrich et al., 2015) offers a better theoretical framework for understanding the mechanisms behind Stroop congruency effects and is the leading model that shall be used throughout this thesis when interpreting the results of Stroop tasks.

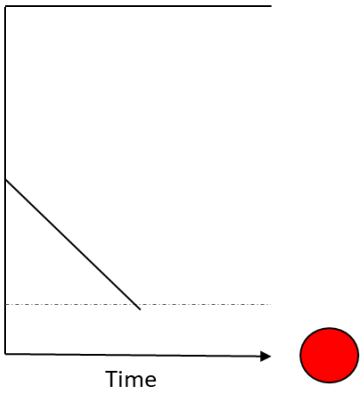
A

RED

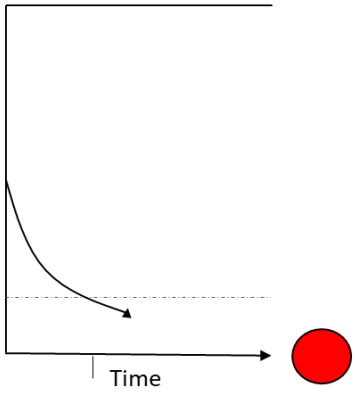
Automatic Process



Controlled Process



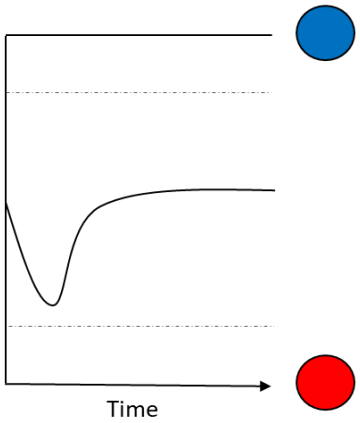
Drift Rate



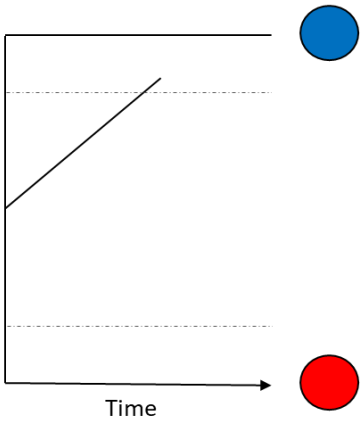
B

RED

Automatic Process



Controlled Process



Drift Rate

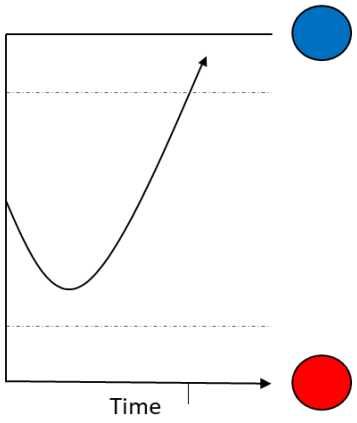


Figure 4. Depiction of the Diffusion Model for Conflict Tasks (Ulrich et al., 2015) for a congruent (panel A) and incongruent (panel B) trial. The basic architecture consists of two response boundaries (red and blue) represented by the task-relevant (ink colour) and task-irrelevant (word) stimuli. Evidence towards each boundary is accumulated until the response boundary (dashed grey line) is reached, after which an overt response is produced. The automatic process is activated by the task-irrelevant stimulus (the word red) and shows evidence is initially accumulated towards this response boundary but decays over time without passing the response threshold. The controlled process is activated by the task-relevant stimulus and accumulates evidence in a linear fashion towards this response boundary. The drift rate is the accumulated activation towards either response boundary. On incongruent trials this may initially be influenced by the response activated by the task-irrelevant stimulus, but only sub-threshold, hence why the incorrect response is not executed and is why the accumulated drift rate (response times) is slow. Conversely, on a congruent trial, both the automatic and controlled process accumulate evidence towards a complementary boundary, therefore the accumulated drift rate is fast.

1.5 Congruency-Sequencing effects

The basic Stroop effect measures the ability to resolve conflict on a given trial. However, it does not provide any context for how the ability to deal with conflict may change throughout the task. In the example given earlier, conflict arose as competition from a 'go' response elicited by a green traffic light and a 'stop' response elicited by a pedestrian stepping out in front of the car. The weighting given to the stop or go response will determine whether the pedestrian was hit or not. In either response eventuality, greater attention will be paid to pedestrians at traffic lights so to minimise future conflict. This demonstrates that previous experience modulated behaviour and results in flexible adjustments of cognitive control.

Gratton et al. (1992) were the first to show how previous experience modulated response conflict in a laboratory setting. They reported that after an incongruent trial, the magnitude of the congruency effect is reduced. This phenomenon is known as the congruency-sequencing effect (see Figure 5) and has since been replicated numerous times (Aschenbrenner and Balota, 2015, Aschenbrenner and Balota, 2017, Botvinick et al., 2001, Botvinick et al., 2004, Botvinick et al., 1999, Duthoo et al., 2014, Kerns et al., 2004, Mayr et al., 2003).

To expand upon the congruency-sequencing effect, trials in conflict tasks are subdivided into four categories according to the congruency of the both the previous and current trial: congruent trials preceded by congruent trials (cC); congruent trials preceded by incongruent trials (iC); incongruent trials preceded by congruent trials (cI); incongruent trials preceded by incongruent trials (iI). Note, the capitalised letter refers to the congruency of trial *n* and the lowercase letter the congruency of trial *n*-1. Gratton et al. (1992) reported that in their Flanker task, the congruency effect when the previous trial was congruent (cI-cC) was 55ms, whereas the congruency effect when the previous trial was incongruent (iI-iC) was 42ms, thus producing a reliable congruency-sequencing effect ((cC-cI)-(iI-iC)) of 7ms. This demonstrates an altered pattern of responding that aims to optimise performance based on

240 the congruency of the previously experienced trial. The congruency-sequencing effect will form the
241 key outcome measure of the thesis in trying to discern the mechanisms underlying these flexible
242 adjustments to conflict referred to as conflict adaptation.

243 There are three key accounts of the mechanisms underpinning the congruency-sequencing effect. As
244 an overview, two are top-down accounts that suggest this behaviour reflects cognitive adjustments to
245 minimise conflict: the repetition expectancy account, first put forward by Gratton et al. (1992; see
246 Figure 5A), is a proactive account which suggests sustained cognitive adjustments are made by pre-
247 empting conflict, whereas the Conflict-Monitoring model (Botvinick et al., 2001; see Figure 5B)
248 suggests transient cognitive adjustments arise in response to experiencing conflict. These both differ
249 from Feature-Integration account (Hommel, 1998, Hommel et al., 2004; see Figure 5C) which is a
250 bottom-up account that suggests that certain aspects of stimulus features bias the processing of a
251 given stimulus sequence.

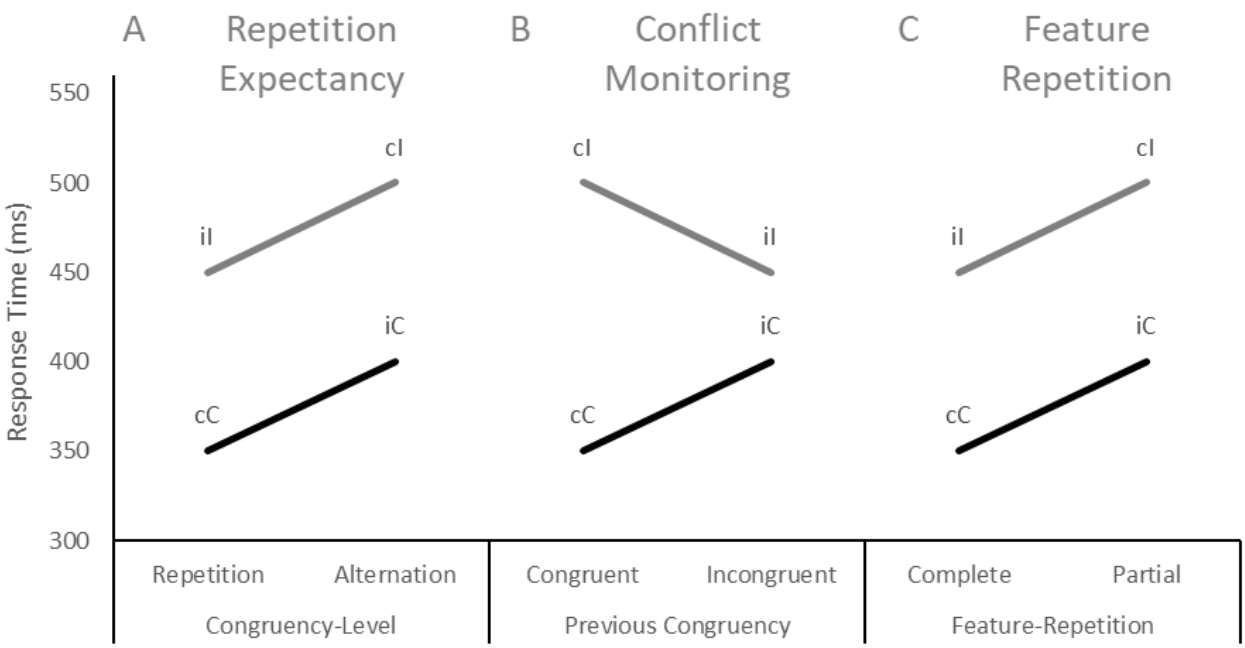


Figure 5. Three proposed models that explain the congruency-sequencing effect. It is important to highlight that all panels display the same data points, however, each are plotted according to the proposed mechanisms underlying each model. Current congruent trials are shown by the black lines, whereas current incongruent trials are indicated by grey lines. The trial transition each data point pertains to is also indicated. ***A – Repetition Expectancy****: The x-axis separates trials on which the congruency repeats (cC and iI) from those where it does not (cI and iC). Participants expect the congruency to repeat from the previous to the current trial, therefore congruency-level repetition trials are faster because expectations are met (see Section 1.6.2).* ***B – Conflict-Monitoring model****: The x-axis plots trials according to the congruency of the previous trial. Previous levels of conflict, as determined by the congruency of the previous trial, differentially activates control processes through the conflict-monitoring loop to maximise facilitation from the task-irrelevant stimulus after a congruent trial and minimise its distraction after a congruent trial (see Section 1.6.1.).* ***C – Feature Integration****: The x-axis separates trials based on the type of feature-repetition encountered. Complete repetitions refers to the exact stimulus-response repetition or alternation which Hommel et al. (2004) has associated with speeded responses and are present in only cC and iI trials. Conversely, partial repetitions, such as those present in cI and iI trials are associated with slower response because of an incomplete activation of the previously formed stimulus-response episodic pairing with the current response required from the stimulus (see Section 1.7.).*

1.6. Top-Down Accounts

1.6.1. Reactive Control

The section will provide the evidence for the highly influential Conflict-Monitoring Model of Botvinick et al. (2001) to explain the congruency-sequencing effect (see Figure 6). This *reactive* top-down account proposes that conflict itself, as signalled by co-activation of competing response pathways from the task-relevant and task-irrelevant stimuli, leads to up-regulation of cognitive control centres to target attention to the task-relevant stimuli on the subsequent trial. It implicates two key structures: the anterior cingulate cortex (ACC) for conflict detection and the dorsolateral prefrontal cortex (DLFPC) for control implementation.

1.6.1.1. The Role of the ACC

The anterior cingulate cortex (ACC) is positioned on the medial surface of the frontal lobe, next to the corpus callosum (Botvinick et al., 2001) and the caudal aspect has long been considered involved in the regulation of conflict (Van Veen and Carter, 2002). Using positron emission tomography (PET) measures, Pardo et al. (1990) reported greater regional cerebral blood flow to the ACC on incongruent compared to congruent Stroop trials. This finding has since been replicated by functional magnetic resonance imaging (fMRI) studies (Botvinick et al., 1999, Carter et al., 2000, Kerns et al., 2004), which have reported a larger blood-oxygen-level dependent (BOLD) response on incongruent compared to congruent trials. Further analyses considering trial sequences revealed that ACC activation on incongruent trials could further be distinguished by the previous level of conflict. Incongruent trials preceded be congruent trials (cI) elicited greater ACC activation than incongruent trials preceded by incongruent trials (iI) (Botvinick et al., 1999). This demonstrates that ACC activation is positively correlated with conflict. Such findings form the foundations of the Conflict-Monitoring Model which neuroanatomically localises conflict detection to the ACC.

Carter et al. (2000) further used fMRI to explore ACC activation whilst manipulating the level of conflict (the task congruency). The Conflict-Monitoring Model proposes that cognitive control mechanisms will be less engaged in a Stroop task containing a high percentage of congruent trials, therefore, the rare occurrence of an incongruent trial will generate a high level of response conflict and greater ACC activation. In contrast, when incongruent trials are frequent, cognitive control will be highly engaged, therefore, the response conflict experienced on a given incongruent trial will be relatively small, as reflected through less ACC activation. Carter et al. predicted that if the ACC itself is responsible for top-down control changes, then ACC activation will be high when control mechanisms are engaged (mainly incongruent blocks). Conversely, if the ACC serves only as an evaluative conflict detection mechanism then its involvement will be most prominent on incongruent trials during high conflict (mainly congruent) blocks. Results showed a greater BOLD response in the ACC on incongruent compared to congruent trials, but only in the high conflict blocks (where congruent trials were common). They, therefore, supported the findings of the Conflict-Monitoring Model, and Carter and colleagues concluded that the ACC serves only as an evaluative mechanism and is not itself responsible for implementing and up-regulating control.

1.6.1.2. The Role of the DLPFC

The initial Conflict-Monitoring Model proposed by Botvinick et al. (2001) emphasised the ACC as the source of conflict detection, which then triggered the need for external adjustments. Evidence from their earlier fMRI study suggests such adjustments in control may be implemented through the DLPFC. Botvinick et al. (1999) reported that trials eliciting the greatest ACC activity (cI) were followed by relatively strong left DLPFC activation. This finding was replicated by Kerns et al. (2004), except that they found the DLPFC activity was contained to the right hemisphere. Although most of the research implicates the left DLPFC (Banich et al., 2000, Carter et al., 2000, MacDonald et al., 2000, Milham et al., 2003, Milham et al., 2002, Vanderhasselt et al., 2006), there are others (Egner et al., 2008, Egner and Hirsch, 2005) who suggest the right DLPFC is key for conflict adaptation, however, such findings

are often derived from Stroop variations involving faces. Regardless of the lateralised effect, both suggest the DLPFC serves to minimise interference on subsequent trials.

A key study by MacDonald et al. (2000) sought to dissociate the roles of the ACC and DLPFC in conflict tasks. To do so, they used fMRI during a Stroop task in which both colour-naming and word-reading instructions were alternated across trials. Following the instructional cue, a delay period allowed for preparatory control implementation (directed towards the task-relevant for colour-naming) after which the stimulus was presented. During the delay period there was selective engagement of the left DLPFC which induced a larger BOLD response during colour-naming that word-reading trials. This demonstrates the role of the left DLPFC in control implementation. Additionally, during the stimulus presentation, there was a larger BOLD response in the ACC for incongruent compared to congruent trials. This supports the role of conflict detection put forward by Botvinick et al. (2001).

Finally, components of the event-related potentials (ERP) recorded via electroencephalograms (EEG) confirm the timings of ACC activation to further support the above fMRI results. Recorded from the ACC, the N2 component of the ERP occurs at around between 250 and 380ms after stimulus presentation of a Stroop task (Clayson and Larson, 2011, Yeung et al., 2004). Both Yeung et al. (2004) and Clayton and Larson (2011) consider the N2 to indicate conflict detection and report a larger negative peak after incongruent compared to congruent trials. Additionally, Yeung et al. (2004) claim that the error-related negativity (ERN) component of the ERP can differentiate between correct and incorrect responses. After an incorrect response, there is often continued evidence accumulation towards the correct response boundary even after the response has been executed. Such response conflict is not present on correct trials and as such, the ERN recorded from the ACC is larger on incorrect than correct responses. This further emphasises the role of the ACC in conflict detection.

In summary these findings highlight the roles of the ACC (conflict detection) and the DLPFC (control implementation) within conflict monitoring. Carter and van Veen (2007) later updated the conflict-monitoring loop to localise up-regulation in control functions to the DLPFC. This control is applied as altered activation to the deliberate, task-relevant or direct, task-irrelevant pathways on subsequent trials in accordance with the level of conflict detected by the ACC on the previous trial (see Figure *6*). The left DLPFC has since been implicated in cognitive flexibility (Armbruster et al., 2012) and has been linked to inhibition of task-irrelevant information (Toepper et al., 2010).

1.6.1.3. Integrating Conflict Monitoring and Congruency-Sequencing Effects

This section will explicitly state how the neural activity of the Conflict-Monitoring loop results in the congruency-sequencing effect (a smaller congruency effect following an incongruent trial). As a novel interpretation, this thesis has combined the Conflict-Monitoring account of the congruency-sequencing effect with the Diffusion Model for Conflict Tasks (Ulrich et al., 2015) to explain how trial-to-trial variations in the Stroop effect produces the congruency-sequencing effect. As a reminder, the DMC proposes responses from the task-relevant and task-irrelevant stimuli are represented by response boundaries. Evidence accumulates towards these boundaries until a threshold is surpassed and an overt response executed. Figure 6 first displays an incongruent trial where the ACC detects conflict (co-activation of competing response pathways originating from the task-relevant and task-irrelevant stimulus). The ACC signals to the DLPFC to upregulate control towards the task-relevant stimulus so to minimise the conflict experienced on trial *n*+1. If trial n+1 is also incongruent (iI; see stimulus two on Figure 6), then such adjustments will minimise the interference from the task-irrelevant stimulus and result in fast evidence accumulation and response times (see the second graph in Figure *6*). Conversely, if trial n+1 is congruent (iC; see stimulus three of Figure 6), the increased attentional control towards the task-relevant stimulus minimises the facilitation congruent trials usually experience from the task-irrelevant stimulus. As such, the rate of evidence accumulation is slower, and this is reflected through increased response times (see the third graph in Figure 6).

During a congruent trial (see stimulus three on Figure 6), both the task-relevant and task-irrelevant stimulus led to the same response, therefore, ACC activation was low due to the lack of conflict. This time, the DLPFC is recruited to direct attentional control towards the task-irrelevant stimulus so to maximise its facilitation on the next trial. If the next trial is also congruent (cC; see stimulus four on Figure 6), this will maximise the facilitation from the task-relevant stimulus. As such, the rate of evidence accumulation is fast, and a response is achieved quickly. Therefore, congruent trials are faster when preceded by a congruent trial (cC) compared to incongruent trial (iC). Conversely, if the next trial were incongruent (cI, see stimulus five on Figure 6), the attentional control shift towards the task-irrelevant stimulus will be detrimental to performance because it will maximise its interference. Consequently, evidence accumulation will be initially directed towards the incorrect response, so the overall response time will be slow. Therefore, incongruent trials will be slower when preceded by a congruent trial (cI) than an incongruent trial (iI).

As such, the congruency-sequencing effect ((cI-cC)-(iI-iC)) represents a reduced congruency effect, that is, less conflict, following an incongruent trial. These micro-adjustments in control represent adaptive performance that serves to minimise subsequent conflict. Such a mechanism may be used in the avoidance of undesirable situations such the previously described scenario with a green light and pedestrian. In that example, the previously experienced conflict (the green light and the pedestrian) serves as a trigger to attend more to pedestrians who are on the edge of the pavement who may create a similar conflicting situation.

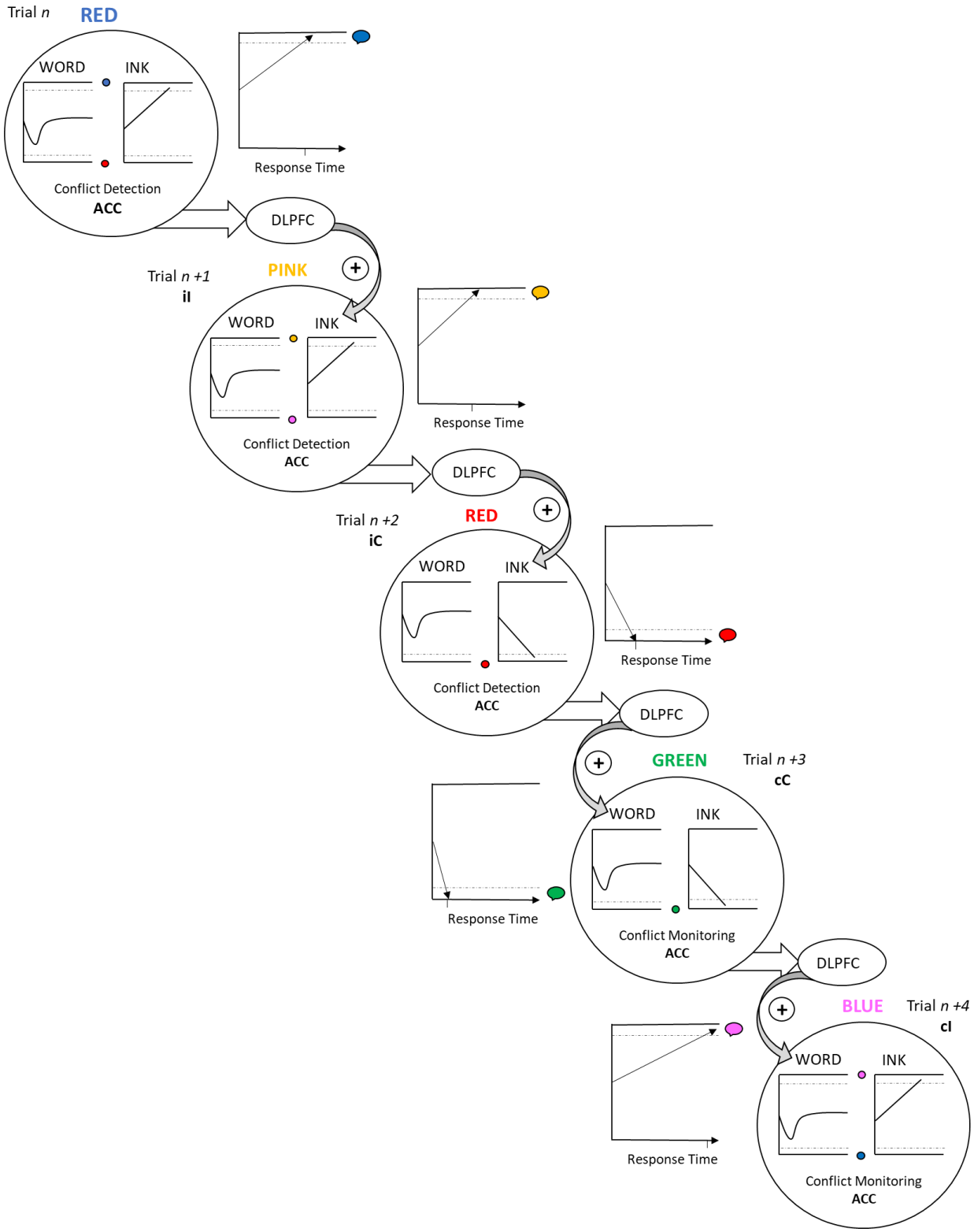

Trial n
RED
WORD
INK
Conflict Detection
ACC
Response Time
DLPFC
Trial n +1
iI
PINK
WORD
INK
Conflict Detection
ACC
Response Time
DLPFC
Trial n +2
iC
RED
WORD
INK
Conflict Detection
ACC
Response Time
DLPFC
Trial n +3
cC
GREEN
WORD
INK
Conflict Monitoring
ACC
Response Time
DLPFC
Trial n +4
cI
BLUE
WORD
INK
Conflict Monitoring
ACC
Response Time

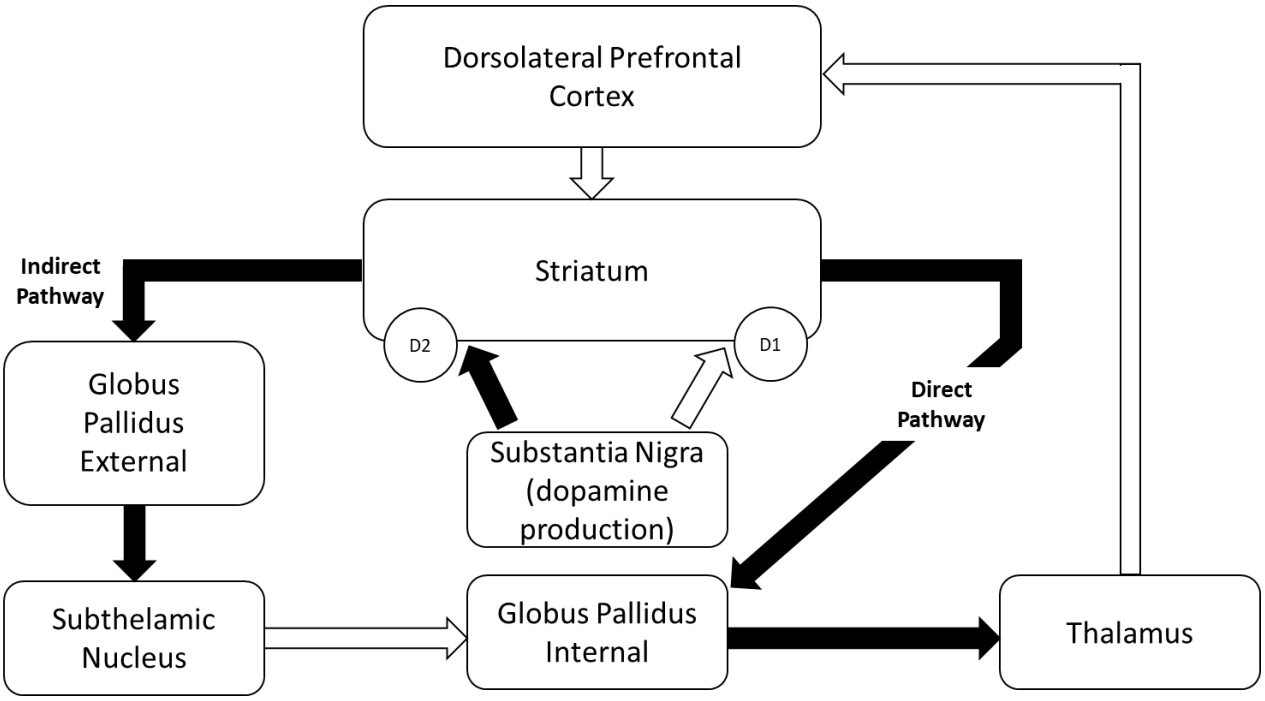
Figure 6. An interpretation of how the Diffusion Model for Conflict Tasks interacts with the Conflict-Monitoring loop to produce congruency-sequencing effects in a Stroop task. As explained in Section 1.4, the Diffusion Model for Conflict Tasks (Ulrich et al., 2015) explains the Stroop effect by proposing that the processes activated by the task-relevant and task-irrelevant stimuli are represented by response boundaries that each accumulate evidence until a threshold is surpassed and a response executed. These are shown by the graphs whereby the threshold for the task-relevant stimulus is at the top and the task-irrelevant stimulus at the bottom – coloured patches are included to indicate the response associated with each stimulus on each trial. Once one of the boundary thresholds is surpassed, an overt response is executed, as shown by the speech bubble. Botvinick et al. (2001) proposes the conflict (or lack thereof) between the task-relevant and task-irrelevant stimulus occurs in the ACC. This triggers recruitment of the DLPFC which allocates resources to the task-relevant and task-relevant depending on the congruency just experienced. Trial n is incongruent, and the task-irrelevant word will lead to the incorrect response, therefore, on the next trial the influence of the task-relevant stimuli is amplified. Trial n+1 is incongruent, so this attentional adjustment will benefit performance and explains faster iI trials. These attentional adjustments can be observed for all trial transitions – iI (trial n to n+1); iC (n+1 to n+2); cC (n+2 to n+3); cI (n+3 to n+4) and explain the mechanisms resulting in the congruency-sequencing effect.

1.6.2. Proactive Control

Gratton et al. (1992) initially proposed the congruency-sequencing effect resulted from changes in attentional processing derived from the participants' expectancy of the congruency of the subsequent trial. If the participant were to expect the congruency of the subsequent trial to repeat, this would manifest as faster congruency-repetition trials (cC and iI) than congruency-alternation trials (cI and iC) to produce the congruency-sequencing effect, as shown in Figure 5B. For this reason, the term 'repetition expectancy' (Egner, 2007) is also often used to refer to a proactive control strategy. The subtle differences between global proactive control and repetition expectancy are discussed in Chapter Five. Until then, proactive control should be considered to operate similarly to a reactive control strategy in that attentional adjustments are implemented by the DLPFC but that said recruitment occurs via a dopaminergic *'early selection'* (Braver, 2012, De Pisapia and Braver, 2006) opposed to a '*conflict driven'* mechanism (Botvinick et al., 2001, Egner, 2007).

1.6.2.1. The Basal Ganglia and Fronto-Striatal Loops

The basal ganglia are a set of subcortical nuclei consisting of the caudate nucleus, putamen, and nucleus accumbens (which collectively form the striatum); the globus pallidus; substantia nigra; and the subthelamic nucleus (Banich and Compton, 2018). The substantia nigra and adjacent ventral tegmental area are the primary production sites of the neurotransmitter dopamine. Dopamine interacts with cells by binding to receptors, of which there are two main classes: D1 and D2; with receptor type affecting whether dopamine has an excitatory or inhibitory influence on the post-synaptic cell. When dopamine is release from the substantia nigra to the striatum, D1 receptors allow for disinhibition of the DLPFC via the direct pathway through the globus pallidus interior. Striatal D2 receptors allow continued inhibition of cortex via the indirect pathway through the globus pallidus external and subthelamic nuclei. These fronto-striatal pathways (see Figure 7) play an important role in proactive control by modulating the function of the DLPFC via selective (dis)inhibition.



411 *Figure 7. Depiction of the direct and indirect fronto-subcortical pathways connecting the DLPFC to the basal ganglia, replicated*
412 *from Litcher et al. (2013). White arrows represent excitatory, glutaminergic connections, whereas black arrows represent*
413 *inhibitory, GABAergic connections. Dopaminergic innovation of the striatum via the substantia nigra and ventral tegmental*
414 *area (not depicted) is excitatory via D1 receptors to the direct pathway (globus pallidus internal, thalamus, and cortex) and*
415 *inhibitory via D2 receptors to the indirect pathway (globus pallidus external, subthelamic nucleus, globus pallidus internal,*
416 *thalamus and cortex).*

Proactive recruitment of the DLPFC is proposed to occur through midbrain dopamine projection that modulate the influence of 'context-specific' information in the DLPFC (Braver and Barch, 2002, Braver and Cohen, 1999, Braver and Cohen, 2000, Miller and Cohen, 2001). Context-specific information refers to any source of information which biases performance and could relate to: the task instruction (i.e., the task-relevant stimulus); the most informative source of information (i.e., task-relevant stimulus in a mostly incongruent task, or the task-irrelevant stimulus in a mostly congruent task); or the congruency of the previous trial. The model proposes that dopamine-inputs to the DLPFC operate through a '*gating mechanism*' whereby when the gate is open, context-specific information is maintained within the DLPFC, conversely, when the gate is closed, the DLPFC is protected from distraction. The timings of the gating signals are learned through a dopamine-dependent predictive learning mechanism (Braver and Barch, 2002).

1.6.2.2. Integrating Proactive Control and Congruency-Sequencing Effects

Although not explicitly stated by Braver et al. (2002), it is clear to see how this account of proactive control can be applied to a Stroop task. When context-specific information (congruent *n*-1 trial) anticipates trial *n* to be congruent, the gating mechanism is opened. As such, dopamine floods the DLPFC to allow greater influence of task-irrelevant information. If trial *n* is congruent this benefits performance and response times are fast on cC trials. If trial *n* is incongruent, the task-irrelevant stimulus is a source of distraction and responses to cI trials are slow. Conversely, when context-specific information (incongruent *n*-1 trial) anticipates trial *n* to be incongruent, the gate is closed to minimise distractions from the task-irrelevant stimulus. If trial *n* is incongruent this minimises the distraction of the task-irrelevant stimulus and iI trials are fast. If trial *n* is congruent, this minimises the facilitation from the task-irrelevant stimulus and iC trials are slow. Hence, during congruency-level repetitions when these predictions are correct (cC and iI trials), performance is facilitated compared to congruency-level alternations and when they are not (cI and iC trials; see Figure 5C). As such, the gating mechanism can bias the DLPFC to generate the same cognitive control adjustments as triggered by the

Conflict-Monitoring loop to produce a congruency-sequencing effect. Therefore, it is not possible to discern proactive from reactive mechanisms from the mean response times of the congruency-sequencing effect.

1.6.3. Proactive versus Reactive Control: A Summary

Whilst both proactive and reactive control can elicit the congruency-sequencing effect, there are two key differences to be highlighted: 1) the timing of DLPFC recruitment. A reactive strategy can be considered a '*late correction mechanism'* (Jacoby et al., 1999b) that is implemented only after (in response to) conflict, whereas a proactive strategy is known as an '*early selection mechanism*' (Jacoby et al., 1999) that is engaged in anticipation to minimise conflict. 2) The trigger for recruitment for the DLPFC: The Conflict-Monitoring Model (reactive) proposes a conflict detection unit (ACC) triggers recruitment of the DLPFC, whereas the proactive account suggests this occurs through midbrain dopamine connections to the DLPFC (Braver and Barch, 2002, Braver and Cohen, 1999, Braver and Cohen, 2000). The similarity is that both models implicate the DLPFC as the source of control implementation. Therefore, it can be expected that any deficit to the DLPFC may result in impaired cognitive control (see Section 1.7.).

1.7. Neurodegeneration in Healthy Ageing

1.7.1. Frontal Regions

Healthy ageing is associated with shrinkage of the brain, resulting in an approximately 6% reduction in whole brain volume (Haug and Eggers, 1991). According to West (1996)'s influential frontal lobe hypothesis of ageing, the prefrontal cortex is particularly susceptible to age-related decline and does so at an accelerated rate compared to other brain regions. Early research showed a 10% volume loss of the prefrontal cortex, compared to only a 1% loss in the temporal, parietal, and occipital lobes in 65 – 75-year olds (Haug and Eggers, 1991; West, 1996). More recently, it has been demonstrated that this is due to loss of grey matter volume (Cabeza et al., 2018, Peters, 2006), specifically through loss of neuronal dendrites and synaptic connections (Fuster, 2015). The ACC is a renowned site for cognitive decline in healthy ageing that shows reduced grey matter volumes (Vaidya et al., 2007) that is accelerated compared to other (cingulate) regions (Mann et al., 2011). Pardo et al. (2007) correlated ageing with hypometabolism of glucose in the ACC, which they propose may underlie age performance differences in Stroop tasks.

1.7.2. Midbrain Regions

Healthy ageing is associated with declines in many aspects of the brain's dopamine system (Berry et al. 2016). Using PET, Ota et al. (2006) has reported that dopamine synthesis is reduced in the ACC and particularly in the DLPFC, with ageing. Additionally, the availability of both D1 and D2 receptors declines at a rate of 7% per decade of age in the striatum, and more pronouncedly by 11-14% per decade the DLPFC (Kaasin and Rinne, 2002).

1.7.2.1. Behavioural Implications for Cognitive Decline

It stands to reason that healthy ageing is associated with accelerated neuroanatomical decline in the frontal cortex, basal ganglia, and dopaminergic circuitry, this may be reflected through behavioural

differences in cognitive tasks. It is well documented that older adults perform sub-optimally in conflict tasks as revealed through greater error rates and larger congruency effects compared to younger adults (Spieler et al., 1996, West and Moore, 2005). In a series of cognitive tasks, including word recognition, Bäckman et al. (2000) reported that D2 striatal receptor density predicted task performance over and above age. Additionally, Ota et al. (2006) suggests that reduced dopamine synthesis in the DLPFC may play a role in declined cognitive performance with ageing. Together, this emphasises the importance of the mid brain and frontal loops in cognitive tasks.

1.7.2.2. Neurological Compensatory Mechanisms

This can be further supported when considering neurological diseases such as Parkinson's, which is characterised as dopamine depletion, particularly affecting the putamen (de la Fuente-Fernández 2012). Executive dysfunction is observed in patients with Parkinson's disease arising from dysfunction of the fronto-striatal loop at the level of the basal ganglia (Tekin and Cummings, 2002). However, it is reported that the direct pathway to the DLPFC is often hyperactive in early disease states and may represent a compensatory mechanism to combat executive dysfunction (de la Fuente-Fernández, 2012). Similarly, striatal dopamine synthesis is increased in older compared to younger adults (Berry et al., 2016). This too may reflect a compensatory mechanism against such declines in the overall dopamine synthesis and receptor density. Such a mechanism may prevent against age-related declines in proactive control.

Additionally, Milham et al. (2002) have reported that healthy older adults showed reduced BOLD responses in the DLPFC in conjunction with increased ACC activity to both congruent and incongruent stimuli compared to younger adults. This may also represent a heightened state of readiness for conflict to account for a reduced ability to implement attentional control via the DLPFC due to accelerated neuroanatomical decline. As such, this may also reflect a compensatory mechanism against age-related declines in reactive control.

1.7.2.3. Summary

As initially outlined, there are three possible mechanisms underpinning the congruency-sequencing effect. The two top-down accounts of cognitive control have been discussed, and if either play a role in conflict adaptation, it can be expected this would manifest as a smaller congruency-sequencing effect among older adults. Although, possible compensatory strategies have been highlighted. An age-related decline in the congruency-sequencing effect would not, however, differentiate between either top-down account. The next section will outline the final mechanism possibly underpinning conflict adaptation, which is not expected to be impaired with ageing.

1.8. Feature-Integration Account

An alternative explanation of the congruency-sequencing effect that does not require top-down control, has been put forward. Hommel (1998, Hommel et al., 2004)'s Feature-Integration account (see Figure 5C) supports the dual-processing principle of the DMC, but contests that the automatic route leads to the involvement of top-down regulation. Instead, it suggests the congruency-sequencing effect is a product of *bottom-up priming* effects that result from the specific stimulus-response pairings from the previous trial. For example, in a two-choice conflict task such as the Simon task, participants may be asked to respond to a triangle stimulus with their left hand, and circle stimulus with their right hand, with responses facilitated when the triangle (task-relevant stimulus) is presented on the left (task-irrelevant stimulus) and the circle on the right of the screen (see Figure 1B). They suggest that, on each trial, the specific stimulus and response combination merge to form a temporary stimulus-response pairing or "event-file" within the episodic memory and it is the repetition and alternation of this stimulus-response pairing on subsequent trials that is responsible for the behavioural pattern of the congruency-sequencing effect.

To continue the example from the Simon task, this is because every correct response on a congruent trial, a triangle will be associated with a left response, and a circle with a right response, therefore, the

stimulus-response pair left/left and right/right are formed. If trial *n* is a triangle presented on the left and the next trial is identical (see second column of row one and row four of Figure 8), this provides a stimulus-response advantage because the response required from the given stimulus is the one that has just been executed and should, therefore, result in a faster response time (Pashler and Baylis, 1991). This is an example of positive priming. If trial *n*+1 is a complete alternation such as a circle stimulus (denoting a right response) presented on the right, this will not interfere with the previously formed triangle/left stimulus-response pairing, but will create a new circle/right stimulus-pairing without any priming from the previous trial occurring (see column three of row one in Figure 8). However, if trial *n*+1 was a triangle presented on the right (see second column of row two in Figure 8), this involves repetition of the triangle stimulus in the absence of a left response and constitutes a partial activation that violates the previously formed triangle/left stimulus-response pairing and thus result in slower response times. Equally, if trial *n*+1 was a circle presented on the left (see third column of row two in Figure 8) this is a repetition of the left response in the absence of the triangle stimulus and also partially activates the previously formed triangle/left response. Trials that partially activate previously formed stimulus-response pairing are termed feature-repetition trials. With the except of the aptly named positive-priming trials, all feature-repetitions are associated with a response time detriment. Trials where the task-irrelevant stimulus on one trial is repeated as the task-relevant stimulus on the next (see rows 10 and 13 on Table 1) are known as negative priming trials (Tipper, 2001) and have the most detrimental influence on response times.

Egner (2007) acknowledged that in a two-choice task such as the Simon or Flanker, the feature-repetitions associated with each trial transition type (cC, iC, cI, iI) are different than in a Stroop task. Figure 8 demonstrates all the feature-repetitions according to trial transition type that occur in a Simon task. A key premise to Hommel et al. (2004)'s Feature Integration account of congruency-sequencing effects is that, in a two-choice task, congruency and feature-repetitions are characteristically confounded. That is, complete feature-repetitions or complete feature-alternations would occur on all

cC and iI trials – the trials comparatively fastest in the congruency-sequencing effect. Conversely, cI or iC trials *always* contain a partial-feature repetitions which are slower due to partial activation of the previously formed event file. Independently of Hommel's findings, Mayr et al. (2003) raised the same concerns that speeded responses on cC and iI trials compared to cI and iC trials could in fact be due to exact stimulus-response repetitions, opposed to top-down modulations in control.

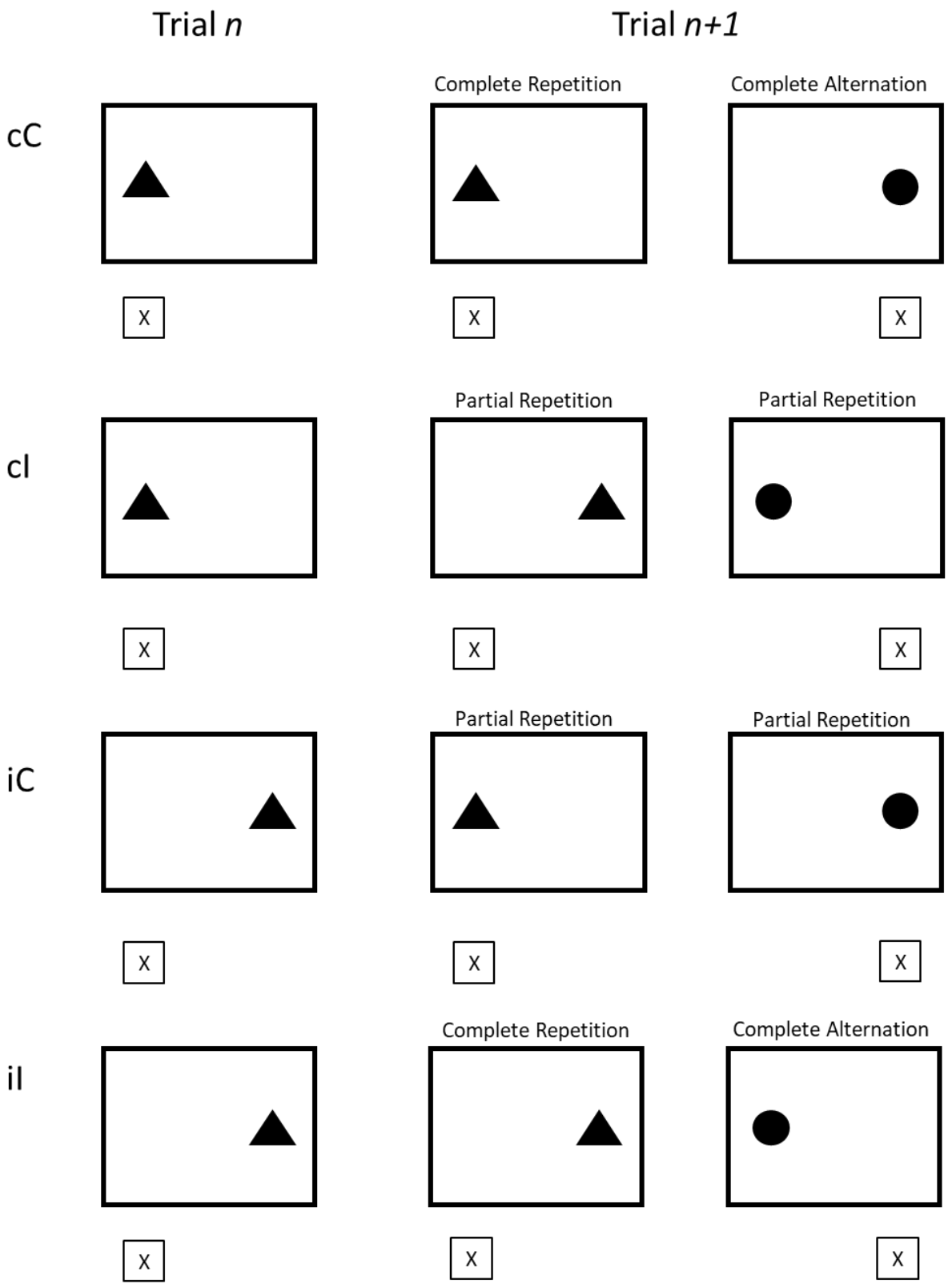

Trial *n*
Trial *n+1*
cC
Complete Repetition
Complete Alternation
X
X
X
cI
Partial Repetition
Partial Repetition
X
X
X
iC
Partial Repetition
Partial Repetition
X
X
X
iI
Complete Repetition
Complete Alternation
X
X
X

Figure 8. The feature-repetitions associated with a Simon task for each trial transition type (cC, cI iC, iI). The stimulus is displayed in the rectangular box and the response is shown in the small crossed square underneath. In this task the instruction is to respond to a triangle with a left button press and a circle with a right button press. The leftmost stimulus represents trial n and the subsequent two stimuli on each row are the two possible stimuli on trial n+1 and whether they include a complete or partial feature-repetition or whether they are a complete alternation (no feature-repetition). Row one shows that to complete a cC sequence, the subsequent trial could be either a complete-repetition or a complete-alternation. The same is true to complete an iI sequence, as shown in row four. On the other hand, to complete either an iC or cI sequence, all possible stimuli incur a partial feature-repetition of either the stimulus (middle column) or the response (right column), and as a result will be slower.

1.8.1. Controlling for Feature-Repetitions

To investigate the influence of feature-repetitions on the magnitude of the congruency-sequencing effect, Mayr et al. (2003) analysed data from a Flanker task in accordance with whether the cC and iI transitions were a complete feature-repetition or feature-alternation of the previous trial type. The Conflict-Monitoring Model does not differentiate between stimulus-response repetitions or alternations, whereas the Feature-Integration account predicts the congruency-sequencing effect will be eliminated on cC and iI trials where the stimulus-response features alternated from the previous trial. They found that complete feature-repetition trials generate a large congruency-sequencing effect that was absent during the feature-alternation trials, which they concluded to suggest minimal top-down involvement. These findings were further replicated in a Stroop task (Notebaert et al., 2006). In contrast, both Gratton et al. (1992) and Ullsperger et al. (2005) performed the same analyses of their Flanker tasks and reported a reliable congruency-sequencing effect on both stimulus-response exact feature-repetitions and complete feature-alternations. The latter was concluded to support top-down influences underpinning the congruency-sequencing effect. In summary, there is some evidence to suggest the congruency-sequencing effect may be confined to trials containing feature-repetitions but there is also evidence to suggest the trial-by-trial modulation of response times may be driven by other (top-down) mechanisms.

In a seminal study, Kerns et al. (2004) claimed to address the feature-repetition confound within a Stroop task by post-hoc removal of feature-repetition trials during their analysis. They found a robust congruency-sequencing effect whereby the Stroop effect was 55ms smaller when the previous trial was incongruent. This was further supported by their fMRI data that found increased BOLD activity in the ACC during incongruent trials that was coupled with increased right DLPFC BOLD activity on the subsequent trial. This was the first compelling evidence in support of the conflict-monitoring account that acknowledged the feature-repetition confound. Since then, post-hoc removal of feature-repetitions had become common practice, however, it is not an optimal approach for two reasons.

Firstly, this thesis contests that the effect of the feature-repetitions trials on the remaining and analysed feature-alternation trials is unknown and may differ from a task that was designed to not include any feature-repetitions. Secondly, some studies only remove exact stimulus-response repetitions without accounting for partial feature-repetitions (Aschenbrenner et al., 2015), the latter have been shown to influence response times (Tipper et al., 2001). Therefore, this thesis argues against the post-hoc removal of feature-repetitions from a conflict task (such is commonly practised), may not be the most suitable approach for eradicate the possibility that feature-repetitions underpin the congruency-sequencing effect. Instead, it is more fitting to design a task in which no feature-repetitions occur and consists exclusively of feature-alternation trials (rows 1, 5, 8 & 15 on Table 1).

As demonstrated in Figure 8, it is not possible to design a sequence that exclusively contains feature-alternation trials from a two-choice task because all iC and cI trials contain a partial feature-repetition (Hommel et al., 2004). Therefore, as acknowledged by Egner (2007) it is most prudent to use a Stroop task because this includes an infinitely large stimulus-response pool which would allow for feature-alternation only trials and thus isolate any top-down influence of the congruency-sequencing effect. In a five-choice Stroop task, the cC trials still contain an exact stimulus-response repetition on 50% of the trials (see rows 1-2 of Table 1), however, due to a larger stimulus-response pool, this probability changes for iI trials. Now there are fewer exact, stimulus-response repetitions but more partial feature-repetitions (see rows 10-14 of Table 1). This has two important implications. First, it can be expected the influence of exact feature-repetitions will be lessened on iI trials because fewer trials will contain exact feature-repetitions and more trials will contain partial feature-repetitions than those in two-choice task as described in Mayr et al. (2003). Secondly, due to the disproportion number of cC trials containing an exact stimulus repetition compared to iI trials (which contain more partial feature-repetitions (see rows 11-15 of Table 1), the comparison of the congruency-sequencing effect during feature-repetitions/ alternations performed by Mayr et al. is no longer suitable, representing a need to completely remove feature-repetitions.

Feature Integration				
	Stimulus Example	Complete Repetition-Repetition	Partial Feature-Repetition	Complete Alternation (No priming)
Congruent – Congruent (cC)				
1)	RED_{red} → RED_{red}	X (+ve)		
2)	RED_{red} → $BLUE_{blue}$			X
Congruent – Incongruent (cI)				
3)	RED_{red} → RED_{blue}		X	
4)	RED_{red} → $BLUE_{red}$		X	
5)	RED_{red} → $BLUE_{yellow}$			X
Incongruent – Congruent (iC)				
6)	RED_{blue} → RED_{red}		X	
7)	RED_{blue} → $BLUE_{blue}$		X	
8)	RED_{blue} → $GREEN_{green}$			X
Incongruent – Incongruent (iI)				
9)	RED_{blue} → RED_{blue}	X (+ve)		
10)	RED_{blue} → $BLUE_{red}$		X (-ve)	
11)	RED_{blue} → $YELLOW_{blue}$		X	
12)	RED_{blue} → $BLUE_{yellow}$		X	
13)	RED_{blue} → $YELLOW_{red}$		X (-ve)	
14)	RED_{blue} → RED_{yellow}		X	
15)	RED_{blue} → $GREEN_{yellow}$			X

Table 1. An outline of all possible feature-repetition types in a Stroop task according to trial sequence type. The first column refers to a complete feature-repetition during which the task-relevant stimulus, task-irrelevant stimulus and response are all exactly the same. The second column refers to a partial feature-repetition where either the task-relevant or task-irrelevant stimuli repeat. Column three represents a complete alternation on which neither the task-relevant nor task-irrelevant stimuli repeat from trial n to trial n+1. Additionally, '+ve' and '-ve' highlights example stimuli that contain particular feature-repetitions that constitute positive or negative priming, respectively.

1.8.2. Removing Feature-Repetitions

Whilst the notion of designing a task without feature-repetitions may seem intuitive, very few papers have utilised such a design. Of those who have, the findings are mixed. Duthoo and Notebaert (2012) and Duthoo et al. (2014) report reliable congruency-sequencing effects in the absence of feature-repetitions, However, Puccioni and Vallesi (2012b) performed a manual Stroop task in the absence of feature-repetitions and failed to report a robust congruency-sequencing effect. It should be noted that they used a long inter-stimulus-interval (ISI), which may explain why they were unable to observe a congruency-sequencing effect because longer ISIs have been correlated with smaller congruency-sequencing effects (Egner, 2007, Jackson and Balota, 2013). More recently, Aschenbrenner and Balota (2017) have shown a reliable congruency-sequencing effect in a vocal Stroop task in which all feature-repetitions were removed a-priori from the trial sequence. This provides some initial support that the congruency-sequencing effect is not exclusively a product of feature-repetitions and endorses the use of an appropriately elicited congruency-sequencing effect as a behavioural index for investigating top-down modulation of response conflict: conflict adaptation. This provides a paradigm to expand on the research that has been using the congruency-sequencing effect in tasks including feature-repetitions to explore differences in processing across populations, such as ageing (Aschenbrenner and Balota, 2017, Larson et al., 2016, West and Moore, 2005) or Parkinson's disease (Wylie et al., 2009a, Wylie et al., 2009b).

1.9. Overall Thesis Aims

At present, there are three possible mechanisms that may underpin the congruency-sequencing effect. Chapter Three designed a vocal Stroop task free from feature-repetitions to identify whether a top-down component contributes to the congruency-sequencing. This provided a paradigm that isolated the top-down component of conflict adaptation to investigate age-related differences. Chapter Four used non-invasive brain stimulation to provide causal evidence for the involvement of top-down control, specifically the left DLPFC, in producing the congruency-sequencing effect. Chapter Five used behavioural manipulations to differentiate between proactive and reactive top-down control processes. Overall, this thesis aims to determine which of the three models proposed in Figure 5 most likely produces the congruency-sequencing effect.

Chapter Two: General Methods:

This section will outline the specific task design for a feature-repetition free (FRF) Stroop task. This task is used in its entirety in Chapters Three and Four. An abbreviated version is used during the test-phases of repetition/ alternation manipulations of experiment one of Chapter Five.

2.1. Participants

All chapters and experiments included younger adults, however, chapter one also included older adults. Younger adults (aged 18-39) were recruited from the School of Sport, Exercise and Rehabilitation Science at the University of Birmingham. Older adults (aged 55-85) were recruited through two advertisement branches: the 1,000 Elders' database and community sampling. The 1,000 Elders is a bank of older volunteers who have agreed to be contacted regarding research opportunities at were tested at the University. Through links with a local church group, an advert was also placed to recruit participants from the community and testing took place in the local vicarage. Participants were offered course credit for participation (where applicable) or remunerated £7 in addition to travel expenses. All participants provided written informed consent and all studies were performed in accordance with the Declaration of Helsinki. And approved by the University of Birmingham's STEM research ethics committee (ERN_15_1573; ERN_18-2077AP6 ERN)

Participants self-identified against the following exclusion criteria: 1) They were not colour-blind; 2) They must be native English speakers because the Stroop effect relies on the conflict between the automaticity of reading and the task instruction and as such, is reduced in bilinguals (MacLeod, 1991); 3) They must not have a speech impediment such as a stutter that would prevent precise detection of the vocal response onset; 4) They must not have a visual impairment not corrected via glasses; 5) They

must not have suffered any neurological conditions such as stroke, dementia, Alzheimer's or Parkinson's disease and should be considered neurological healthy.

2.2. Apparatus and Materials

Participants were seated comfortably at a desk with an audio technical cardioid ATr20 microphone positioned. They viewed and responded verbally to Stroop stimuli presented on a 16.9" Sony desktop monitor (1366 x 768 pixels, 60Hz refresh rate). The screen was distanced approximately 70cm to provide horizontal and vertical viewing angles of 16.7° and 2.5°, respectively. The experiment was conducted with two desktop computers: the first computer conducted the experiments where stimuli was displayed using Psychopy software v.1.8. (Peirce et al., 2019); and the second computer recorded the microphone responses, digital triggers and photodiode output using a Micro-1401 analogue-digital converter and Signal version 6.01 software (both Cambridge Electronic Design, Cambridge, UK) operating with a 2000ms sampling rate. Digital triggers coded in Psychopy were sent to the Micro-1401 using a Labjack U3 (LabJack Corporation, Lakewood, Colorado, USA). A photodiode was placed in the bottom right corner of the stimulus screen to detect changes in screen luminosity that were coupled with the stimulus presentation.

2.3. Task Design and Procedure

Procedure: All participants completed a five-choice vocal Stroop test (Stroop, 1935) featuring the words red, blue, yellow, green, and pink. Participants were instructed to verbally respond *'as quickly and accurately as possible'* to the ink colour of the word as soon as it was presented, as per Figure 9. They were asked to avoid stammering before giving their response, for example, "errr… green", to ensure a clear response onset was detected from the microphone trace (see Figure 9). They were further instructed to avoid coughing or making other voluntary sounds that may be detected by the microphone. The experimenter sat out of view and recorded incorrect responses.

Trial Overview: At the beginning of each trial, Psychopy sent a digital trigger through the LabJack via the 1401 to second computer to initiate a new frame recording in Signal. Approximately 50ms later, the stimulus is displayed on screen, coupled with a small, coloured square in the bottom right-hand corner. The photodiode detects the change in luminosity from the coloured square and the change in Voltage from <1 to ~+3μV is recorded in Signal (see the top trace of Figure 10). This precisely details when the stimulus appeared on screen and is used to calculate the response times. The stimulus remains on screen for 60 frames (~1 second), which can be seen by a decrease in the photodiode trace after this period. While the stimulus is on screen, additional digital triggers are sent to detail: 1) the congruency of the trial; 2) the word displayed; 3) the ink colour of the word. From these triggers, it is known what was the exact stimulus displayed on any given trial. This was followed by an inter-stimulus interval of 500ms (800ms for older adults) during which was a blank, white screen.

Stroop Stimuli: The words red, blue, yellow, green, and pink were presented in the centre of a white background. They were 1cm in height, printed in Calibri font. The colours were presented using the following RBG codes red: [1,-1,-1], blue: [-1,-1,1]; yellow: [1,1,-1], green: [-1,1-1], pink: [1,0,1].

Trial Classification: Trials are congruent if the word and ink colour were the same, for example, the word red printed in red ink, (see Figure 9 trial *n*-1) and incongruent if they were not, for example, red printed in blue ink (see Figure 9 trial *n*).The primary aim of the thesis was to investigate the extent to which response conflict on the previous trial (*n*-1) influenced response times on trial *n*. Therefore, trials were further categorised depending on whether the previous trial (n-1) was congruent or incongruent. Thus, congruent-congruent (cC), congruent-incongruent (cI), incongruent-congruent (iC), or incongruent-incongruent (iI) trial transitions emerge, for example, Figure 9 shows an example stimulus in which a congruent trial is proceeded by an incongruent trial, and is therefore, classified as a cI trial.

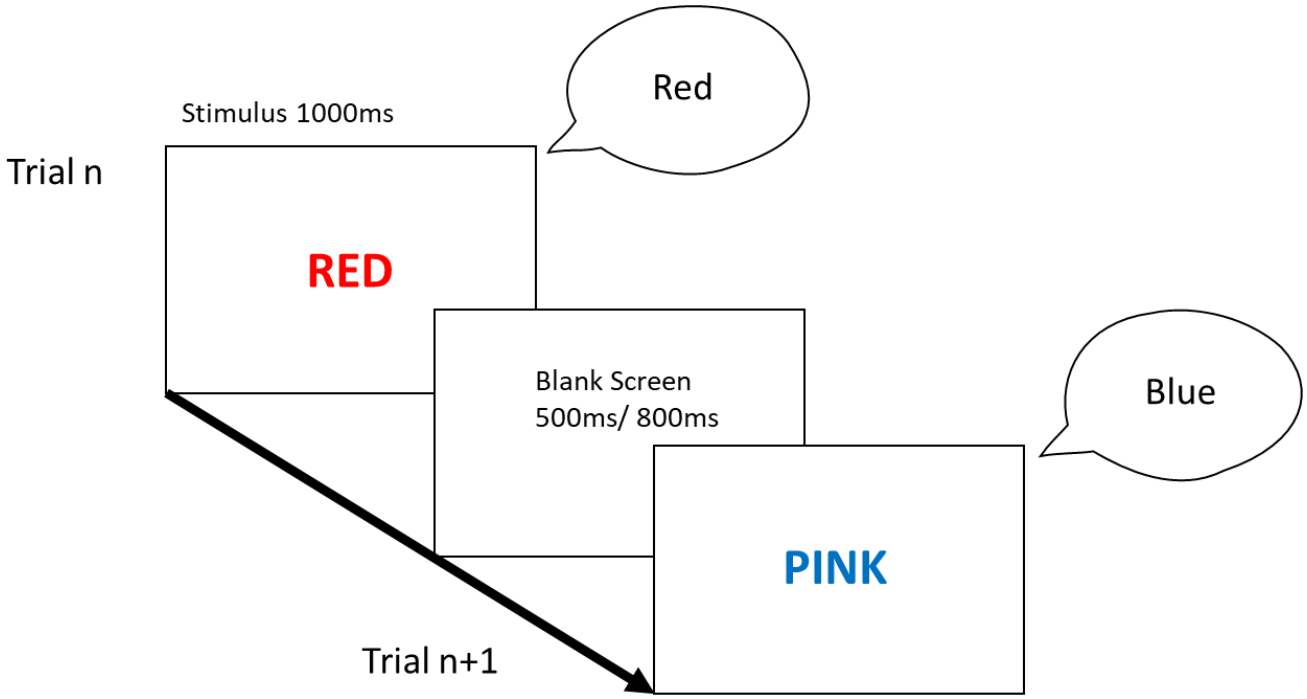


Figure 9. The stimulus displayed for younger and older adults. Trial n displays a congruent trial where the correct response (indicated by the speech bubble) was to say red and trial n+1 an incongruent trial where the correct response was blue. For both groups, the stimulus was presented for 60 frames (~1000ms). During the inter-stimulus interval, younger adults were presented with a blank screen for 500ms, whereas for older adults this was 800ms to accommodate their expected slower responses.

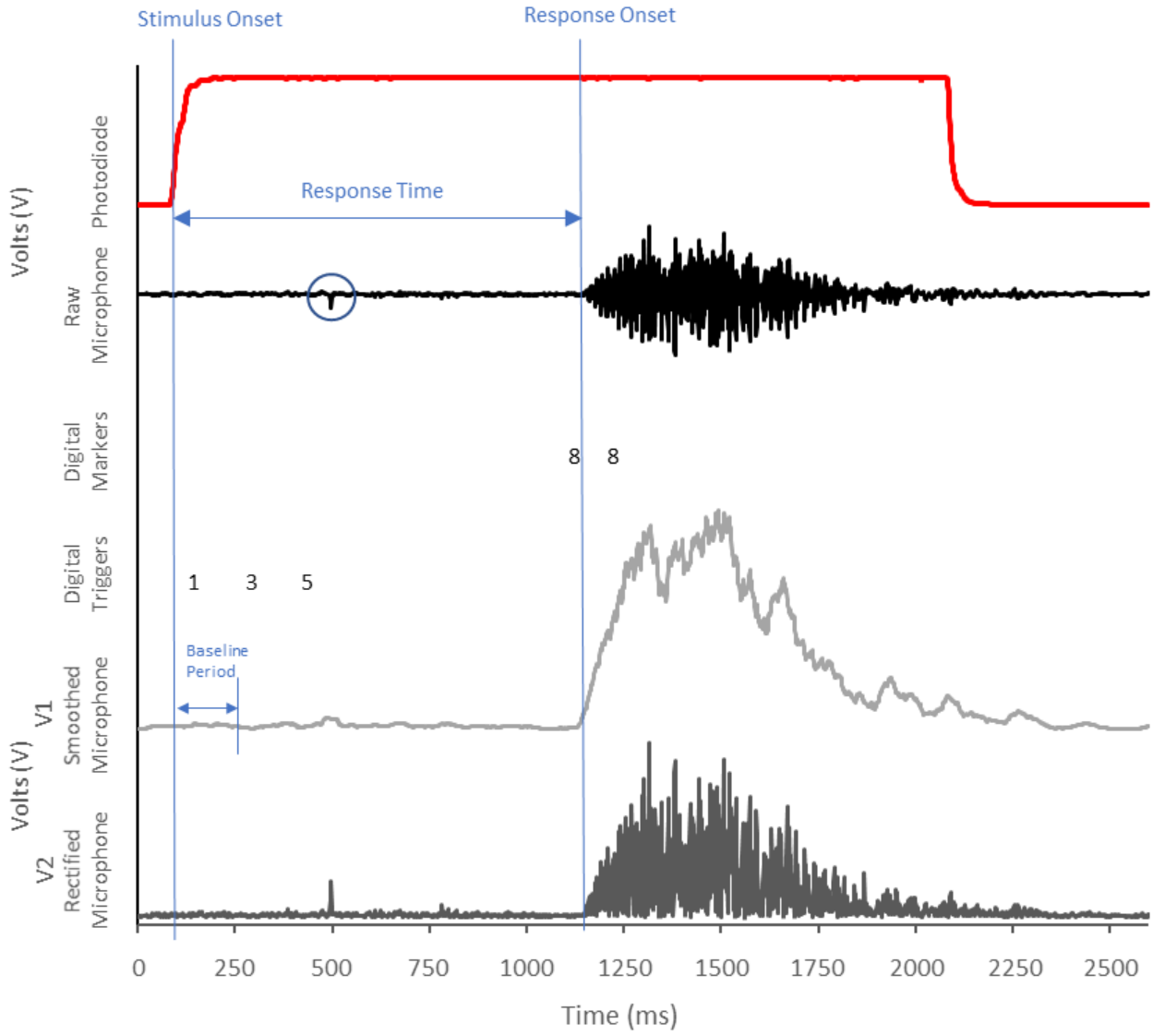


Figure 10. Example raw data of a single frame from Signal (CED) to record one trial of the Stroop task. The top red line is the photodiode trace and indicates the stimulus onset. The black line is the raw microphone trace. This is first rectified (dark grey trace at the bottom) and then smoothed (light grey line) so the analysis script can calculate the response onset. The digital triggers are sent from Psychopy and pertain to the congruency, word, and ink colour of the stimulus. The digital markers are used to identify when the smoothed microphone trace crosses the threshold calculated from the baseline period. Everything in blue has been augmented onto the figure, for example, the blue circle highlights a noise artefact detected from the raw microphone trace. Note, the smoothed channel is relatively unaffected by this artefact, therefore is used to search for the approximate response onset, before returning to the temporarily refined rectified trace to start working backwards from this point to search for the response onset with greater temporal resolution.

2.3.1. Task Choice – The Stroop Test

As outlined in the introduction, a variety of tasks have been designed for measuring different aspects of response conflict (e.g., Flanker, Simon, Stroop). The aim was to investigate the congruency-sequencing effect in the absence of feature repetitions, which is best done in a verbal Stroop task for two reasons. First, the stimulus-response repertoire of the Stroop task can be expanded to include many word-colour stimuli pairings. This was critical when designing a trial sequence free from feature-repetitions. The Flanker and Simon tasks are typically two-choice (left or right) tasks, where it is not possible to remove all feature-repetitions. For example, on a congruent trial (< < <) feature-repetitions can only be avoided by a complete alternation on another congruent trial (> > >). If the next trial were to be incongruent, there is must be repetition of either the task-irrelevant stimulus (> < >) or the task-relevant stimulus (< > <). This could be expanded to a four-choice task (up and down), however, this may introduce an orthogonal confound whereby right stimuli are associated with down and left stimuli with up responses (Weeks and Proctor, 1990). However, a Stroop task can be expanded to include five or more stimulus-response pairings without any such ramifications. A larger response set may be associated with slower response times but this would affect congruent and incongruent trials equally so would not change the Stroop effect (MacLeod et al., 1991).

A verbal Stroop task was chosen over a manual Stroop task due to the lack of complexity on behalf of the participant. In a manual Stroop task with a sufficiently sized stimulus-response pool to remove feature-repetitions, this requires learning of five stimulus-response mappings, typically requiring two hands to perform. Alternatively, others have paired more than one colour with a specific response key, such that the task-relevant stimuli of either red or blue is associated with the same key press. This creates an unintuitive stimulus-response mapping when one of these colours appears as the task-irrelevant stimuli paired with the task-relevant stimuli associated with a different response key. Therefore, a verbal Stroop does not rely on the participant's capacity to maintain the relevant stimulus-response mappings in their working memory throughout the task (MacLeod, 1991).

2.3.2. Feature-Repetitions

As outlined, there are four key trial transitions (cC, cI, iC, iI). The aim is to select stimuli that allows transitions that do not contain any feature-repetitions. For each trial transition, there are four feature-repetition types to be considered: task-relevant to task-relevant – where the ink colour repeats from one trial to the next (column *a* of Table 2); task-relevant-to-task-irrelevant stimulus repetitions – where the ink colour on the previous trial becomes the word on the current trial (column *b* of Table 2); task-irrelevant-to-task-relevant repetitions – where the word on the previous trial becomes the ink colour on the current trial (column *c* of Table 2); as well as task-irrelevant-to-task-irrelevant repetitions – where the word is repeated from the previous to the next trial (column *d* in Table 2).

Table 2 demonstrates the possible feature-repetitions associated with each trial sequence (cC, cI, iC, iI). After a congruent trial (RED_{red}), for example, another congruent trial (cC) can only result in either a complete feature-repetition of the previous stimulus (RED_{red}) or a complete feature-alternation ($BLUE_{blue}$) (see rows one and two of Table 2). However, if the next trial were incongruent (cI) then either the task-relevant ($BLUE_{red}$) or task-irrelevant (RED_{blue}) stimulus feature could repeat onto trial *n*+1 (see rows three and four of Table 2), or a complete feature-alternation, as per row five of Table 2. After an incongruent trial (RED_{blue}), a congruent trial (iC) would incur a task-relevant feature-repetition if trial *n*+1 were blue ($BLUE_{blue}$) or a task-irrelevant feature-repetition were it red (RED_{red}) (see rows six and seven of Table 2). If trial *n*+1 was any colour other than red or blue, then the iC sequence would be a complete feature-alternation (as per row eight of Table 2). If trial *n*+1 was also incongruent (iI) there are many possible feature-repetitions that could occur, for example RED_{blue} or $BLUE_{red}$ would both include repetition of both the task-relevant and task-irrelevant features. $YELLOW_{blue}$ would include a task-relevant feature-repetition and $YELLOW_{red}$ or RED_{yellow} a task-irrelevant feature-repetition. As such, there are far fewer possible word-ink combinations that do not include a feature-repetition of any kind (such as $YELLOW_{green}$) that can be included in the feature-repetition free sequence. This highlights the complexity of designing a task consisting only of designing a feature-repetition free task.

Only trials on which no feature-repetitions were incurred (see Table 2 for examples – row 2 for cC trials; row 5 for cI; row 8 for iC and row 15 for iI trials) were included in the trial sequence. For this reason, a predetermined trial sequence was used for all participants and repeated across all experiments.

		Feature Repetition Types			
Trial Transition Types		Task-Relevant -to- Task-Relevant	Task-Relevant -to- Task-Irrelevant	Task-Irrelevant -to- Task-Relevant	Task-Irrelevant -to- Task-Irrelevant
Congruent – Congruent (cC)					
(1)	RED_{red} → RED_{red}	X	X	X	X
(2)	RED_{red} → $BLUE_{blue}$				
Congruent – Incongruent (cI)					
(3)	RED_{red} → RED_{blue}		X		X
(4)	RED_{red} → $BLUE_{red}$	X		X	
(5)	RED_{red} → $BLUE_{yellow}$				
Incongruent – Congruent (iC)					
(6)	RED_{blue} → RED_{red}			X	X
(7)	RED_{blue} → $BLUE_{blue}$	X	X		
(8)	RED_{blue} → $YELLOW_{yellow}$				
Incongruent – Incongruent (iI)					
(9)	RED_{blue} → RED_{blue}	X			X
(10)	RED_{blue} → $BLUE_{red}$		X	X	
(11)	RED_{blue} → $YELLOW_{blue}$	X			
(12)	RED_{blue} → $BLUE_{yellow}$		X		
(13)	RED_{blue} → $YELLOW_{red}$			X	
(14)	RED_{blue} → RED_{yellow}				X
(15)	RED_{blue} → $YELLOW_{green}$				

Table 2. Examples of possible stimulus trial transitions (cC, cI, iC, cI), with a cross indicating the feature-repetitions they contain. For the trial transition types, the word in capitals pertains to the word (task-irrelevant) displayed, and the subscript letter describes the ink colour in which it was displayed (task-relevant). The descriptor pair before the arrow refers to the stimulus on the previous trial (n-1) with the descriptor after the arrow indicating the stimulus on the current trial (n). Row three, for example, represents the congruent trial red printed in red, followed by the incongruent trial red printed in blue. For each trial transition type the bottom rows (2, 5, 8 and 15) demonstrate transitions on which there are no feature-repetitions, as denoted by no crosses under any of the feature-repetitions and were the only transition types included in this study.

2.3.3. Task Congruency

Another important consideration in task design is how to determine the appropriate level of task congruency. It will become clear that this is inversely related to a concept Schmidt et al. (2007) refers to as the contingency bias that interferes with response times. Consequently, a trade-off between these must be achieved.

In a five-choice a Stroop task, the chance probability of each word appearing in the congruent ink colour is 20%. This results in a task with high percentage (80%) of incongruent trials. When conflict is common, the congruency effect is smaller (Gratton et al., 1992; Carter et al., 2000) and in some instances (i.e., the Simon task) has been shown to reverse (Ridderinkhof et al., 2011, Schmidt and De Houwer, 2011). Additionally, Mordkoff (2012) have failed to observe a congruency-sequencing effect when the task congruency is set to probability levels. For this reason, the task-congruency is often set to 50% (Duthoo and Notebaert, 2012) or even 70% (Mayr and Awh, 2009).

If the congruency ratio is higher than that of chance level, a word will appear more often in the congruent ink colour than that of the other incongruent ink colours. Schmidt et al. (2007) refers to as the contingency bias. They have shown that by presenting a word in one ink colour more frequently than another, participants learn the common S-R pairings and respond faster to these trials because the predicted response (from the task-irrelevant stimuli) will more likely be the correct response. For example, if the word red printed in blue (RED_{blue}) is presented more frequently than the word red printed in yellow (RED_{yellow}) or red printed in red (RED_{red}) the task-irrelevant stimuli red is more predictive of the response blue than yellow or red. Therefore, RED_{blue}, RED_{yellow} and RED_{red} should all be presented equally as often, which can only be achieved through chance levels of task-congruency.

Nevertheless, setting the congruency to 50% is the only way to ensure there is an equal number of trials within each trial transition type (see Table 3), which assists with statistical analyses by ensuring equal power between conditions. For example, if the congruency were set at chance (20%), a task consisting of 400 trials would result in 80 congruent and 320 incongruent trials – this would mean 80% of these incongruent trials would be preceded by an incongruent trial (256 iI trials) and 20% would be preceded by congruent trials (64 cI trials). Likewise, of the 80 congruent trials, 80% would be preceded by incongruent trials (64 iC trials) and only 20% preceded by another congruent trial (16 cC). At chance congruency there are 20 times more iI than cC trials. A task congruency to 50% has also shown reliable congruency-sequencing effects (Aschenbrenner and Balota, 2017, Blais et al., 2014, Duthoo and Notebaert, 2012). For these reasons, the task congruency was set to 50%.

At 50% task congruency, it is no longer possible to equally display each word-colour pairing. On congruent trials (RED_{red}), the task-irrelevant stimulus will be more predictive of the correct response than on incongruent trials (RED_{blue} or RED_{yellow}). However, the contingency bias can be addressed on the incongruent trials to make sure the task-irrelevant stimulus red is not more predictive of the response blue than yellow by displaying RED_{blue} and RED_{yellow} an equal number of times.

To achieve this, the total number of trials must be considered carefully. Table 3 demonstrates that 400 trials provided 100 trials in each trial transition type. 200 trial were congruent, but in the remaining 200 incongruent trials, each word-colour pair were presented equally as often. Further, a pilot study found that participants responded faster to specific colours, specifically that they were faster to the colour red than green. Therefore, it was further ensured that every colour was equally distributed across each trial transition type so that faster responses on a given trial sequence could not be attributed to more frequent presentation of any colour (see Table 4).

The congruency-sequencing effect explores the influence of the congruency of the previous trial on response times, so when designing the task, the start of each block required a 'void' trial to start off the sequence of analysable cC, cI, iC, iI trials. Therefore, the total number of performed trials in each task was the number of analysable trials plus *n* where *n* refers to the number of blocks per task. For example, in the feature-repetition free task, the number of analysable trials is 400 completed over five blocks, therefore 405 were performed, with the first trial of each of the five blocks discarded. Throughout the thesis, only the analysable number of trials (performed trials – *n*) will be referred to in each chapter.

2.3.4. Inter-Stimulus-Interval

The time between trials could have been set as either the ISI, which is defined as the time between the offset of the stimuli on one trial and the onset of the stimuli on the next, or the response-interval, which is defined as the time between the participant's response on one trial and the onset of the stimulus on the next. Use of an ISI would see the task progress at a set speed, whereas use of a response interval would mean that the task would progress according to how quickly the participant responded. This study opted to use a fixed (ISI) opposed to a response-interval interval to remove the possibility of the next trial incorrectly being triggered by background noise opposed to the participant's response (such as the spike highlighted in Figure 10) which would result in inaccurate response times.

There is evidence (Egner et al., 2010, Notebaert et al., 2006, Wuhr and Ansorge, 2005) to suggest the magnitude of the congruency-sequencing effect is influenced by the delay between trials. Egner et al. (2010) reported largest congruency-sequencing effects with ISIs between 500-1000ms that followed a linear decrease in the magnitude of the congruency-sequencing effect associated with longer (6,000 – 7,000ms) ISIs. Therefore, for all experimental tasks performed by younger adults, the ISI was set to

500ms, and to allow for their slower processing times obtained from pilot studies, the ISI was set to 800ms for all experimental tasks performed by older adults.

	% of trials on which the participants say…					
	Total (%)	Red	Blue	Yellow	Green	Pink
Congruent	50	10	10	10	10	10
Incongruent	50	10	10	10	10	10
cC	25	5	5	5	5	5
iC	25	5	5	5	5	5
cI	25	5	5	5	5	5
iI	25	5	5	5	5	5

Table 3. The task design and composition of trials in experiment two. All word-colour combinations are equally distributed across all four congruency-sequence trial conditions.

Stimulus	%	Stimulus	%	Stimulus	%	Stimulus	%	Stimulus	%
RED	**50**	**BLUE**	12.5	**YELLOW**	12.5	**GREEN**	12.5	**PINK**	12.5
RED	12.5	**BLUE**	**50**	**YELLOW**	12.5	**GREEN**	12.5	**PINK**	12.5
RED	12.5	**BLUE**	12.5	**YELLOW**	**50**	**GREEN**	12.5	**PINK**	12.5
RED	12.5	**BLUE**	12.5	**YELLOW**	12.5	**GREEN**	**50**	**PINK**	12.5
RED	12.5	**BLUE**	12.5	**YELLOW**	12.5	**GREEN**	12.5	**PINK**	**50**

Table 4. Addressing the contingency bias: The percentage of trials from each experiment in which each word-colour combination was presented. 50% of the trials are congruent (the task-relevant word is presented in its own ink colour), for the remaining 50% of trials each task-relevant word is presented as frequently in in each task-irrelevant ink colour as each other.

2.4. Data Analysis

2.4.1. Response Times

Response times were calculated as the time between the stimulus onset and the response onset. A delay of one frame in the stimulus presentation would result in 16.67ms inaccurate calculation of response times. This is an unacceptable margin of error due to the discrete difference the congruency-sequencing effect is represented by. Therefore, the photodiode established the onset of the stimulus with a temporal resolution of 0.5ms was used to assure the experiment timings. When the photodiode trace crossed threshold of 1V, this marked the stimulus onset (see Figure 10). From here, the response onset was calculated using an automated script written and applied in the Signal software. First, the raw microphone trace was rectified (see bottom trace on Figure 10) in channel V2 and then smoothed by 10ms to form a continual trace in V1 (the light grey line on Figure 10). The script then calculated the mean and standard deviation of the rectified and smoothed microphone signal during the baseline period (100-250ms). Potential response onsets were digitally marked (see Figure 10) from when the rectified and smoothed microphone signal increased above a mean + 3 * SD threshold and continued to rise for at least 21ms. The advantage of using the smoothed channel is that it is less affected by any 'blips' or false alarms from the microphone that are not valid responses (see circled artefact in Figure 10). Therefore, only once a signal continues to increase for more than 21ms is it considered a potential valid response.

Due to the loss of temporal resolution that occurs by smoothing, the script then returned to rectified and unsmoothed trace to search backwards from the potential response to identify the first time at which the rectified and unsmoothed signal increased above a mean + 5 * SD threshold. This was then identified as the response onset. Every trial was manually checked to ensure an appropriate response onset was identified. Any trials on which there was ambiguity were marked as an 'analysis error'. Additionally, trials on which the script could not detect a response onset, often because the baseline

867 period was contaminated with a very slow response from the previous trial, was also tagged as an
868 'analysis error'.

869 Response times were calculated as the time between the stimulus onset and the response onset. Any
870 responses quicker than 200ms were deemed too fast to be accurate attempts and were removed from
871 all analyses. For each participant, the mean response time for congruent and incongruent trials were
872 calculated separately, and any trials more than 2.5 standard deviations above the means were
873 removed as outliers.

874 Mean response times from specific trials are used to calculate the Stroop effect (incongruent –
875 congruent) as well as the congruency-sequencing effect ((cI-cC)-(iI-iC)).

2.4.2. Delta Plots

876 The diffusion model for conflict tasks (Ulrich et al., 2015) predicts that with slower responses the
877 Stroop effect will be larger. To explore the time course distribution of response times, a quintile
878 analysis was first performed (Ratcliff, 1979). For each participant, response times were first split into
879 congruent and incongruent conditions and then for each condition they were ordered into five
880 quintiles from fastest (quintile 1) to slowest (quintile 5). The Stroop effect was calculated for each
881 response quintile within individual participants and presented in a delta plot as per De Jong et al.
882 (1994). This analysis is predominantly explorative and provides supplementary explanatory power to
883 the main response time analyses.

2.4.3. Block-Wise

884 There is some evidence to suggest the congruency-sequencing effect may be confined to the initial
885 phase of testing. Mayr et al. (2003) decrease in the congruency-sequencing effect from 68ms in the

first ~180 trials, to 4ms during the final ~700 trials of a Flanker task. Therefore, a comparison of the congruency-sequencing effect after each experimental block (80 trials) will examine the longevity of this effect. This is of particular interest to explore the effect of the duration of tDCS stimulation in Chapter Four. However, this also is supplementary to the mean response times.

2.4.4. Data Exclusions

Response Errors: Trials on which the participant outright said the wrong answer ("Blue" on a $BLUE_{red}$ trial) as well as trials on which the participant did not respond or did not clearly say the correct answer (i.e., *"err… red"* or *"Gre-ellow"*) were marked as a response errors by the experimenter during the testing session. The number of response errors analysed are reported as per each experimental chapter.

Analysis Errors: During the analysis of raw signal files (see Figure 10), trials on which a clear response onset could not be identified but were not initially identified as a response error during the testing session were excluded as 'analysis error' trials. No analysis was performed on these trials.

Post-Error Exclusions: Trials after response or analysis errors were also removed. Participants have been found to slow their response times after committing an error in a Stroop task (Regev and Meiran, 2014). Wessel (2018) explains that this could be an adaptive strategy whereby response times are slowed with the intention of improving performance (Botvinick et al., 2001, Ridderinkhof, 2002), as a maladaptive by-product of the error itself (Notebaert et al., 2009) or as a combination of the two (Wessel and Aron, 2017). Irrespective of the underpinning causes, due to the sequential nature of the congruency-sequencing effect, any irregularity on trial *n*-1 may interfere with the response on trial *n*, therefore, trial *n* was also discarded. No analysis was performed on these trials.

2.4.5. Participant Exclusions

Stroop: The basic Stroop effect (incongruent – congruent response times) is a well-established, widely reported behavioural phenomenon (MacLeod, 1990). Any participants who did not show a Stroop effect of at least 5ms were removed from all analyses.

Total Trials: After all trial exclusions (response errors, analysis errors, post-error exclusions, and outliers), participants with fewer than 80% of trials remaining were discarded from all analyses. Blais et al. (2014) reported response errors of typically <1%, thus any participants exhibiting such high response errors are unlikely to have correctly understood the task. Additionally, Duthoo and Notebaert (2012) reported analysing a mean of 83% of all trials in their vocal Stroop task, therefore, a comparable cut-off was also included here.

2.5. Statistical Analysis

JASP (JASP Team (2020), Version 0.11.1) was used for all analyses. Mauchley's test of sphericity was used to test the assumption of the ANOVA and, if violated, Greenhouse-Geisser corrections (denoted with GG after the degrees of freedom) were then used. Multiple comparisons were controlled for by Bonferroni adjustments. The alpha level for statistical significance was set to $p = 0.05$. The analyses presented below were common to all experimental chapters, however, may also include additional variables (age/ stimulation) to accommodate the task design, which have been detailed in accordingly in each chapter.

2.5.1. Response Times

Initially, response times are the dependent variable in a 2 x2 repeated measures analysis of variance (RM ANOVA) with CURRENT-CONGRUENCY (congruent/ incongruent) and PREVIOUS-CONGRUENCY (congruent/ incongruent) as the within-subjects variables. A main effect of CURRENT-CONGRUENCY

would indicate a Stroop effect and an interaction between CURRENT-CONGRUENCY and PREVIOUS-CONGRUENCY would indicate a congruency-sequencing effect.

It is not possible to perform post-hoc analyses on an interaction, therefore, if a reliable congruency-sequencing effect was established, this was then calculated and used as the dependent variable to allow comparison of the magnitude of the congruency-sequencing effect across groups (i.e., age or stimulation etc…).

2.5.2. Power Analyses

A-Priori Sample Size: A-priori power calculations performed using G*Power 3.1.9.4 (Faul et al., 2007) to estimate the required sample size for within-between interactions of a repeated measures ANOVA. Such calculation is applicable to investigate a three-way interaction between PREVIOUS-CONGRUENCY, CURRENT-CONGRUENCY and a third variable between-subjects variable with two levels such as AGE (Chapter Three Experiment One). To observe a small effect size (defined by Cohen, 1998 as 0.1) with an α of 0.05, power (1- β) of 0.8 revealed that a sample size of 32 participants would be required to reveal a significant. The above calculation was repeated for a third within-subjects variable such as TASK (Chapter Three Experiment Two and Chapter Five); or STIMULATION (Chapter Four). This revealed a required sample size of 16 participants. After a reliable PREVIOUS-CONGRUENCY by CURRENT-CONGRUENCY interaction was established, this was used as the dependent variable for subsequent analyses.

Post-Hoc Power: Post-hoc power analyses were used to compute the achieved power for each experimental chapter. β was set to 0.8. Results indicating that the actual power was less than 0.8 would suggest the study was underpowered.

Smallest Effect Size of Interest: To determine the smallest ***meaningful*** difference in the magnitude of the congruency-sequencing effect across two groups/ conditions, the smallest effect size of interest (SESOI) was calculated separately for each experimental chapter. Laken et al., (2018) proposes that when a SESOI has not previously been established in the field, an appropriate starting point is to use the largest reported difference that was not statistically significant from a comparable study. From the original study's alpha and sample size, the following formulae was used to calculate a standardised critical effect size. Thus, if the results obtained from the current study are smaller than the critical effect size, any differences can be considered unmeaningful. The SESOI provides a value against which to perform statistical equivalence tests.

$$\eta_p^2 = F\sqrt{\frac{1}{n_1}+\frac{1}{n_2}}$$

Equation 1. Calculation to determine the smallest effect size of interest, as described by Lakens et al. (2018). Based on previous research, this calculation provides the effect size (partial eta squared) that should be interpreted as a meaningful result by the present study where n equals sample size of each group.

Two One-Sided Tests of Equivalence: For interpreting null effects, two one-sided tests (TOST) of equivalence were used to assess whether the reported results were smaller than the SESOI that, in principle, can be detected within each experiment. This was performed in R version 4.0.3 (RStudio Team, 2020) using the TOSTER package, as outlined by Lakens et al. (2018).

2.5.3. Delta Plots

Separate one-way RM ANOVAs with QUINTILES (1-5) as the within-subjects variable and the Stroop effect and the congruency-sequencing effect as the dependent variables was performed. Polynominal

963 contrasts detailed the relationship of the dependent variable (i.e., linear, quadratic etc…) across the
964 response quintiles.

2.5.4. Block-Wise

965 As per the delta plots, separate one-way RM ANOVAs with EXPERIMENTAL-BLOCK (1-5) as the within-
966 subjects variable and the Stroop effect and the congruency-sequencing effect as the dependent
967 variables was performed. Polynominal contrasts detailed the relationship of the dependent variable
968 (i.e., linear, quadratic etc…) across the experimental blocks.

2.5.5. Response Errors

969 A 2 x2 repeated measures analysis of variance (RM ANOVA) with CURRENT-CONGRUENCY (congruent/
970 incongruent) and PREVIOUS-CONGRUENCY (congruent/ incongruent) as the within-subjects variables
971 and response errors (N) as the dependent variable was performed.

Chapter Three: Exploring Conflict Adaptation and Age

Does the Congruency-Sequencing Effect Reflect Top-Down as Well as Bottom-Up Mechanisms? Is There a Deficit with Ageing?

3.1.0. Introduction:

3.1.1. Cognitive Ageing

In a famous case study, Harlow (1868) tracked and reported changes in Phineas Gage – a patient with damage to the prefrontal cortex inflicted by an iron bar through his frontal regions. After the insult, Gage suffered drastically altered personality and behaviours, from which Harlow deduced the prefrontal cortex must be responsible for these functions. The prefrontal cortex is since known to be responsible for a variety of functions including, personality, language, motor and inhibitory functions, known collectively as executive control (Miller and Cohen, 2001). Successful performance in cognitive tasks often relies on and tests these executive functions. For example, the Stroop test requires inhibition of the prepotent stimulus-response association, a function which has been linked specifically to the dorsolateral prefrontal cortex (Carter and van Veen, 2007, MacDonald et al., 2000, MacLeod, 1991, Miller and Cohen, 2001).

Evidence suggests that older adults are less able to ignore irrelevant stimuli or suppress unwanted behaviours than younger adults (Rey-Mermet and Gade, 2018). This can be studied in a controlled laboratory by using the Stroop task which can measure cognitive inhibition via the basic Stroop effect, as well as conflict adaptation measured via the congruency-sequencing effect, both of which require recruitment of the DLPFC.

A substantial body of literature reports that older adults show larger congruency effects in cognitive tasks such as the Stroop (Andres et al., 2008, Aschenbrenner and Balota, 2015, Belanger et al., 2010, Bugg et al., 2007, Davidson and Zacks, 2003, Hasher and Zacks, 1998, Jackson and Balota, 2013, Puccioni and Vallesi, 2012a, Spieler et al., 1996, West and Moore, 2005). Moreover, this effect is often disproportionally larger than is simply expected to result from their generally slower response times (Aschenbrenner and Balota, 2015, Bugg et al., 2007, Spieler et al., 1996, West and Moore, 2005). West and Alain (2000) reported specific ERP signatures that relate to processing of the task-irrelevant stimulus on incongruent trials in the bilateral frontal regions was diminished in older adults. When considering the Diffusion Model for Conflict Tasks (Ulrich et al., 2015), this suggests that the neuroanatomical changes associated with ageing impair the rate of evidence accumulation towards the task-relevant response boundary. Put simply, older adults are more prone to distraction from the task-irrelevant stimulus due to impaired cognitive inhibition as revealed through a heightened Stroop effect (Andres et al., 2008, Aschenbrenner and Balota, 2015, Bugg et al., 2007, Hasher and Zacks, 1998).

3.1.2. Congruency-Sequencing Effects

As outlined in the General Introduction, there are two top-down accounts of conflict adaptation. Whilst they both suggest recruitment of the DLPFC, a reactive account suggests such recruitment is triggered via the ACC (Botvinick et al., 2001), whereas a proactive account suggests recruitment of the DLPFC is modulated via dopamine release (Braver et al. 2002). The ACC is prone to advanced ageing (Mann et al., 2011, Vaidya et al., 2007) where there is reduced glucose metabolism with ageing (Pardo et al., 2007) that is not seen in other brain regions, for example the primary motor cortex (Pardo et al., 2019). Pronounced declines in the brain's dopamine systems are reported with healthy ageing (Berry et al., 2016). Optimal cognitive performance operates on an "inverted-U-shaped" function, whereby too much or too little dopamine will impair performance (Cools and D'Esposito, 2011). Taken together, both accounts of conflict adaptation would predict reduced congruency-sequencing effects among older adults.

To explore age-related differences in conflict adaptation, West and Moore (2005) performed a manual Stroop task and reported a reliable congruency-sequencing effect in both younger (68ms) and older adults (121ms) that did not statistically differ with age (p=.22). Based on the previously reported anatomical declines in the DLPFC (Cabeza et al., 2018; Furster et al., 2015, West et al., 1996), it is perhaps surprising that firstly, the congruency-sequencing effect did not differ with ageing, but also that the results suggests the congruency-sequencing effect may be larger in older adults which would hint towards *heightened* functioning of the DLPFC that is not predicted by anatomical decline. This is consistent with other who have performed age comparisons on the magnitude of the congruency-sequencing effect during a Simon task (Wylie et al., 2009a); Flanker task (Larson et al., 2016) and vocal Stroop task (Aschenbrenner and Balota, 2015).

To consider why these studies do not report age-related differences in behavioural measures of the functions of the DLPFC, the premise that the congruency-sequencing effect solely reflects top-down mechanisms must be questioned. As fully outlined in the General Introduction, three potential models of the congruency-sequencing effect have been proposed, but only two of these engage top-down control strategies (Conflict-Monitoring model and Repetition Expectancy Model) and require the involvement of the DLPFC. In contrast, the Feature-Integration model (Hommel et al., 2004) proposes that feature-repetitions that naturally occur within conflict tasks can mimic the classic behavioural congruency-sequencing effect pattern due to basic episodic memory files without engaging top-down control strategies. It is, therefore, problematic to use the congruency-sequencing effect as a behavioural index for cognitive control capabilities if the cognitive task has not been designed to exclude feature-repetitions. Unfortunately, the aforementioned studies (Aschenbrenner and Balota, 2015, Larson et al., 2016, West and Moore, 2005, Wylie et al., 2009) suffer from this problem and it cannot be determined whether feature-repetition effects may have been masking any top-down deficits with ageing and may account for why they did not report and age differences.

Attempts to control for these feature-repetition confounds are conducted with varying degrees of rigor. Often researchers follow Kerns et al. (2004)'s approach of conducting a standard Stroop task where feature-repetitions freely occur and then remove such trials from analysis post-hoc. Aschenbrenner and Balota (2015) reported a reliable congruency-sequencing effect during the Stroop task in their life-span study of participants aged 30-96 where they addressed feature-repetitions through post-hoc analyses. Due to the greater prevalence of feature-repetitions following an incongruent trial (iC and iI trials), they performed a separate post-hoc analysis to remove feature-repetitions, but only did so when the previous trial was congruent (cC and cI). They reported that the congruency effect when the previous trial was congruent was of a similar magnitude to when analysing

all trials. They, therefore, concluded the congruency-sequencing effect was not due to priming confounds even though they did not check for this after incongruent trials.

This is not the most eloquent way to address feature-repetitions. It is more prudent to remove them (a-priori) from the task design. To best knowledge, Puccioni and Vallesi (2012a) are the first of very few studies to do so when exploring changes in the congruency-sequencing effect with age. In agreement with the previously reported studies that did not address feature-repetitions, they too did not report any age-related differences in the congruency-sequencing effect in their manual Stroop task. However, Puccioni and Vallesi (2012b) did not observe a reliable congruency-sequencing effect, even in their earlier study of younger adults using the same methodology (Puccioni and Vallesi, 2012a). This is not a considered a limitation of the a-priori exclusion of feature-repetition trials because Duthoo et al. (2014) have used a vocal Stroop task free-from feature-repetitions and reported a reliable congruency-sequencing effects of 22ms when investigating only younger adults. In summary, it is considered that by removing feature-repetitions it is possible to isolate the top-down role underpinning the congruency-sequencing effects to explore age-related differences in cognitive functioning localised to the DLPFC. At the time of performing this experiment (2016), no such study had been performed. Since then, Aschenbrenner and Balota (2017) have also removed feature-repetitions a-priori from their Stroop task and the results will be highlighted in the discussion.

3.1.3. Aims and Hypotheses

The overarching aim of this chapter was to explore one of the proposed functions of the DLPFC (conflict adaptation) and to investigate any age-related deficits in behaviour (the congruency-sequencing effect) that may arise due to previously reported neuroanatomical declines of the DLPFC. This chapter includes two experiments: a feature-repetitions free (FRF) task that is used in experiment one and two,

and a task with feature-repetitions (FRW) that is only included in experiment two. Younger and older adults are investigated in both experiments. The specific aims are detailed below.

Experiment One

Aim One: To isolate the top-down component of conflict adaptation by designing a vocal Stroop task in a feature-repetitions free (FRF) task by a-priori removal in the task design.

Hypothesis One: A) In a task free-from feature-repetitions, a congruency-sequencing effect will emerge, evidencing that factors other than bottom-up influences contribute to the congruency-sequencing effect. B) Acknowledging the role of feature-repetitions in producing the congruency-sequencing effect, it is expected the congruency-sequencing effect will be smaller in a feature-repetition free task than those previously reported in the literature that have conducted post-hoc removal of feature-repetitions.

Aim Two: To use the congruency-sequencing effect as a behavioural measure of DLPFC functioning to inspect any age-related differences.

Hypothesis Two: A) Consistent with reported neuroanatomical declines in DLPFC functioning, older adults will produce a smaller or diminished congruency-sequencing effect compared to younger adults. B) Older adults will also produce a heightened Stroop effect to reflect impaired conflict inhibition of the DLPFC.

Experiment Two

Aim Three: A) To investigate the contribution of feature-repetitions in producing the congruency-sequencing effect compared to a pure FRF task design. This was achieved by designing a second task (with feature-repetitions; FRW Task) where feature-repetitions were meticulously included. B) The

specific contributions of positive and negative priming trials can be isolated to examine their effects on response time. C) To compare the magnitude of the congruency-sequencing effect during post-hoc removal of feature-repetitions (first performed by Kerns et al., 2004) against a pure FRF task design.

Hypothesis Three: A) The FRW task will produce a larger congruency-sequencing effect than the FRF task due the additive influence of both bottom-up and top-down influences. B) Positive priming trials will lead to faster response times and negative priming trials to slower response times compared to the mean iI trials during the FRW task. C) The magnitude of the congruency-sequencing effect on feature-alternation trials in the FRW task will be larger than the FRF task due to the influence of the subsequently removed feature-repetition trials in the FRW task.

Aim Four: To compare the influence of feature-repetitions in producing the congruency-sequencing between younger and older adults.

Hypothesis Four: Experiment two includes two tasks (FRF and FRW). As per hypothesis two, it is predicted that the FRF task (that isolates the top-down component of cognitive control) will elicit a smaller congruency-sequencing effect for older adults. However, it is predicted the FRW task will elicit a larger congruency-sequencing effect in older compared to younger adults. This would support the findings highlighted in the introduction that, seemingly counterintuitively, report a larger congruency-sequencing effect for older adults.

3.2.0. Methods:

3.2.1. Participants

Experiment One: Thirty-seven younger adults aged 19–38 (M 22.5 years) were recruited from the School of Sport, Exercise and Rehabilitation Sciences. Thirty-four older adults aged 65–86 (M 74.1 years) were recruited. Participants were offered course credit (where applicable) or a £10 Amazon voucher as remuneration for their time and travel expenses.

Experiment Two: Forty-three younger adults aged 18–38 (M 20.7 years) and 30 older adults aged 61 – 82 (M 71.1 years) were recruited in the same manner. The two participant pools are separate, that is, no one who completed experiment one also completed experiment two. All participants provided written informed consent and all studies were performed in accordance with the Declaration of Helsinki.

3.2.2. Task Design and Procedure

Both experiments utilised a between-subjects design whereby younger and older adults performed the same task(s) on one occasion.

Experiment One: Participants performed only one task that contained no feature-repetitions in the trial sequencing, and as such, this task is referred to as the feature-repetition free (FRF) task.

Experiment Two: Participants performed two tasks in a counterbalanced order. In addition to the FRF task, participants also performed a task specifically designed with feature-repetitions (FRW).

3.2.2.1. Feature-Repetition Free (FRF) Task

The FRF task was designed specifically to only include feature-alternations. This corresponds to the following rows of Table 2: row 2 for cC trials; row 5 for iC trials; row 8 cI trials and row 15 for iI trials. These rows highlight that neither the task-relevant nor task-irrelevant stimuli repeat from trial *n-1* to

trial *n*. The task consisted of 400 trials split over 5 blocks and the overall congruency was set to 50% as shown in Table 3. As per the general methods, note that within the parameters of the 50% congruency, the contingency bias was also addressed by presenting every word in each incongruent ink colour with equal frequency (see Table 4).

3.2.2.2. Feature-Repetitions With (FRW) Task

In a standard Stroop task, by chance, 50% of cC, 33% of cI, 33% of iC, and 85% of iI trials would include feature-repetitions. Therefore, as shown in an overview of the FRW task-design in Table 5, of the 420 trials in the FRW task, ~70% (290 trials) included feature-repetitions and ~30% (130 trials) were feature-alternations. Table 5 shows how the trials of the FRW task were divided between the four trial transitions and five colours for the feature-repetitions and the feature-alternation trials. Table 6 demonstrates that all the possible feature-repetition types (task-relevant to task-relevant; task-relevant to task-irrelevant; task-irrelevant to task-relevant; task-irrelevant to task-irrelevant) for each of the trial transition types (cC, cI, iC, iI). Table 6 further shows the number of each type of feature-repetitions included in each trial transition. This highlights that some types of feature repetitions, and combinations thereof, occur only in certain trial transitions. For example, rows one and two on Table 6 show that cC trials can only occur with either a complete feature-repetition (i.e., all feature-repetition types) or a complete feature-alternation (i.e., no feature-repetitions). Whereas, unlike a congruent trial, on an incongruent trial, the task-relevant and task-irrelevant stimulus are different colours, therefore, there are far more combinations of task-relevant and task-irrelevant stimuli that enable a feature-repetition to occur for iI transitions (see rows 9-14 of Table 6). This is important to highlight because not all feature-repetitions are thought to have the same influence on response times. For example, when looking at iI trials, those where the task-irrelevant stimuli on the previous trial becomes the task-relevant stimuli on the subsequent trial (i.e., negative priming trials – see row 13 on Table 6) will have a slowing influence (Tipper et al., 2001). Equally, task-relevant to task-relevant feature-

repetitions (see row 11 of Table 6) are considered positive priming trials and are associated with faster responses. Therefore, it should be ensured that these trials did not occur more often than chance.

As mentioned, in the FRW task, feature-repetitions occurred at chance probability, therefore, not on every trial. The bottom of Table 6 also shows the overview of the 130 trials that did not include a feature-repetition within the FRW task (50% of cC trials, 33% of iC, 33% cI and 15% iI trials across the entire FRW task). These trials, which have been labelled as feature-alternations, were also equally distributed across all five possible colours so to avoid any discrepancies in response times to certain colours.

OVERVIEW of With-Feature-Repetitions (FRW) Task (N = 420)							
	%	**N**	**Red**	**Blue**	**Yellow**	**Green**	Pink
Congruent	52%	220	44	44	44	44	44
Incongruent	48%	200	40	40	40	40	40
Feature – Repetitions	69%	290	58	58	58	58	58
Feature – Alternations	31%	130	26	26	26	26	26

Table 5. An overview of the trials in the FRW task. To fall in line with the FRF task (see general methods) the task congruency was kept close to 50%. Feature-repetitions occurred at chance probability (69%) as determined by the feature-repetition possibilities highlighted in Table 6 below. Finally, the trials were equally distributed across the response colours.

Trials including FEATURE-REPETITIONS in the FRW Task (n = 290)								
	Type of Feature Repetition	**Complete/ Partial**	**Stimulus e.g.**	**Red**	**Blue**	**Yellow**	**Green**	**Pink**
cC (n =60)								
1	Task-Relevant > Task-Relevant *and* Task-Relevant > Task-Irrelevant *and* Task-Irrelevant > Task-Relevant *and* Task-Irrelevant > Task-Irrelevant	Complete Repetition	RED > RED	12	12	12	12	12
cI (n = 70)								
3	Task-Relevant > Task-Irrelevant *and* Task-Irrelevant > Task-Irrelevant	Partial	RED > RED	8	8	8	8	8
4	Task-Relevant > Task-Relevant *and* Task-Irrelevant > Task-Relevant	Partial	RED > BLUE	6	6	6	6	6
iC (n = 70)								
6	Task-Irrelevant > Task-Relevant *and* Task-Irrelevant > Task-Irrelevant	Partial	RED > RED	7	7	7	7	7
7	Task-Relevant > Task-Relevant *and* Task-Relevant > Task-Irrelevant	Partial	RED > BLUE	7	7	7	7	7
iI (n = 90)								
9	Task-Relevant > Task-Relevant *and* Task-Irrelevant > Task-Irrelevant	Complete Repetition	RED > RED	2	2	2	2	2
10	Task-Relevant > Task-Irrelevant *and* Task-Irrelevant > Task-Relevant	Partial	RED > BLUE	3	3	3	3	3
11	Task-Relevant > Task-Relevant	Partial	RED > PINK	4	4	4	4	4
12	Task-Relevant > Task-Irrelevant	Partial	RED > BLUE	2	2	2	2	2
13	Task-Irrelevant > Task-Relevant	Partial	RED > PINK	4	4	4	4	4
14	Task-Irrelevant > Task-Irrelevant	Partial	RED > RED	3	3	3	3	3
Trials including FEATURE-ALTERNATIONS in the FRW Task (n=130)								
cC (n=60)								
2	Complete-Alternation		RED > BLUE	12	12	12	12	12
cI (n=30)								
5	Complete-Alternation		RED > PINK	6	6	6	6	6
iC (n=30)								
8	Complete-Alternation		RED > PINK	6	6	6	6	6
iI (n=10)								
15	Complete-Alternation		RED > PINK	2	2	2	2	2

Table 6. Prevalence of feature-repetitions (top) and feature-alternations (bottom) during the FRW task. The top section reports all the possible feature-repetition types and the number included in the task according to colour of the task-relevant stimuli. The bottom section reports the trial breakdown of the 30% of trials that did not include a feature-repetition in the FRW task.

3.2.3. Data Analysis

Data analysis was performed as per the General Methods, but a brief overview is provided below. Trials labelled as response errors, analysis errors or post-error exclusions were removed from the response time analysis through which the Stroop and congruency-sequencing effects were calculated. Response errors (<2% of trials) are also reported.

2.3.1. Data Exclusions

Any participants with less than 80% of valid trials in both tasks (320 in the FRF task and 336 in the FRW task) were also removed from the analysis. This led to the removal of one younger adult and four older adults in experiment one (analyses were performed on 36 younger and 30 older adults) and the removal of four younger adults and two older adults from experiment two (analyses were performed on 39 younger and 28 older adults).

3.2.3.2. Response Times

A 2x2x2 RM ANOVA against PREVIOUS-CONGRUENCY, CURRENT-CONGRUENCY and AGE was performed. For experiment two, the same analyses were performed with the additional within-subjects factor of TASK (FRF/ FRW).

Stroop: A main effect of CURRENT-CONGRUENCY shows a Stroop effect. This is compared across AGE and TASK.

Congruency-Sequencing Effects: A reliable PREVIOUS-CONGRUENCY by CURRENT-CONGRUENCY interaction evidences a congruency-sequencing effect. Once established, this is calculated ((cI-cC)-(iI-iC)) and used as the dependent variable in separate ANOVAs to provide suitable post-hoc age and task comparisons. This also aids with multiple comparisons by reducing the number of variables.

3.2.3.3. Power Analyses

Post-Hoc Power: As per the General Methods, a post-hoc power analysis was performed to determine whether each experiment was adequately powered to observe a difference in the magnitude of the congruency-sequencing effect between age groups.

Smallest Effect Size of Interest: Experiment One – The SESOI was not calculated for the FRF task because the Aschenbrenner et al. (2017) is the only known study to perform an age comparison in an FRF paradigm, however, they inadequately report the data required (the PREVIOUS-CONGRUENCY, CURRENT-CONGRUENCY by AGE interaction) for this.

Experiment Two – The SESOI was calculated using the formulae provided in the General Methods using the data from West and Moore (2005) for two reasons: 1) their protocol most closely mirrored that performed in the present study; 2) they reported the largest non-significant difference in the magnitude of the congruency-sequencing effect between younger and older adults (53ms).

3.2.3.4. Time Course Analyses

Block-Wise: To compare the magnitude of the two outcome measures across experiment blocks, separate RM ANOVAs were performed, whereby the Stroop and congruency-sequencing effect were the dependent variables. The within-subjects variable was BLOCK (1-5), and the between-subjects factor was AGE (younger/ older).

Delta Plots: Delta plots were produced to compare the time-course of the Stroop effect across response speeds. Full details are provided in the General Methods. The Stroop effect was the dependent variable, QUINTILE (1-5) the within-subjects variable, and AGE (younger/ older) the between-subjects variable.

3.2.3.5. Response Errors

Any trials on which the participant said the incorrect response underwent the same analyses as the response times to investigate Stroop and congruency-sequencing effects.

3.2.3.6. Within FRW Comparisons

These analyses pertain only to experiment two. Within the FRW task, 30% of trials were feature-alternations. Therefore, in addition to the comparisons *between* the FRF and FRW tasks, further exploration of the influence of feature-repetitions *within* the FRW task was performed by comparing the magnitude of the congruency-sequencing effect on feature-repetition (see top of Table 6) and feature-alternation trials (see bottom of Table 6) in the FRW task. The magnitude of the congruency-sequencing effect on the feature-alternation trials (FRW) was compared against the FRF task to support the premise for designing a feature-repetition free task and not performing post-hoc removal of feature-repetitions.

Repetition/ Alternations: A 3x2 RM ANOVA where the congruency-sequencing effect was the dependent variable and TRANSITION-TYPE (feature-repetition/ feature-alternation/ FRF Task) was the within-subjects variable and AGE (younger/ older) was the between-subjects variables.

Priming: Further, it was predicted positive priming trials would speed and negative priming trials slow response times in iI trials. Therefore, a RM ANOVA with PRIMING (all iI trials, positive priming iI, negative priming iI) as a within-subjects variable, AGE as the between-subjects variable and response time of the iI trials as the dependent variable. This additional analysis will support the specific roles feature-repetitions play in driving the congruency-sequencing effect reported in the literature (Pashler

and Baylis, 1991, Tipper, 2001) and provides a means to compare our results from a relatively novel paradigm to the larger body of literature including feature-repetitions.

The results sections will first report the results from experiment one, which included only the FRF task (Section 3.3.1). Next, the results from experiment two, the FRF and FRW task, are reported (Section 3.3.6). Finally, there is a comparison of the FRF tasks from experiment one and two (Section 3.3.12).

3.3.0. Results:

Experiment One:

3.3.1. Response Times

Figure 11 shows the response times for the younger and older adults. As expected, there was a significant main effect of AGE $F(1,64)=22.5$, $p<.001$, $\eta_p^2=.30$ on response times. The older adults were 88 ±19ms slower than the younger adults ($p<.001$, $d=0.6$).

Stroop Effect: Figure 11A displays response times according to the current trial congruency, denoting the basic Stroop effect, and is supported by main effect of CURRENT-CONGRUENCY $F(1,64)=276.0$, $p<.001$, $\eta_p^2=.81$. Congruent trials were 89 ±5ms quicker than incongruent trials ($p<.001$, $d=0.9$). In contrast to hypothesis two, there was not a significant interaction between CURRENT-CONGRUENCY and AGE $F(1,64)=0.22$, $p=.64$, $\eta_p^2=.00$ which shows the magnitude of the Stroop effect did not differ between the younger (88 ±7ms) and older (93 ±8ms) adults.

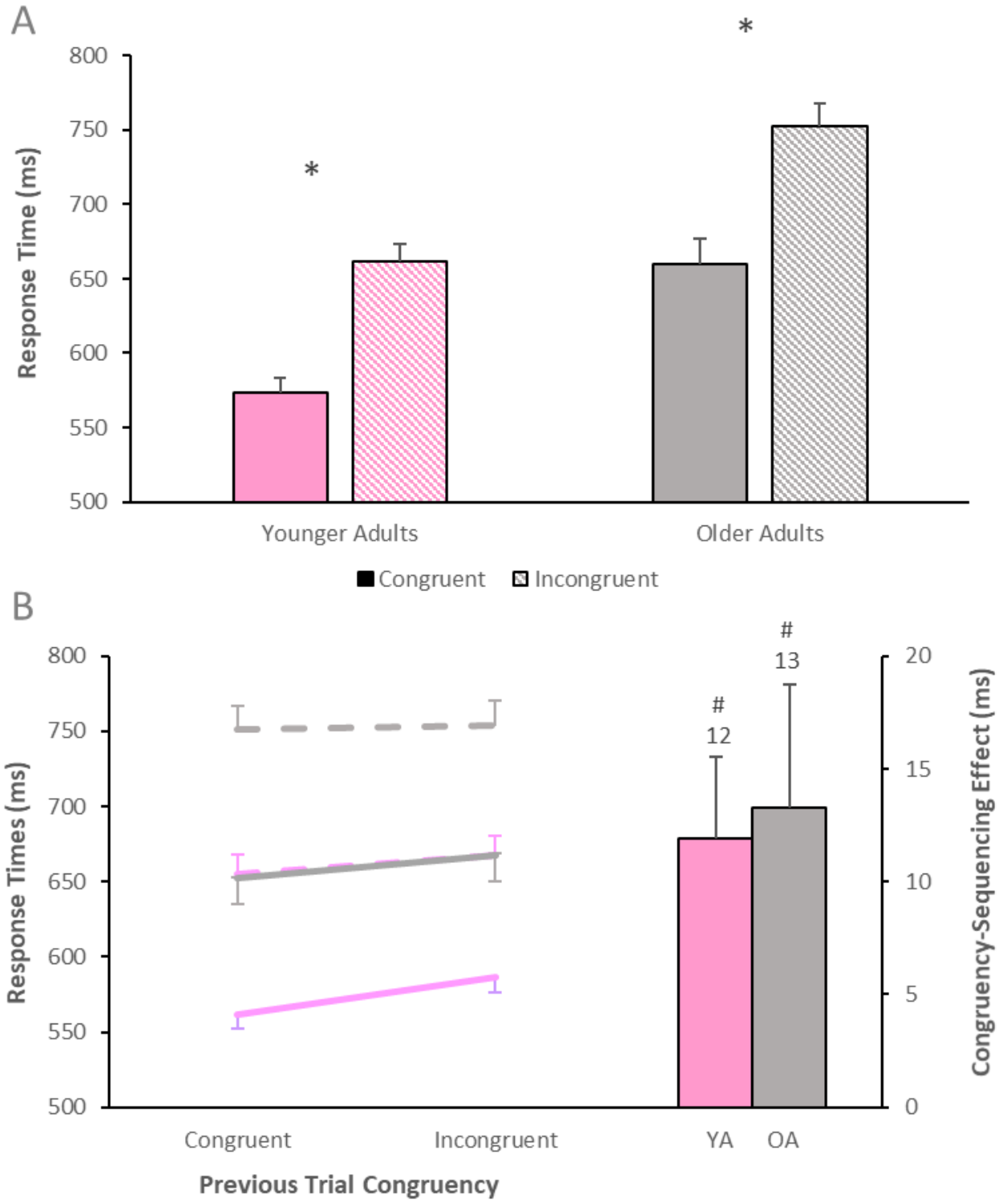
Congruency-Sequencing Effect: Figure 11B further subcategorises the response times according to the previous trial congruency with the resultant congruency-sequencing effect displayed on the right. The older adults were generally slower than the younger adults but showed a similar response pattern. There was a significant interaction between the PREVIOUS-CONGRUENCY and CURRENT-CONGRUENCY and hence an overall congruency-sequencing effect $F(1,64)=15.6$, $p<.001$, $\eta_p^2=.20$. When the previous trial was congruent, the Stroop effect (i.e., cI – cC trials) was 96 ±6ms ($p<.001$, $d=2.1$). Whereas when the previous trial was incongruent (i.e., iI – iC trials), the congruency effect was

reduced to 84 ±6ms (p <.001, d=1.8). This is an integral finding to support the role of top-down control underpinning the congruency-sequencing effect, the implications of which will be later discussed.

In contrast to our prediction of an age-related deficit in top-down control, there was not a significant three-way interaction between PREVIOUS-CONGRUENCY, CURRENT-CONGRUENCY and AGE F(1,64)=0.04, p=*.84*, η_p^2=.00, demonstrating that the congruency-sequencing effect did not differ between the younger and older adults. To establish whether there was evidence for a congruency-sequencing effect in both age groups, the above analysis was performed separately for younger and older adults. The younger adults displayed a 12ms congruency-sequencing effect which yielded a significant PREVIOUS-CONGRUENCY by CURRENT-CONGRUENCY interaction F(1,35)=11.0, p=*.002*, η_p^2 =.24. Similarly, the older adults displayed a 13ms congruency-sequencing effect which was also significant F(1,29)=5.8, p=*.023*, η_p^2=.17.

3.3.1.1. Power Analyses

Post-hoc Power: The obtained power (1-β) from the within-between interaction of PREVIOUS-CONGRUENCY, CURRENT-CONGRUENCY, and AGE was 0.3 (η_p^2=.00). This is below the accepted power of 0.8 and suggested the experiment was underpowered to observe differences in the congruency-sequencing effect and age.



1247 *Figure 11. Response times for younger (pink) and older (grey) adults. Panel A displays the response times for congruent (solid)*
1248 *and incongruent (hatched) trials to indicate the Stroop effect. The asterisks represent a significant Stroop effect (p<.05).*
1249 *Leftmost of panel B shows the response time for congruent (solid) and incongruent (dashed) trials in accordance to the*
1250 *congruency of the previous trial. The resultant difference is displayed as the congruency-sequencing effect on the right, where*
1251 *YA refers to the younger adults and OA, the older adults. The hash shows a significant congruency-sequencing effect (p<.05).*

3.3.2. Block-Wise Analysis

As outlined in the General Methods, there is some evidence to suggest the congruency-sequencing effect may be a transient, short-lived phenomenon that cannot be observed in long experiments (Mayr et al., 2003). To investigate any fluctuations throughout the experiment, Figure 12 shows the response times as per the Stroop effect (panel A) and congruency-sequencing effect (panel B) across experimental blocks (80 trials).

Stroop: There was an interaction between BLOCK and AGE $F(4, 256(GG))=3.3$, $p=.016$, $\eta_p^2 = .05$, suggesting fluctuations in the Stroop effect across the experiment were different for younger and older adults. However, this is driven by the heightened Stroop effect for the older adults in the early portion of the experiment such that the Stroop effect in block two was ~30ms larger in blocks three to five ($p < .05$, $d = .05$). Whereas there were no differences in the Stroop effect across blocks for the younger adults, indicating a consistent effect.

Congruency-Sequencing Effects: Despite the congruency-sequencing effect fluctuating between 6 ±6ms and 20 ±7ms in the younger adults and -3 ±9ms and 21 ±10ms in the older adults, as shown in Figure 12B, there was no significant main effect of BLOCK $F(4, 256(GG))=0.8$, $p=.539$, $\eta_p^2 = .01$, nor interaction with BLOCK and AGE $F(4, 256(GG))=1.6$, $p=.169$, $\eta_p^2 = .03$ on the congruency-sequencing effect.

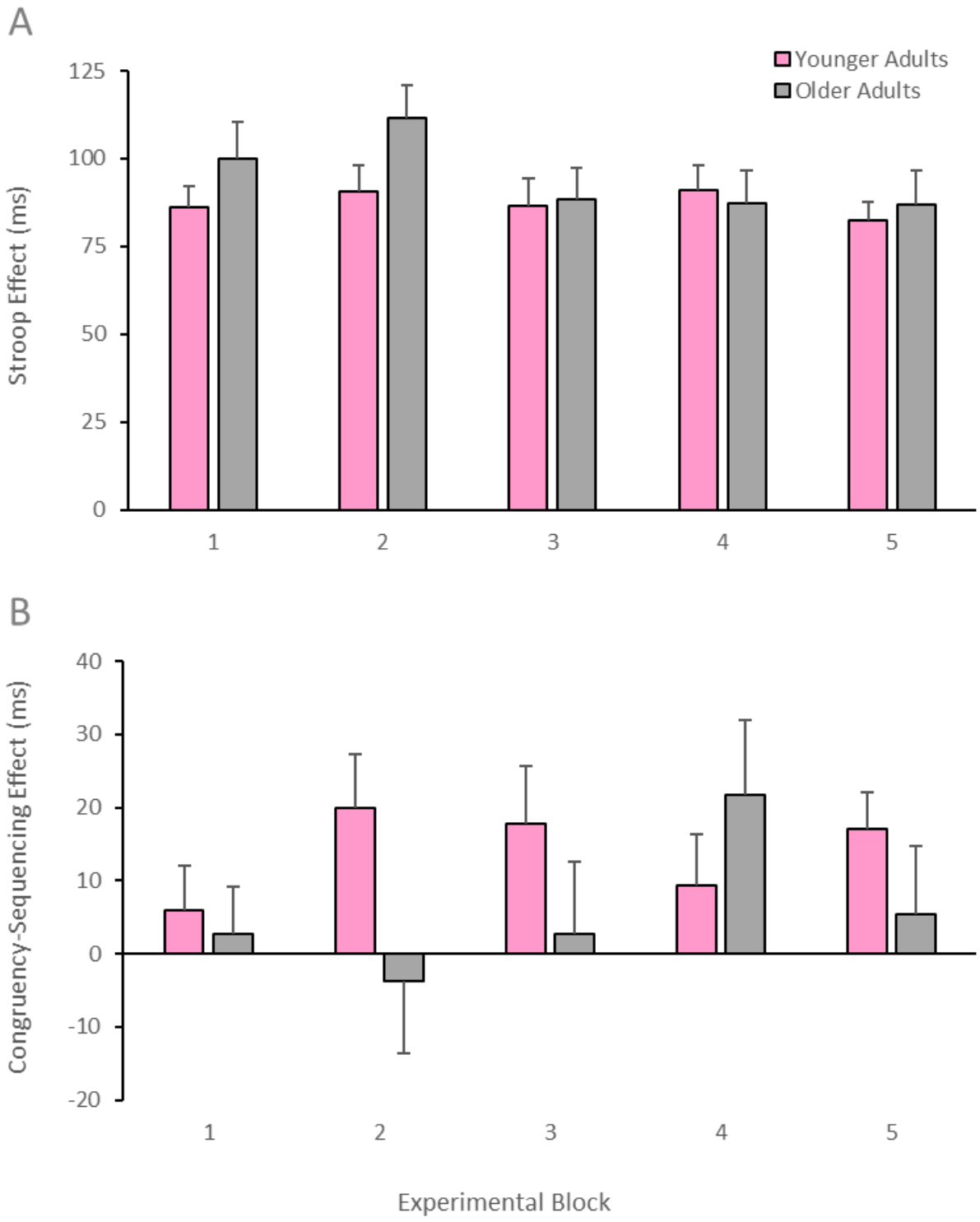


Figure 12. The magnitude of the Stroop effect (panel A) and the congruency-sequencing effect (panel B) for younger (pink) and older (grey) adults across each experimental block throughout the experiment.

3.3.3. Delta Plots

Mean response times provide a broad approach to detecting differences in cognitive functioning. A more subtle approach is to delve into changes in the (Stroop) effect across response time (Gajdos et al., 2019, Balota et al., 2010, De Jong et al., 1994, Pratte et al., 2010). If the pattern of responding differs between two groups (younger and older adults), this can infer different processing strategies implemented at the cognitive level which may go undetected by response times alone (Balota and Yap, 2011).

Figure 13 plots the Stroop effect across response quintiles for younger and older adults. There was a significant interaction between QUINTILE and AGE $F(1.64, 105.4(GG))=7.2$, $p=.002$, $\eta_p^2 = .10$. The shape of the delta plots was different between the two age groups. To investigate further, the data from each age group was analysed separately. The younger adults displayed a positive linear effect (t=10.7, $p<.001$) such that the Stroop effect was 76 ±6ms for the fastest response quintile (mean response of 510ms) and steadily increased by 39 ±6ms (t=6.4, $p <.001$) to 113 ±9ms for the slowest response quintile (mean response of 761ms).

In contrast, the older adults did not display a main effect of QUINTILE $F(1.47, 42.7(GG))=2.7$, $p=.094$, $\eta_p^2 = .09$ thus the Stroop effect did not change as a function of response times.

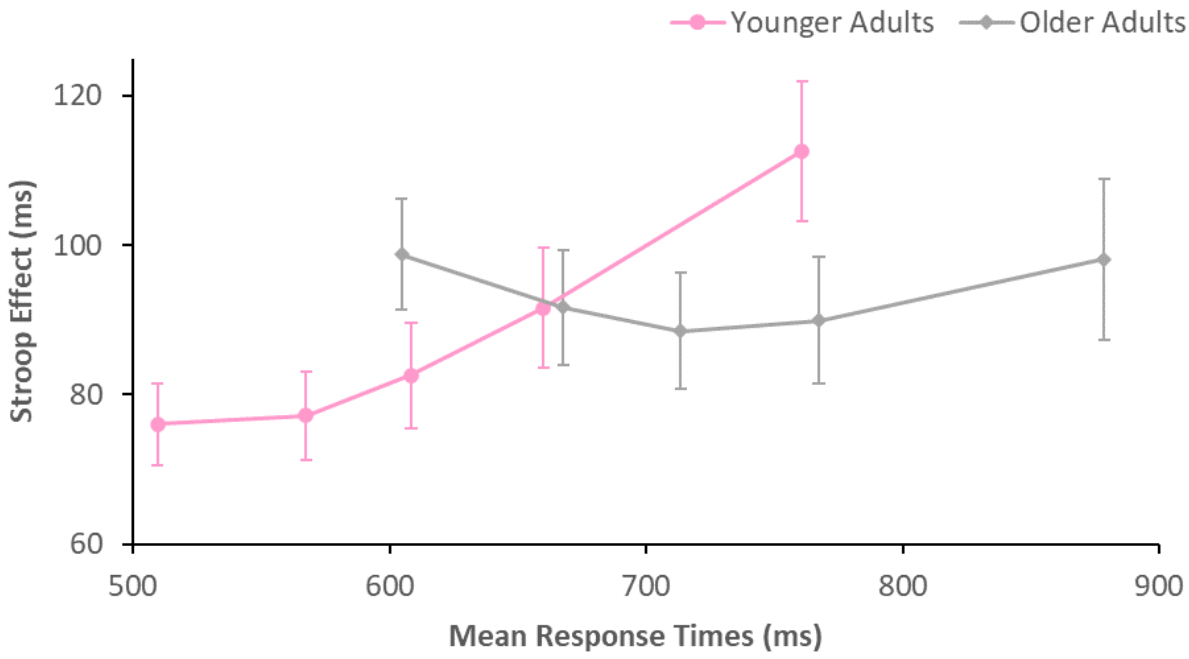


Figure 13. Delta plots displaying the magnitude of the Stroop effect according to response speeds for younger (pink) and older (grey) adults.

3.3.4. Response Errors

Figure 14 shows the response errors of younger and older adults during the FRF task in experiment 1. Response errors were defined as trials where the participant clearly said the incorrect colour. There was a main effect of CURRENT-CONGRUENCY $F(1,64)=26.0$, $p<.001$, $\eta_p^2=.29$. Participants made 1.3 ± 0.3 more errors for incongruent compared to congruent trials ($p<.001$, $d=.62$). Importantly, there was a significant two-way interaction of PREVIOUS-CONGRUENCY and CURRENT-CONGRUENCY $F(1,64)=4.5$, $p=.005$, $\eta_p^2=.12$, however, the three-way interaction showed that this was unaffected by AGE $F(1,64)=1.5$, $p=.23$, $\eta_p^2=.02$. When the previous trial was congruent, there were 1.6 ± 0.3 more errors for incongruent compared to congruent trials ($p<.001$, $d=.72$). Whereas when the previous trial was incongruent, there were 1.0 ± 0.3 more errors for incongruent compared to congruent trials ($p=.003$, $d=.44$). The data reported here mirrors that obtained in the response time data reported in Section 3.3.1.

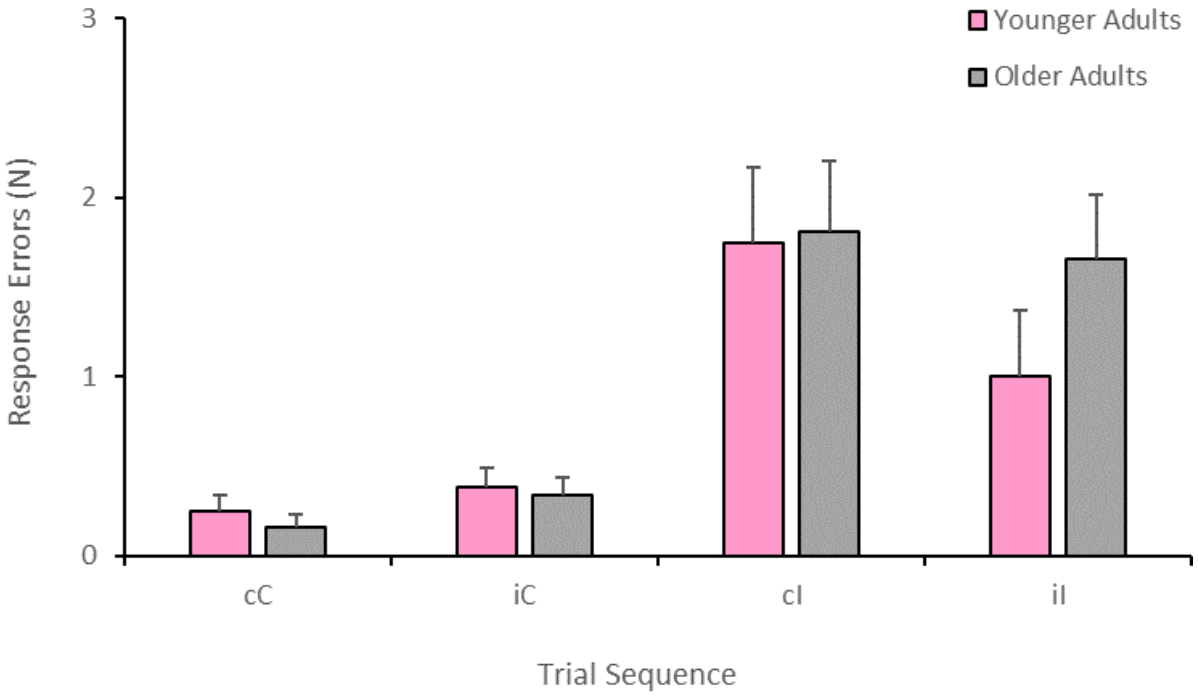


Figure 14. Response errors according to trial sequence or younger (pink) and older (grey) adults. The capital letter refers to the congruency of trial n and the lowercase letter the congruency of trial n-1 where C refers to congruent and I incongruent, in both instances.

3.3.5. Summary

The first aim of this experiment was to design a Stroop task without including any feature-repetitions. This was achieved and a reliable congruency-sequencing effect emerged. This demonstrates that feature-repetitions are not solely responsible for the congruency-sequencing effect and that it likely reflects top-down control produced by the DLPFC.

Due to reports of accelerated neuroanatomical decline of the DLPFC with healthy ageing, it was of interest to observe whether older adults displayed impaired performance on behavioural measures such as the Stroop or congruency-sequencing effect which rely on functioning of the DLPFC. It was hypothesised that older adults would display a larger Stroop effect which would represent impaired cognitive inhibition and a smaller or diminished congruency-sequencing effect. In contrast to hypothesis two, the results from experiment one did not report a heightened Stroop, nor a diminished congruency-sequencing effect in the older compared to younger adults.

The results from this experiment were smaller than anticipated. For this reason, experiment two sought to replicate the results from experiment one whilst further investigating the role of feature-repetitions and ageing.

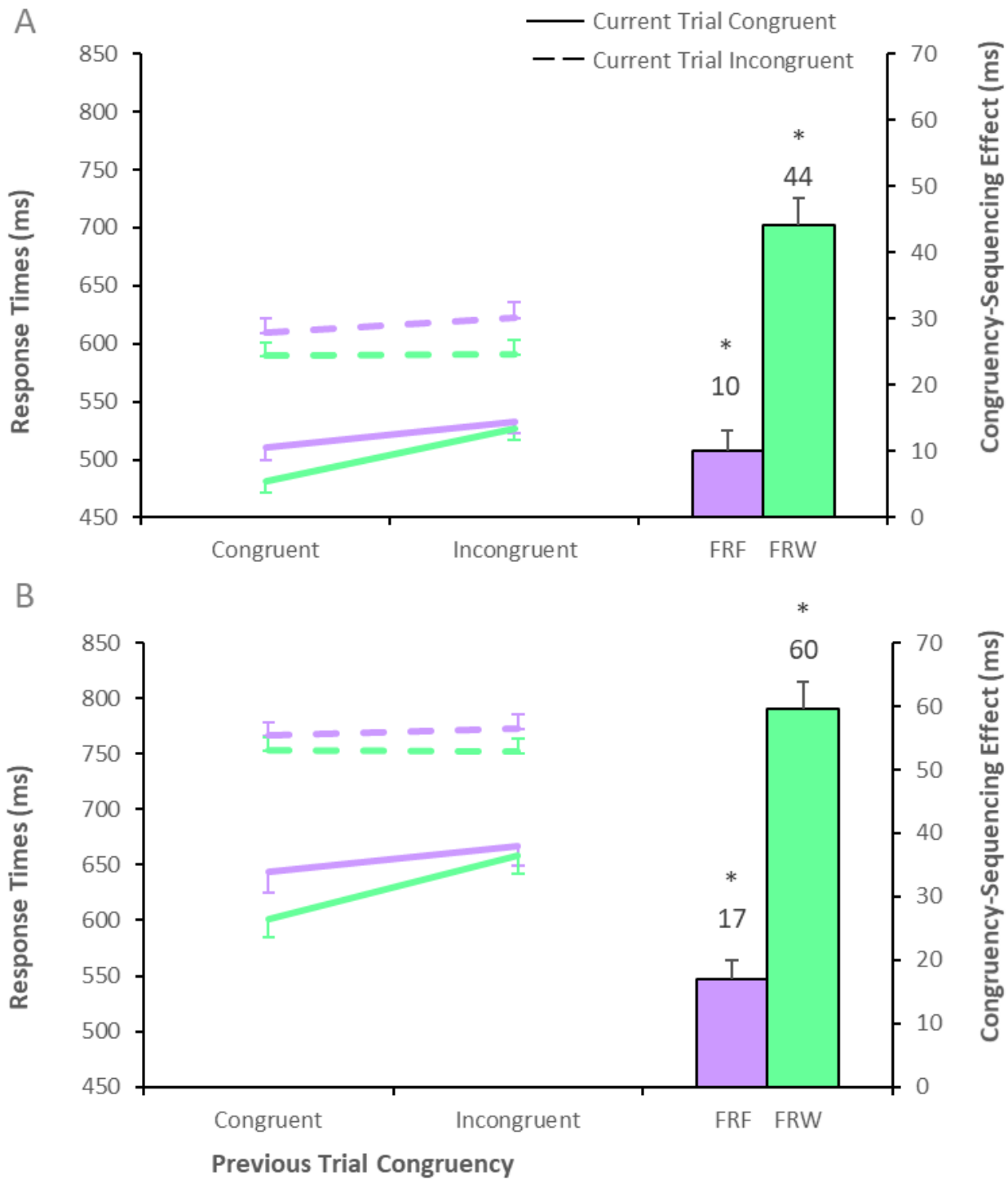
3.3.6. Response Times

Figure 15 reports the response speeds for both the FRF and FRW tasks for younger and older adults. As with experiment one, there was a significant main effect of AGE $F(1,65)=70.1$, $p<.001$, $\eta_p^2=.52$ on response times. Across both tasks, the older adults were 144 ±17ms slower than the younger adults ($p<.001$, $d=1.0$). There was a main effect of TASK $F(1,65)= 7.7.22$, $p=.64$, $\eta_p^2=.00$, which shows that overall, participants were 21.2 ±4ms faster in FRF than the FRW task ($p<.001$, $d= 0.6$).

Stroop Effect: Figure 16A plots the Stroop effect for younger and older adults during both FRF and FRW tasks. There was an overall significant main effect of CURRENT-CONGRUENCY $F(1,65)=414.7$, $p<.001$, $\eta_p^2=.86$ on response times. The congruent trials were 102 ±5ms quicker than the incongruent trials ($p<.001$, $d= 1.3$). There was a significant interaction between CURRENT-CONGRUENCY and AGE $F(1,65)= 7.7$, $p=.64$, $\eta_p^2=.00$ on response times. The Stroop effect was 29 ±10ms ($p=.007$, $d=0.34$) greater in older than younger adults. With the Stroop effect as the dependent variable, there was an interaction between TASK and AGE $F(1,65)= 5.6$, $p<.05$, $\eta_p^2=.08$ such that in the FRW task, the Stroop effect was 38 ±3ms bigger for the older than younger adults ($p=.006$, $d= 0.4$).

Congruency sequencing effect: Figure 16B shows there was a significant interaction between the PREVIOUS-CONGRUENCY and CURRENT-CONGRUENCY on response times $F(1,65)=139.9$, $p<.001$, $\eta_p^2=.86$. This reveals the overall presence of a congruency-sequencing effect such that when the previous trial was congruent, the Stroop effect (i.e., cI – cC trials) was 121 ±5ms ($p<.001$, $d=2.8$), whereas when the previous trial was incongruent (i.e., iI – iC trials), the Stroop effect was reduced to 88 ±5ms ($p<.001$,

d=2.0). For ease of comparison across age and tasks, the congruency-sequencing effect reported in Figure 15 is reported again in Figure 16. Importantly, there was a three-way interaction with PREVIOUS-CONGRUENCY, CURRENT-CONGRUENCY and TASK $F(1,65)=78.9$, $p<.001$, $\eta_p^2=.55$ such that the congruency-sequencing effect was 37 ±4ms larger in the FRW than FRF task (p <.001, d=1.08). This finding is key to support our hypothesis that feature-repetitions magnify the congruency-sequencing effect. Further, there was a three-way interaction of PREVIOUS-CONGRUENCY, CURRENT-CONGRUENCY and AGE $F(1,65)=4.05$, $p=.048$, $\eta_p^2=.00$ which demonstrates a difference in the congruency-sequencing effect between younger and older adults. However, there was not a four-way interaction of PREVIOUS-CONGRUENCY, CURRENT-CONGRUENCY, AGE and TASK $F(1,65)=1.0$, $p=.32$, $\eta_p^2=.02$ so although the older adults displayed an 11ms ±6ms larger congruency-sequencing effect than the younger adults (p =.048, d=0.25) this increase was not specific to a particular task.

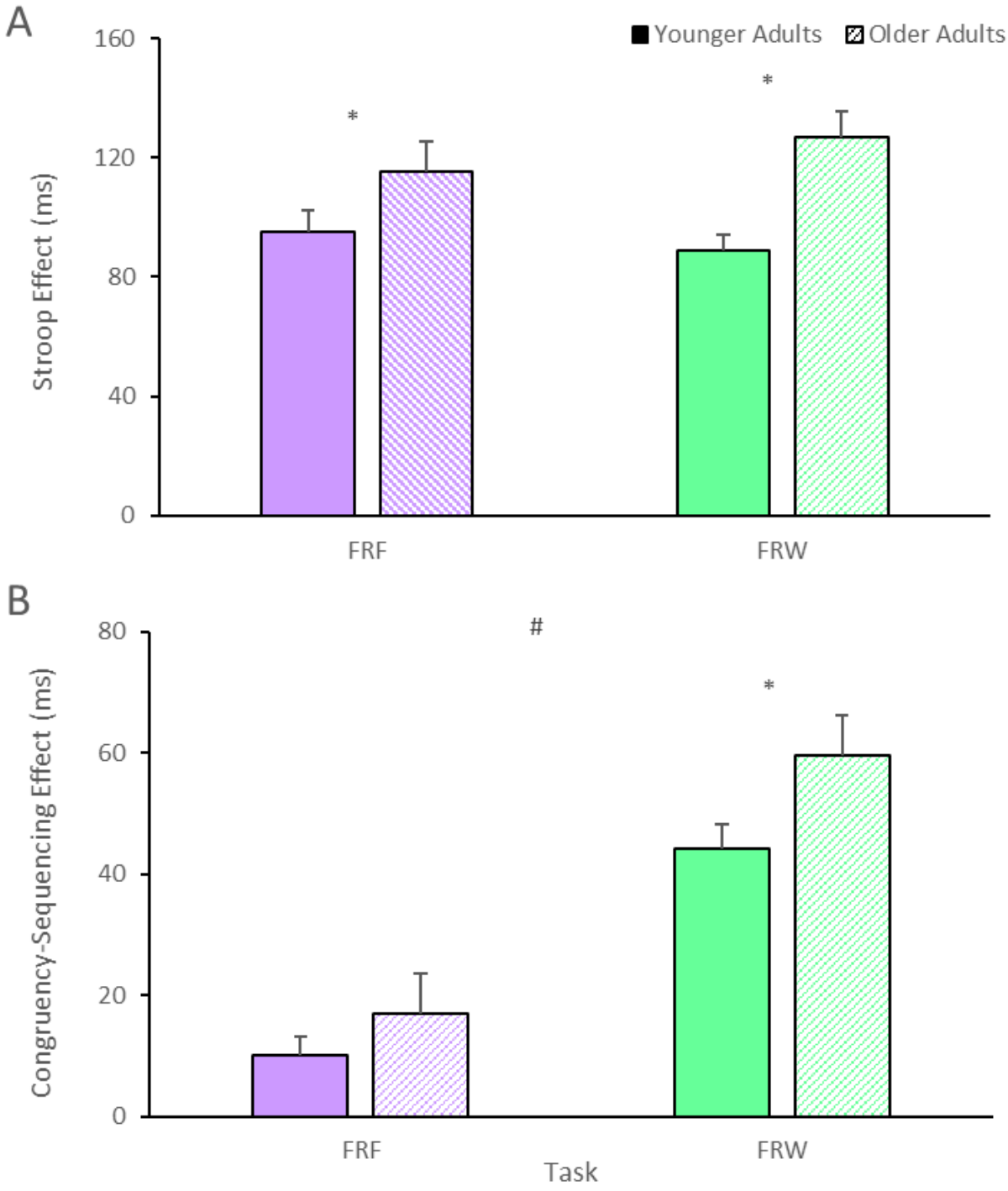


1344 *Figure 15. Response times from the FRF (lilac) and FRW (mint green) tasks for younger (panel A) and older (panel B) adults.*

1345 *Solid lines represent when the current trial is congruent, and the dashed when the current trial is incongruent according to the*

1346 *congruency of the previous trial. The resultant congruency-sequencing effect is displayed on the right-hand side whereby the*

1347 *asterisks represent this was significant in all conditions (p<.05).*



1348 *Figure 16. The Stroop (panel A) and congruency-sequencing effect (B) from the FRF (lilac) and FRW (mint green) tasks for*
1349 *younger (solid) and older (hatched) adults. The asterisks show significant difference of age and the hash show a significant*
1350 *difference of task (p<.05).*

3.3.6.1. Power Analyses

Post-hoc Power: The obtained power (1-β) from the within-between interaction of PREVIOUS-CONGRUENCY, CURRENT-CONGRUENCY, and AGE (η_p^2=.00) was 0.05. This is below the accepted power of 0.8 and suggested the experiment was underpowered to observe differences in the congruency-sequencing effect and age. A further calculation of the four-way interaction of PREVIOUS-CONGRUENCY, CURRENT-CONGRUENCY, AGE, and TASK (η_p^2=.02) revealed the obtained power was also 0.05 and was underpowered to report any differences in the congruency-sequencing effect across tasks between younger and older adults.

Smallest Effect Size of Interest: The SESOI was calculated from the data published in West and Moore (2005) who reported a large, non-significant difference in the magnitude of the congruency-sequencing effect between younger and older adults (53ms). They reported the AGE by PREVIOUS-CONGRUENCY, CURRENT-CONGRUENCY by AGE interaction as "*F*(1,22) = 1.63, *p* >.22, (n= 24)". Therefore, using the formulae described in the General Methods, the critical effect size is η_p^2 = 0.67. Section 3.3.6. reported the PREVIOUS-CONGRUENCY by CURRENT-CONGRUENCY by AGE interaction yielded a η_p^2 = 0.041 which is below the calculated critical effect size. Therefore, despite a 11ms larger congruency-sequencing effect in older compared to younger adults (*p*=.048), this difference is not considered meaningful.

3.3.7. Block-Wise Analysis

As per experiment one, the stability of the Stroop effect and the congruency-sequencing effect were compared across blocks in both FRF and FRW tasks for younger and older adults, as shown in Figure 17.

Stroop Effect: There was no main effect of BLOCK $F(3.4,223\ (GG))=2.2$, $p=.084$, $\eta_p^2=.03$, and this did not interact with AGE $F(3.4,223\ (GG))=1.6$, $p=.193$, $\eta_p^2=.02$, nor TASK $F(3.1,204\ (GG))=0.4$, $p=.752$, $\eta_p^2=.00$. This shows a consistent Stroop effect throughout the experiment for each age group.

Congruency-Sequencing Effects: In contrast to experiment one, there was a main effect of BLOCK $F(3.6,232\ (GG))=5.2$, $p<.001$, $\eta_p^2=.07$. The congruency-sequencing effect in block five is 20 ±5ms larger than block one ($p<.001$, $d=0.5$); 17 ±4ms larger than block two ($p=.002$, $d=0.5$); 17 ±5ms larger than block three ($p<.05$, $d=0.4$); and 16 ±5ms larger than block four ($p<.05$, $d=0.5$). This suggests the congruency-sequencing effect increased at the last stage of the experiment although it is unclear why this may happen. This effect of block did not interact with AGE $F(3.4,223\ (GG))=1.3$, $p=.287$, $\eta_p^2=.02$, nor TASK $F(3.5,224\ (GG))=196$, $p=.922$, $\eta_p^2=.00$.

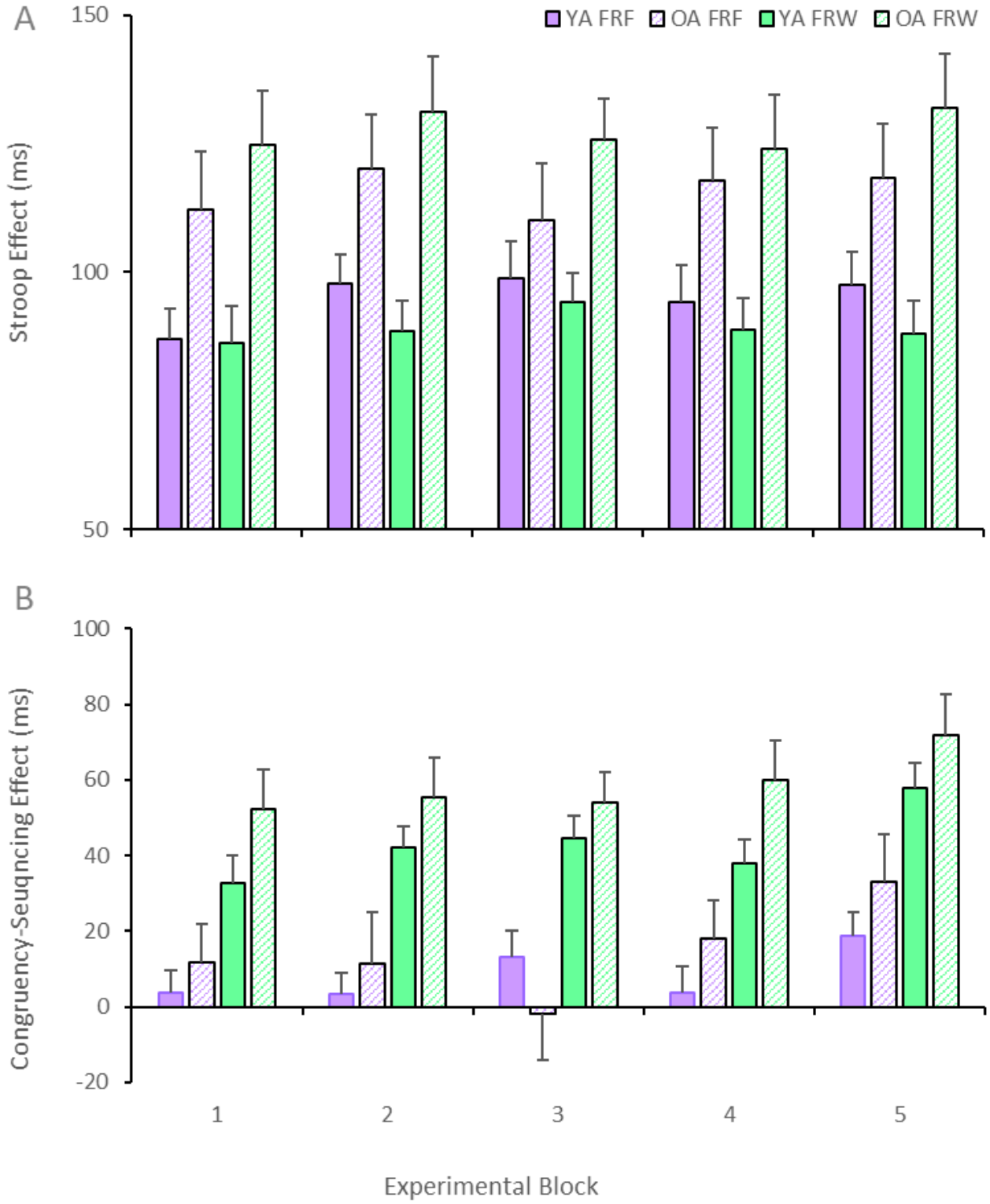
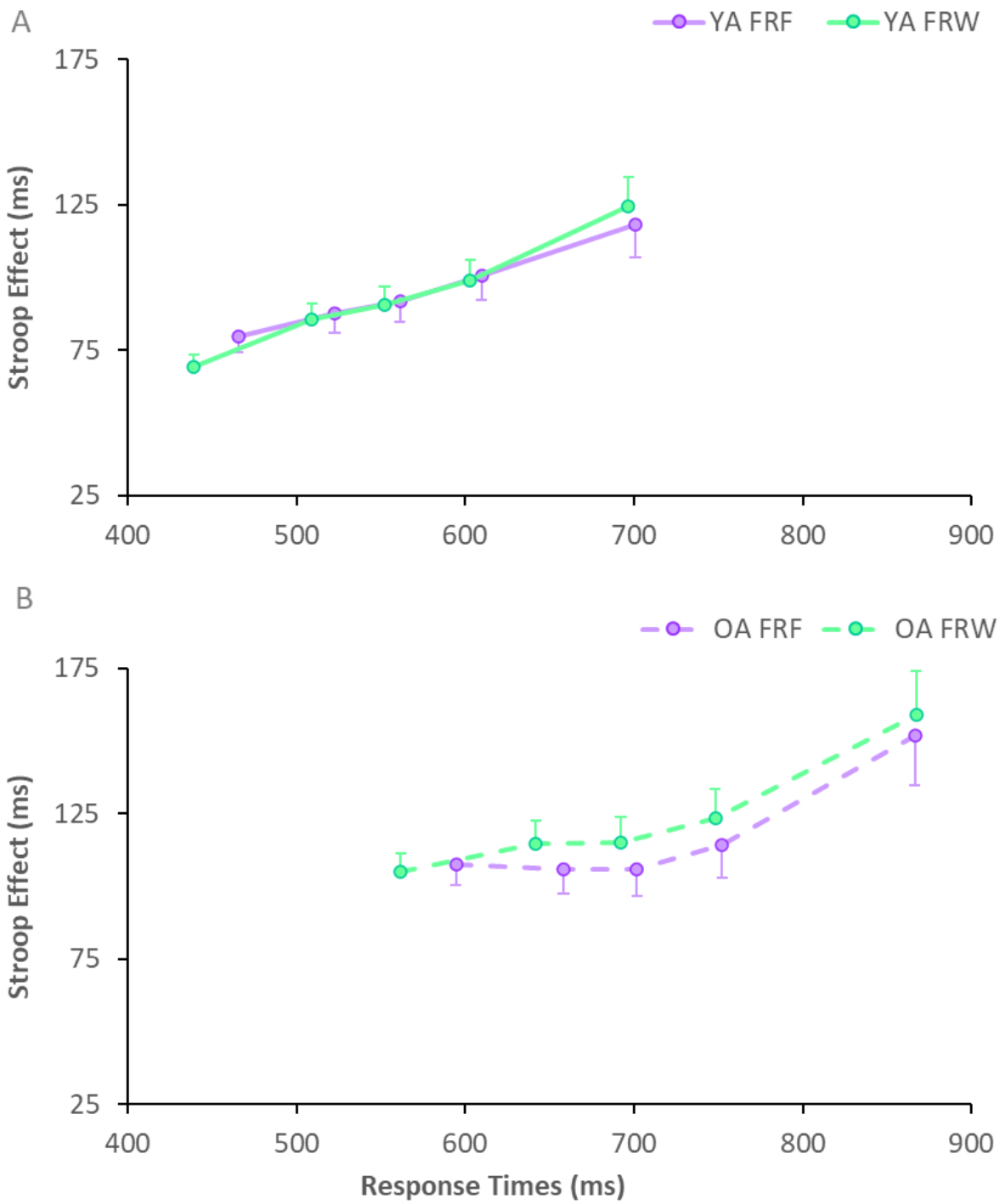


Figure 17. The magnitude of the Stroop effect (panel A) and the congruency-sequencing effect (panel B) for younger (solid) and older (hatched) adults across each experimental block throughout the FRF (lilac) and FRW (mint green) tasks.

3.3.8. Delta Plots

Figure 18 shows the delta plots during the FRF and FRW task for younger (panel A) and older (panel B) adults. There was a significant overall main effect of QUINTILE $F(4,65)=61.9$, $p<.001$, η_p^2**.** The Stroop effect at the fastest quintile is 55 ±7ms smaller than the slowest (Q5) response quintile ($p<.001$, $d=1.0$). There was a significant interaction between QUINTILE and AGE $F(1.8,88.3\ (GG))=10.0$, $p<.001$, $\eta_p^2=.13$, which shows the delta plots differ between the younger and older adults, as seen by through the right and upwards shift from panel A to B of Figure 18, primarily driven by the response times. The magnitude of the Stroop effect at the fastest response quintile is 70ms for the younger and 106ms for the older adults. At the slowest response quintiles, this increases to 122ms for the younger and 156ms for the older adults.

As per experiment one, separate polynominal contrasts were performed to explore the shape of the delta plots for younger and older adults. This time, *both* the younger ($t=15.1$, $p<.001$) and older ($t=10$, $p<.001$) adults displayed a linear relationship between their Stroop effect and response time. Further, Figure 18 shows that both the younger and older adults followed a similar pattern of responding for both the FRF and FRW task. This was supported by a non-significant interaction between TASK and QUINTILE $F(1.4, 88.3\ (GG))=3.1$, $p=.068$, $\eta_p^2=.05$.



1397 *Figure 18. Delta plots displaying the magnitude of the Stroop effect from the FRF (lilac) and FRW (mint green) task for younger*

1398 *(panel A) and older (panel B) adults.*

3.3.9. Response Errors

Figure 19 displays the number of response errors committed according to trial sequence during the FRF and FRW tasks for younger and older adults. There was a main effect of AGE $F(1, 65)=6.5$, $p=.013$, $\eta_p^2 = .09$. Younger adults made 0.9 ±0.4ms more errors than older adults ($p=.013$, $d=0.31$). There was a main effect of TASK $F(1, 65)=4.8$, $p=.032$, $\eta_p^2 = .07$. Participants made 0.2 ±0.1ms more errors on FRF than FRW task ($p=.025$, $d=.28$).

Figure 19 clearly shows there is main effect CURRENT-CONGRUENCY $F(1, 65)=62.7$, $p<.001$, $\eta_p^2 = .49$. Participants made 2.9 ±0.4ms more errors on incongruent (cI and iI) than congruent (cC and iC) trials ($p<.001$, $d=0.99$). There was a significant interaction of PREVIOUS-CONGRUENCY and CURRENT-CONGRUENCY $F(1, 65)=12.8$, $p<.001$, $\eta_p^2 = .16$, thus mirroring the response time data that showed a congruency-sequencing effect. On incongruent trials, participants made 1.0 ±0.2 more errors when the previous trial was congruent (cI) incongruent than incongruent (iI) ($p<.001$, $d= .59$). Presumably due to the very small error rate on congruent trials, there was no effect of previous trial congruency whereby participants made 0.02 ±0.2 more errors on iC than cC trials ($p=1.00$, $d=.00$).

The three-way interaction shows PREVIOUS-CONGRUENCY by CURRENT-CONGRUENCY further interacted with TASK $F(1, 65)=10.3$, $p=.002$, $\eta_p^2 = .14$. The response times indicated the FRW task to display a larger congruency-sequencing effect, whereas the response errors suggest the FRF task. Figure 19 shows this is driven by the larger decrease in errors during iI compared to cI trials in the FRW opposed to FRF task. There was not a significant four-way interaction between PREVIOUS-CONGRUENCY, CURRENT-CONGRUENCY, TASK and AGE $F(1, 65)=0.1$, $p=.737$, $\eta_p^2 = .00$, showing that the larger congruency-sequencing effect in the FRF task did not differ according to age.

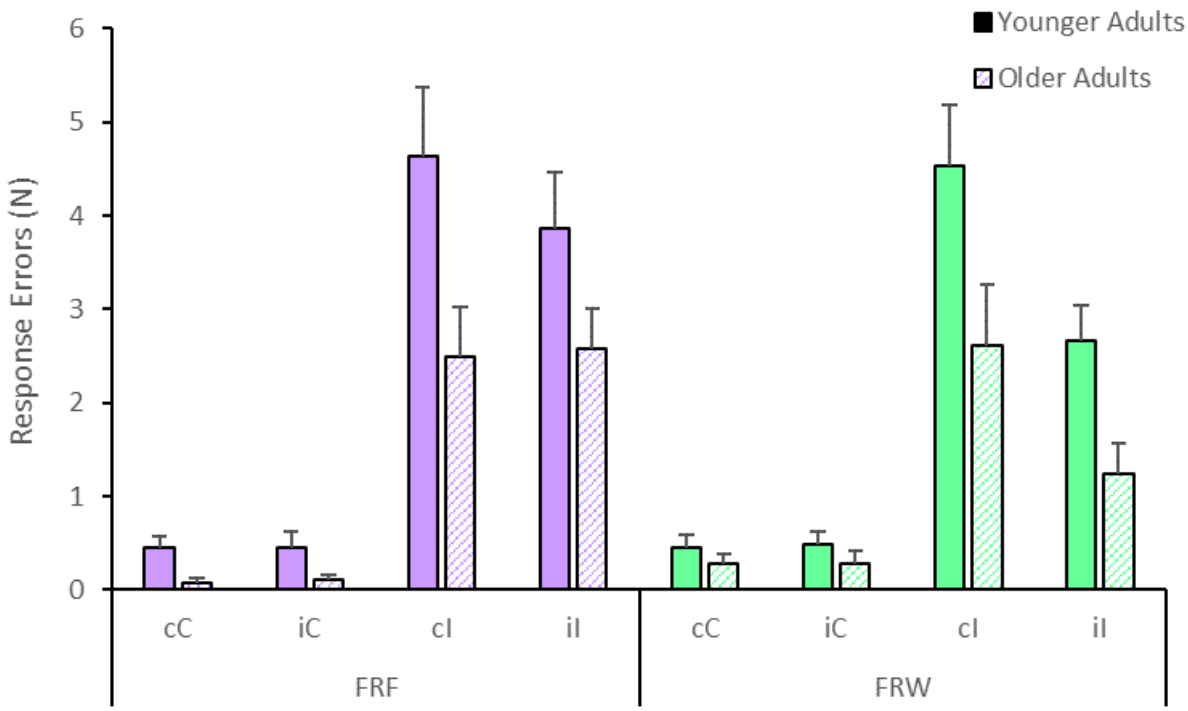
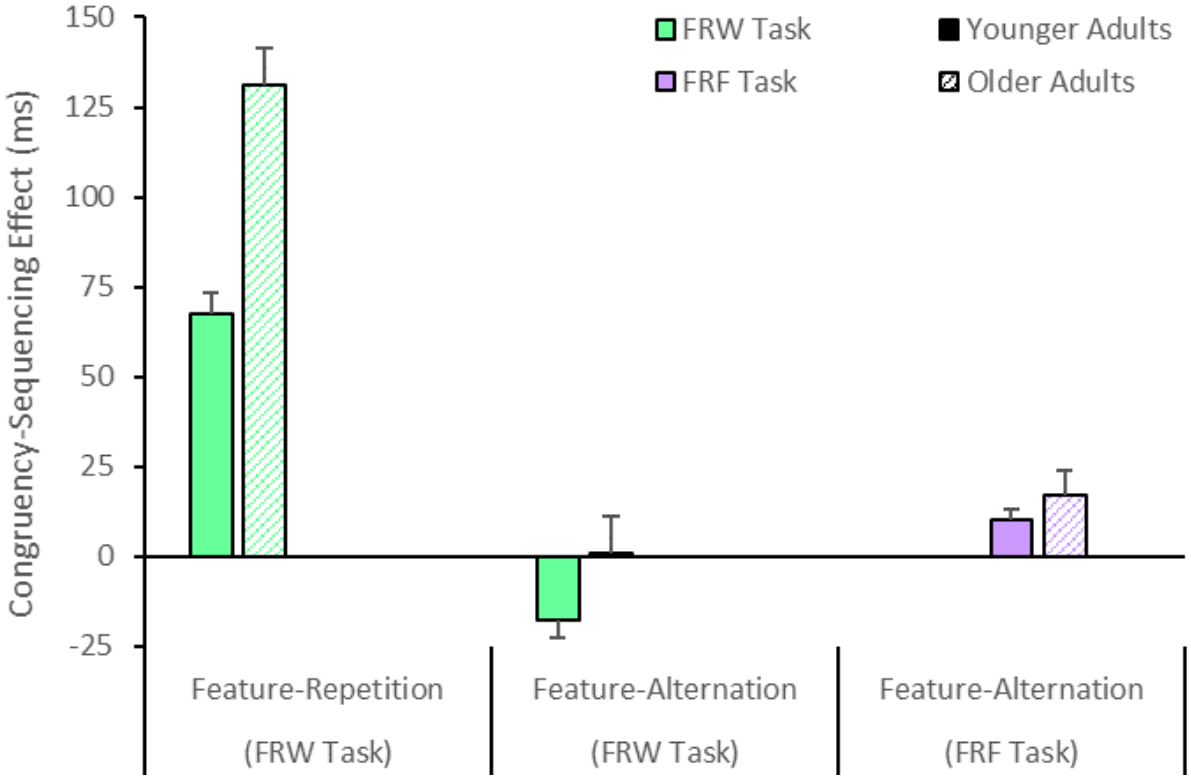


Figure 19. Response errors (N) in the FRF (lilac) and FRW (mint green) tasks across each trial transition type for younger (solid) and older (hatched) adults.

3.3.10. FRW Task Feature-Repetitions Transitions

3.3.10.1. Feature-Repetitions/ Alternations

As expected, Figure 20 shows there was a main effect of FEATURE-TRANSITION $F(1,65)=177.6$, $p<.001$, η_p^2**.** 73 on the congruency-sequencing effect. Feature-repetition trials yielded an 84ms ±6ms larger congruency-sequencing effect than feature-alternation trials ($p<.001$, $d=1.7$). Importantly, there was also a 23 ±5ms difference between the congruency-sequencing effect from the free-from feature-repetition task and the congruency-sequencing effect from the feature-alternation trials (calculated by removing feature-repetition trials from the standard FRW Stroop task) ($p<.001$, $d=0.52$). The degree to which the FEATURE-TRANSITION increases the congruency-sequencing effect was not affected by AGE as seen by the non-significant interaction $F(1,65)=.66$, $p=.52$, η_p^2**.** 01.



1429 *Figure 20. The congruency-sequencing effect from the with feature-repetition task (mint green) in accordance with whether*
1430 *the transition from trial n-1 to trial n includes a feature-repetition (left) or alternation (right) compared to the free-from*
1431 *feature-repetitions task (lilac), for younger (solid) and older (hatched) adults.*

3.3.10.2. Priming-Transitions

Figure 21 shows there was a significant main effect of PRIMING-TRANSITION $F(1.2,77.6(GG))=243.8$, $p<.001$, $\eta_p^2 = .79$, that was not affected by AGE $F(1.2,77.6(GG))=0.11$, $p=.782$, $\eta_p^2 = .00$. As predicted, positive-priming trials were 89ms ±6ms faster than the mean iI response time ($p<.001$, $d=1.7$) and negative-priming trials were 56ms ±4ms slower than the mean iI response time ($p<.001$, $d=1.8$).

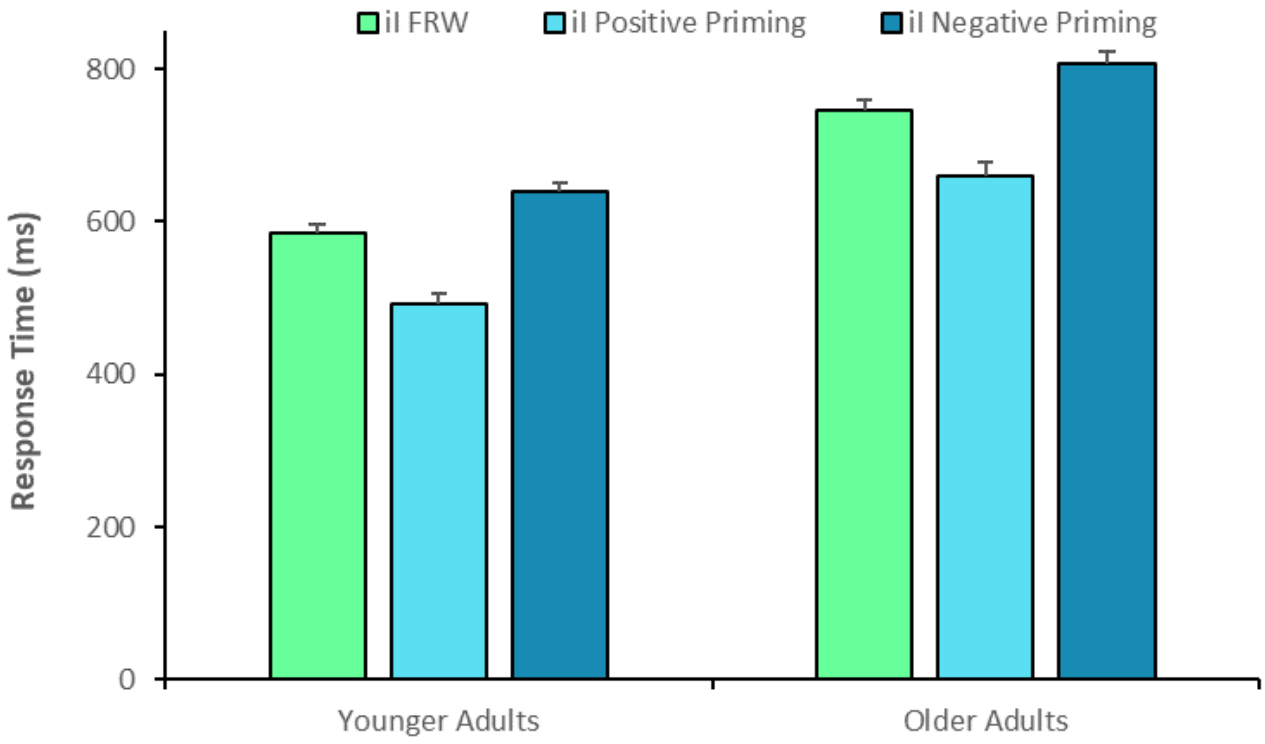


Figure 21. Mean response times for all iI trials in the FRW task (mint green); iI trials with positive-priming transitions (light blue); iI trials with negative-priming transitions (dark blue) for younger (left) and older (right) adults.

3.3.11. Summary

In addition to replicating the results from experiment one where a congruency-sequencing effect was produced from the FRF task, experiment two also implemented a Stroop task that included feature-repetitions. As expected, the FRW task produced a larger congruency-sequencing effect than the FRF task, which reflects the additive contribution of feature-repetitions. Analyses also demonstrated the known influence of specific priming repetitions on response times. Further, evidence was provided to support the utilisation of a feature-repetition free task opposed to the frequently reported post-hoc removal from a standard conflict task.

In keeping with reports from the literature (Puccioni and Vallesi, 2012a, West and Moore, 2005), older adults produced a larger congruency-sequencing effect than younger adults. Hypothesis four anticipated this finding would have been limited only to the FRW task, but this was reported for the FRF and FRW task. In contrast to experiment one, but consistent with hypothesis two, the older adults produced a larger Stroop effect than the younger adults.

Experiment One versus Experiment Two:

This section compares the replicability of results from the FRF tasks across both experiments. For completion, the results from the FRW task are also presented here, however, are not analysed in this section (for a comprehensive comparison of the FRF and FRW tasks, see the results section of experiment two).

3.3.12. Stroop Effects

Experiment two reported a larger Stroop effect in the older compared to younger adults, which was not shown in experiment one. However, a paired samples t-test shows that the Stroop effect reported in the two FRF tasks did not differ for either the younger $t(35) = 0.80$, $p = .425$, $d = 0.14$; nor older adults $t(27) = 1.67$, $p = .107$, $d = .32$. When the results from both experiments are combined (merged red and blue bars on Figure 22), an independent samples t-test showed that the Stroop effect was not larger for the older compared to younger adults $t\ (131) = 1.48$, $p = .071$, $d = 0.26$. This combined result from the *FRF tasks* contrast hypothesis two that expected older adults to display a larger Stroop effect, but note, however, a larger Stroop effect was reported for older compare to younger adults in the *FRW task* (yellow bars of Figure 22). A full discussion of these results is provided in Section 3.4.2.1.

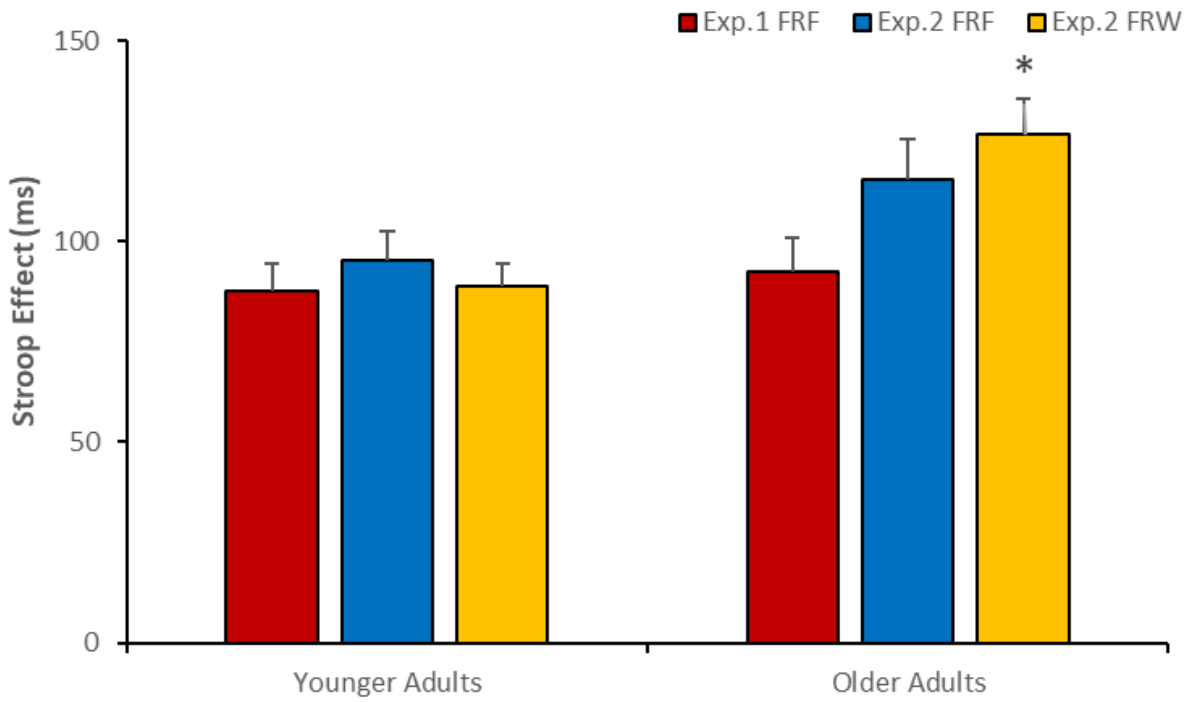


Figure 22. The Stroop effect from experiment one (red), the feature-repetition free task of experiment two (blue), and the with feature-repetitions task of experiment two (yellow) for younger (left) and older (right) adults. There were no significant differences from the combined FRF tasks between younger and older adults but there was for the FRW task as denoted by the asterisk (p<.05).

3.3.13. Order Effects

The Stroop effect was larger in the FRF task of experiment two than experiment one. A potential reason for this could be that in experiment two, half the participants performed the FRW task (which elicited a larger Stroop effect) first which may have carried over into the FRF task. To check for potential order effects of experiment two, the magnitude of the Stroop effect for the FRF and FRW task was compared against the order the tasks were performed (see Figure 23). There was no main effect of ORDER $F(1,63)=0.49$, $p=.49$, η_p^2 **.** 00. Overall, the Stroop effect did not differ according to whether participants performed the FRF or FRW task first, therefore, no carry over effects of task order were detected.

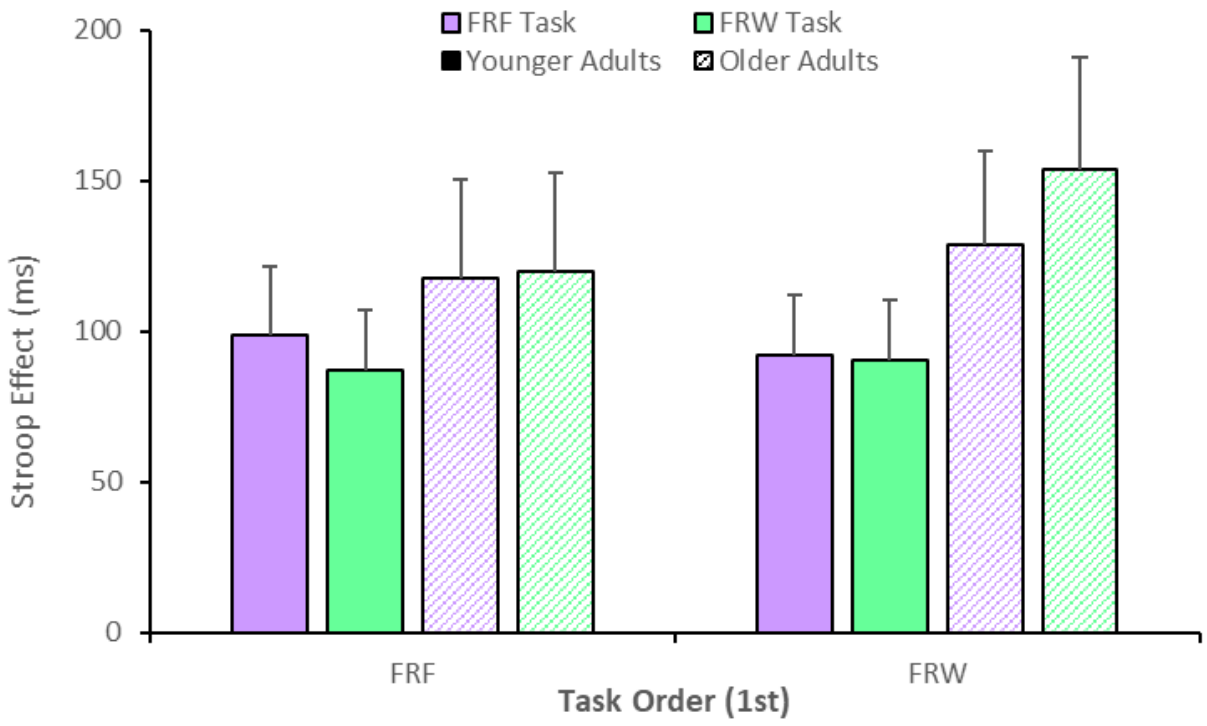


Figure 23. The magnitude of the Stroop effect according to the counterbalanced order the tasks were performed. The Stroop effect is displayed for the both the FRF (lilac) and FRW (mint green) tasks for younger (solid) and older (hatched) adults depending on whether they performed the FRF (left) or FRW (right) task first. There were no significant differences (p<.05).

3.3.14. Congruency-Sequencing Effect

For the younger adults, the congruency-sequencing effect was 12ms and 10ms in experiment one and two, respectively, and an independent samples t-test revealed this difference was not significantly different t (73) = 0.38, p = .702, d = .09 (see Figure 24). Likewise, the older adults reported a congruency-sequencing effect of 14ms in experiment one and 17ms in experiment two, which did not differ significant t (56) = 0.44, p = .664, d = .12. This, once again, shows good concordance between experiment one and two for the younger and older adults in that the magnitude of the congruency-sequencing effect is consistent across experiments for both age groups.

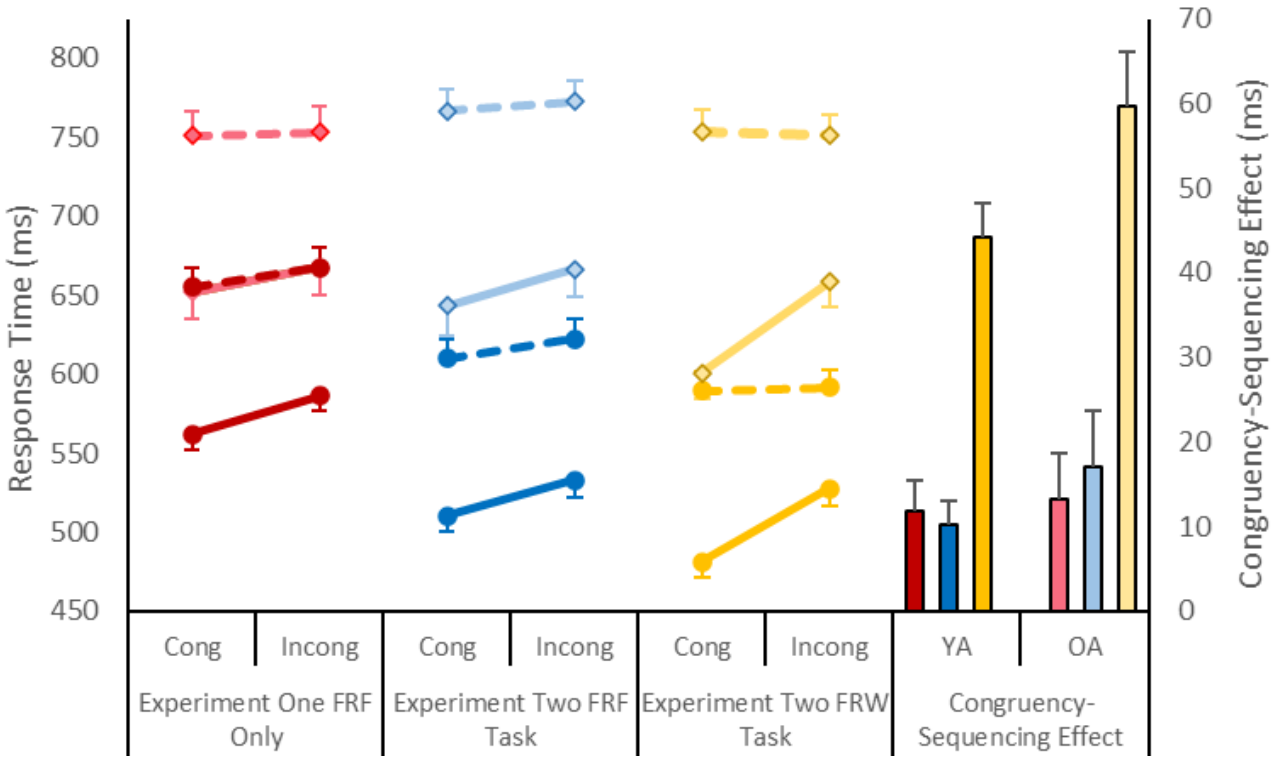


Figure 24. A comparison of the congruency-sequencing effect for experiment one and the FRF task in experiment two. The response times are displayed in the line graphs on the left and the congruency-sequencing effect in the column chart on the right. Experiment one is displayed in red, the FRF task from experiment two in blue and the FRW task in yellow for younger (darker shades and circular markers) and older adults (lighter shades and diagonal markers). There were no significant differences between the two FRF tasks.

3.3.15. Delta Plots

Figure 25 displays the delta plots from experiment one and two. Observe that despite responding marginally slower in experiment one, the solid lines of the younger adults in Figure 25 all follow a linear trend which was constant across all three tasks (experiment one (t=10.7, *p*<.001), experiment two FRF (t=29.5, *p*<.001) and FRW (t=13.1, *p*<.001)). Whilst the response times from the older adults is consistent across tasks, in experiment one, their Stroop effect did not show a main effect of response quintile. However, in experiment two the Stroop effect changed as a linear function of response time during both the FRF and FRW task (t=5.9, p<.001; t=9.6, *p*<.001). In summary, as predicted by the Diffusion Model for Conflict Tasks (Ulrich et al., 2015), experiment two shows that a linear relationship between the Stroop effect with response time can be observed in both the FRF and FRW tasks for both younger and older adults.

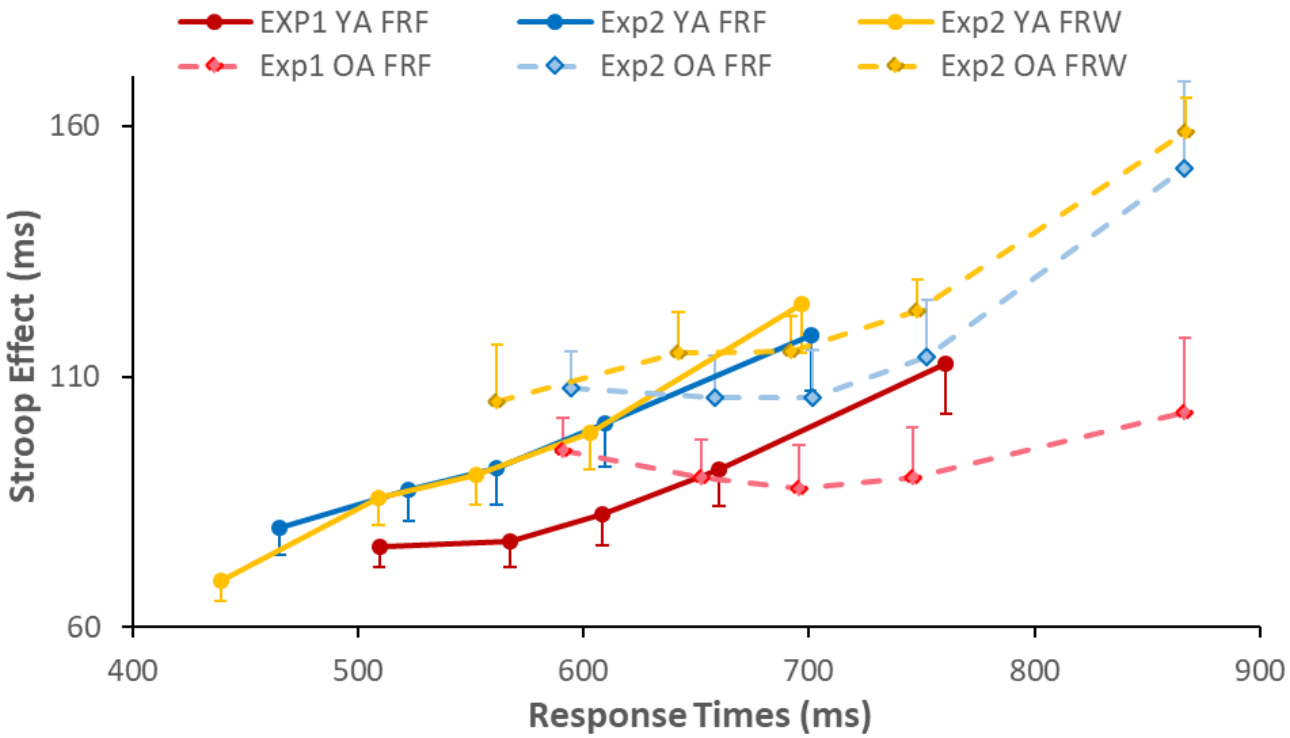


Figure 25. A comparison of the delta plots for the Stroop effect. Experiment one is displayed in red, the FRF task in experiment two in blue, and the FRW task in yellow. The darker solid lines refer to the younger adults and the lighter dashed lines to the older adults.

3.3.16. Classifications

Both experiments demonstrated a congruency-sequencing effect in the absence of feature repetitions in that the Stroop effect was reduced following an incongruent trial. However, the typical congruency-sequencing effect as reported by Gratton et al. (1992) suggests the response times of incongruent trials should be quicker when preceded by an incongruent (iI) opposed to congruent (cI) trial. This is demonstrated by a downward sloping top line in Figure 5A. Interestingly, the response times of experiment one and two do not follow this trend, but instead, as seen in Figure 11 and Figure 15, the gradient of the incongruent line is less steep than that of the congruent line, thus producing a congruency-sequencing effect, but not perhaps in the expected manner. Such a pattern of results was also reported by Duthoo et al. (2014) in a Stroop task designed to remove feature-repetitions a-priori. This draws the question of whether congruency-sequencing effects of the same magnitude utilise the same underlying mechanisms if the pattern of responding is different. Therefore, to further explore possible mechanisms underlying the congruency-sequencing effect and by extension, any differences in mechanisms between groups, the following criterion will be used to classify the congruency-sequencing effect.

Classification One: Participants display an overall congruency-sequencing effect of >5ms whereby cC trials are at least 2.5ms faster than iC trials and iI trials are at least 2.5ms faster than cI trials. This is the classical pattern referred to by Gratton et al. (1992) (see Figure 5B) and reflects an interaction of previous-trial and current-trial congruency whereby the Stroop effect is smaller following an incongruent trial.

Classification Two: Participants display a congruency-sequencing effect of >5ms where cC trials are at least 2.5ms quicker than iC trials, but iI trials are less than 2.5ms faster than cI trials. This represents a main effect of previous-trial congruency whereby responses are faster when the previous trial was

congruent. An overall congruency-sequencing effect is achieved by the current-trial congruent slope being steeper than the current-trial incongruent. Participants displaying this pattern of classification are considered post-congruent adapters.

Classification Three: Participants display a congruency-sequencing effect of >5ms where iI trials are at least 2.5ms quicker than cI trials, but cC trials are not more than 2.5ms quicker than iC trials. This represents a main effect of previous-trial congruency whereby the responses are faster when the previous trial was incongruent. An overall congruency-sequencing effect is achieved because the slope to the current-incongruent trial is steeper than the current-congruent trial. Participants displaying this pattern of classification are considered post-incongruent adapters.

Classification Four: Participants display a congruency-sequencing effect between -5 and +5ms suggesting they are not changing their performance on a trial-by-trial basis. Both the current trial congruent and incongruent line are almost parallel, but the direction of the lines could be positively linear (as per class. 2); negatively linear (as per class 3), or perpendicular (as shown in Figure 26).

Classification Five: Participants display a *negative* congruency-sequencing effect greater than -5ms. That is, the interaction of previous-trial and current-trial congruency is such that the Stroop effect is larger following an incongruent trial. This classification does not seek to differentiate between the different mechanisms that could produce a negative congruency-sequencing effect. These participants are not cognitively inflexible *per se* but are not adapting their performance in a beneficial way.

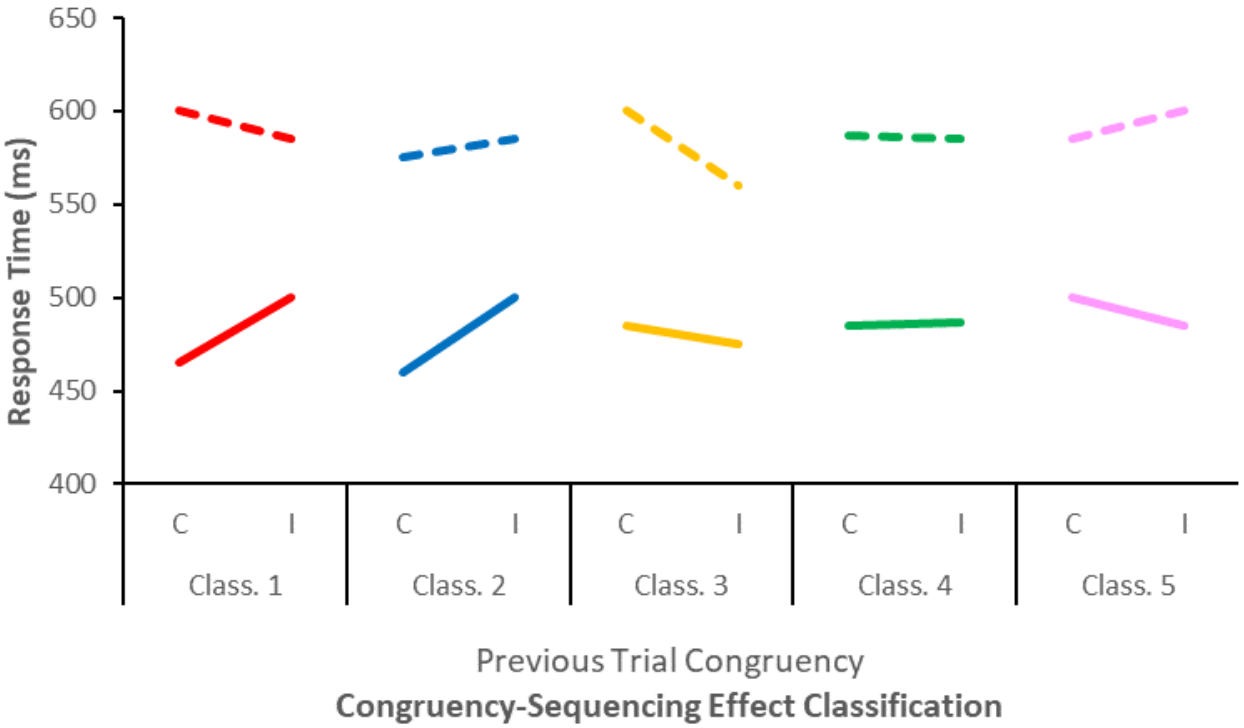


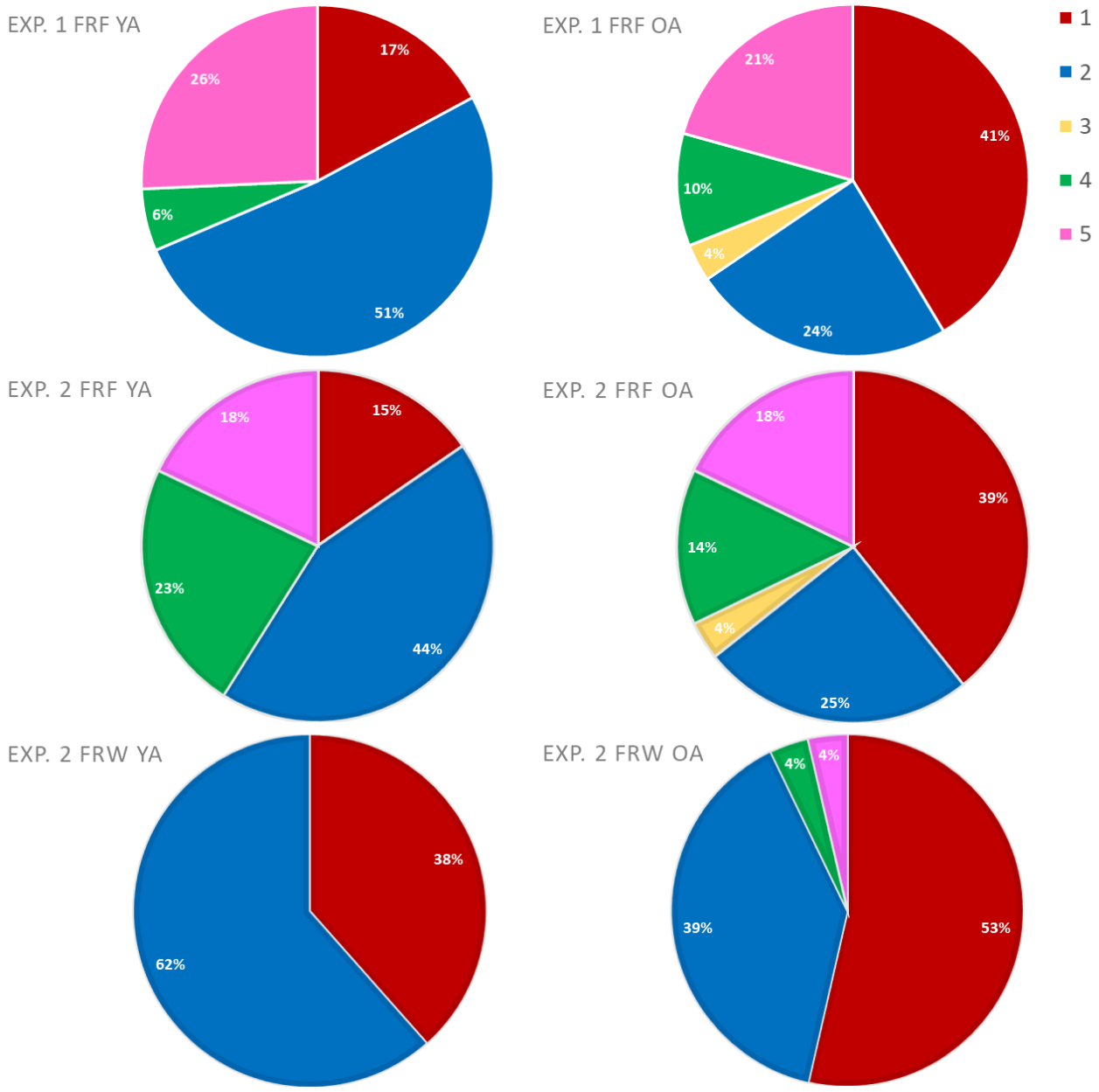
Figure 26. The proposed congruency-sequencing effect classifications one through five from left to right. Example data has been used so all participants report a Stroop effect of 100ms and class one through three show a congruency-sequencing effect of 30ms. Current trial congruent is represented by solid lines, and incongruent trials by dashed lines. C and I refer to the congruency (C= congruent; I = incongruent) of the previous trial.

Figure 26 contains example data to demonstrate each of the classifications. Each classification demonstrates a Stroop effect of 100ms. The congruency-sequencing effect displayed in classifications one, two and three are all 30ms, classification four is 4ms (between -5 and +5ms), and classification five is -30ms. Paying particular attention to classifications one through three, this pertinently illustrates that the magnitude of the congruency-sequencing effect on its own (each 30ms) may mask differences in response strategies posed above and potential differences that may occur with ageing. Hypothesis two stated that older adults would display a cognitive inflexibility by a reduced congruency-sequencing effect, yet no differences with age were found in either experiment, which prompted this exploratory classification analysis. For both experiments, the congruency-sequencing effect was categorised for

each participant and displayed as a percentage of the total number of participants (to account for differences in participant numbers across experiments), as shown in Figure 27. For the younger adults, the most frequent classification was class two, followed by class one in all tasks. Whereas the older adults show class one, followed by class two to be the most frequently reported classification. The data from both FRF tasks has been pooled due to good consistency across experiments and is compared against the classification distributions of the FRW task in Figure 27 and reported in the statistics below.

To compare the distribution of classification responses, a Pearson's Chi-Squared test with CLASSIFICATION (1, 2, 3, 4, 5) and AGE (younger/older) was first performed for the combined values of the two FRF tasks. This showed a moderate effect of AGE $\chi 2$ (4) = 13.2, p =.010 (Cramer's V = .315) suggesting the younger and older adults displayed differing distributions across the congruency-sequencing effect classifications. Post-hoc analyses showed that significantly more older adults had a class one congruency-sequencing effects than younger adults, and that there were significantly more younger adults with class twos. This suggests that older adults placed a greater reliance on both previous and current-trial congruency to inform their responses, whereas younger adults typically responded faster after a previously congruent trial, regardless of the current-trial congruency. This may represent a compensatory responding strategy which is explored further in Section 3.4.2.2.

The same analyse was performed for the FRW task. The bottom of Figure 27 clearly shows that this time, almost all participants are responding as class one or two. There was no main effect of AGE $\chi 2$ (4) = 7.0, p =.135, which showed this was true for both younger and older adults, although numerically, as with the FRF task, the younger adults favoured more class ones and the younger adults more class twos task. This suggests that any compensatory responding strategy is less pronounced under conditions where top-down control may be less influential to responding. Due to the exceptionally small error rates, no such classification was produced in conjunction with the response error data.



1578 *Figure 27. The percentage of each congruency-sequencing effect classification for younger (left) and older (right) adults in*

1579 *experiment one (top) and the FRF (middle) and FRW (bottom) tasks of experiment two.*

3.4.0. Discussion:

Experiment one addressed aims one and two: 1) to isolate the top-down component of the congruency-sequencing effect; 2) to explore behaviourally whether age-related differences in the DLPFC translate to impaired cognitive flexibility via the congruency-sequencing effect. Experiment two addressed aims two and three: 3) to observe the contribution of feature-repetitions in the congruency-sequencing effect from the FRW task and whether this is affected by ageing.

3.4.1. Does the Congruency-Sequencing Effect Reflect Top-Down Mechanisms?

A fundamental aim of this chapter was to first observe whether a congruency-sequencing effect would emerge in a conflict (Stroop) task specifically designed to remove feature-repetitions from the trial sequence (FRF task). The results from both experiments support a congruency-sequencing effect in a relatively novel testing paradigm free from any feature-repetitions, and thus, likely reflects a top-down mechanism. This was important to establish because there are currently three key models that are posited as the underlying mechanisms: 1) Conflict-Monitoring model (Botvinick et al., 2001); 2) Repetition Expectancy Model (Egner, 2007); 3) Feature-Integration Model (Hommel et al., 2004). The first two are top-down accounts which both implicate the DLPFC in driving the effect, whereas the third is a bottom-up account that suggests the congruency-sequencing effect arises due to episodic memory confounds between sequential trials. Despite the wealth of neurophysiological evidence provided in the General Introduction in support of a top-down account (Botvinick et al., 1999, Carter et al., 2000, Clayton and Larson, 2011, MacDonald et al., 2000, Yeung et al., 2004), the tasks from which this evidence was acquired all used standard conflict tasks where feature-repetitions are freely present. As such, it cannot be definitively concluded that feature-repetitions are not predominantly driving the congruency-sequencing effect and magnifying the congruency-sequencing effect.

In 2004, Kern et al. provided a reprieve for the feature-repetition confound by performing a standard Stroop task and removing feature-repetitions post-hoc from the analysis. They reported a robust congruency-sequencing effect after post-hoc removal of feature-repetitions and therefore concluded that their contribution was minimal. Subsequentially, this approach of post-hoc removal of feature-repetitions has since been taken favour among researchers and is frequently reported (Aschenbrenner and Balota, 2015, Lemaire and Brun, 2016, Notebaert et al., 2006). A novel critique from this thesis is that post-hoc removal of feature-repetitions may yield different results from a task purely designed without any feature-repetitions. This is discussed in Section 3.4.3.1. Due to the popularity and ease of execution of post-hoc removal of feature-repetitions, it was not until far later that a pure testing paradigm such as the free-from feature-repetition task was used (Aschenbrenner et al., 2017, Duthoo et al., 2014, Puccioni and Vallessi, 2012a and b).

Interestingly, Puccioni and Vallesi (2012a) failed to report a congruency-sequencing effect under such conditions in their sample of younger adults and subsequently report no age-related difference in their sample of older adults (Puccioni and Vallesi, 2012b) where they also did not report a reliable congruency-sequencing effect. Whilst these results may suggest a minimal top-down role underlying the congruency-sequencing effect, instead, it appears their task design was not optimised to observe a congruency-sequencing effect. For example, they have used a manual Stroop task which has fewer degree of dimensional overlap (Kornblum et al., 1990), thus inducing less conflict between the stimulus and the response and resulting in a smaller Stroop effect (Augustinova et al., 2019). Further, they used a long inter-stimulus-interval which has been correlated with smaller congruency-sequencing effects (Egner, 2007, Jackson and Balota, 2013). A combination of these factors may explain why Puccioni and Vallesi were unable to observe a congruency-sequencing effect in the absence of feature-repetitions. Duthoo et al. (2014) have in fact reported reliable congruency-sequencing effects in an array of tasks (Stroop, Flanker and Stroop-Like) in a feature-repetition free paradigm, and more recently so too have

Aschenbrenner et al. (2017). This provides support for a top-down mechanism and is consistent with the results from experiment one which were replicated in experiment two.

3.4.1.1. Beyond Mean Response Times of the Congruency-Sequencing Effect

As discussed, the results from both experiments reported a reliable congruency-sequencing effect in the FRF tasks, however, the results reported here (and by Aschenbrenner and Balota, 2015, Duthoo et al., 2014) do not display the pattern of results typical of a congruency-sequencing effect. For example, Figure 5 demonstrates that iI trials are faster than cI trials, as per the original congruency-sequencing effect reported by Gratton et al. (1992). The results from experiment one, presented in Figure 11, and experiment two, presented in Figure 16, display a congruency-sequencing effect but without faster iI than cI trials. This drew to question whether all congruency-sequencing effects represent the same mechanism. To delve further, this thesis introduced a novel classification system to investigate whether the congruency-sequencing effect is in fact driven by adaptation to conflict on incongruent trials (resulting in a smaller Stroop effect after incongruent trials) or is instead driven by a larger Stroop effect following congruent trial.

Lamers and Roelefs (2011) approached this question by including neutral trials to compare the Stroop effect after all three (congruent, incongruent and neutral) trial types. They found a 5ms reduction in the Stroop effect following incongruent compared to neutral trials, however, the driver of their congruency-sequencing effect was a larger Stroop effect after congruent trials compared to neutral (11ms) and most strongly, compared to incongruent trials (16ms). Compton et al. (2012) replicated this behavioural data and provided further support from EEG data, where they recorded alpha power (10-14Hz) from the frontal regions, including the DLPFC. Post-congruent trials elicited lower alpha power, suggesting greater cognitive processing, than post-neutral and post-incongruent trials, whose alpha did not differ. Compton suggests this alpha desynchronization could reflect enhancement of the

task-relevant stimuli or inhibition of the task-relevant stimuli, both of which would benefit only congruent trials, thus leading to a heightened Stroop effect following a congruent trial. Both studies suggest that perhaps conflict adaptation is not in response to conflict from incongruent trials but arises from changes following congruent trials, thus warranting further analyses in our own behavioural datasets.

As shown in Figure 26, class one suggests adapting after both congruent and incongruent trials; class two is post-congruent adaptation only (as per Lamer and Roelefs (2011) and Compton et al., (2012)'s suggestion); class three is post-incongruent adaptation only; class four is minimal adaptation; class five is negative adaptation. Adaptation post-congruent and post-incongruent trials (class one) would rely on very rapid, trial-by-trial reactive adaptations to allow facilitation from task-irrelevant stimuli on congruent trials but its inhibition on incongruent trials. Most participants display either a class one or class two congruency-sequencing effect, which both require adaptation following a congruent trial. Conversely, very few participants display a class three, which would rely on adaptation only following an incongruent trial. Section 3.4.2.2. will return to the classifications for deciphering different mechanisms between younger and older adults underpinning the congruency-sequencing effect. Overall, this classification system provides a novel insight into the response time patterns of participations.

3.4.2. Behavioural Deficits in Older Adults?

3.4.2.1. Stroop Effects

Aim two was to explore any age-related deficits arising in the Stroop performance between younger and older adults. Hasher and Zacks' (1998) inhibitory deficit hypothesis suggested older adults exhibit a larger congruency effect due to reduced inhibitory processes that occur with ageing. As expected, across all three tasks the older adults were typically 115 ±13ms slower than the younger adults. Over

and above a generalised slowing account, there is a large body of literature supporting an impaired cognitive inhibition in older adults as denoted by a heightened Stroop effect (Aisenberg et al., 2018, Bugg et al., 2007, Jackson and Balota, 2013, Mutter et al., 2005, Spieler et al., 1996, West and Moore, 2005) but this was not a consistent finding across both experiments. Experiment one (FRF task) reported an 88 ±7ms and 93 ±8ms Stroop effect for older and younger adults which did not reflect an age-related difference. However, experiment two reported a heightened Stroop effect in the older adults that was 38 ±3ms larger in the FRF task and 60 ±7ms larger in the FRW task. There are two ways to interpret these inconsistencies: differences in the task (FRF vs FRW) or differences between the participant samples (experiment one vs experiment two).

In lieu of the conflicting results arising from the FRF task in experiment one and two, a meta-analysis across the two experiments was performed (see Section 3.3.12.). This reported that, overall, in contrast to hypothesis two and previous findings, the older adults did not report a heightened Stroop effect compared to the younger adults in the FRF task. An obvious difference between the previous findings who reported a heightened Stroop effect with age (Aisenberg et al., 2018, Bugg et al., 2007, Jackson and Balota, 2013, Mutter et al., 2005, Spieler et al., 1996, West and Moore, 2005) and the results from the current FRF experiments is that the former all used a Stroop task where feature-repetitions were present. This could be interpreted that, although typically only considered in playing a role in the congruency-sequencing effect, feature-repetitions also contribute to the Stroop effect, however, the exact mechanism for how this would work is currently unclear. This explanation is unlikely given that both Puccioni and Vallessi (2012b) and Aschenbrenner et al. (2017) reported a larger Stroop effect for older compared to younger adults in their FRF paradigms. Instead, the inconsistency in the results between experiment one and two may not arise from differences in the task (i.e., the difference in the combined results of the FRF task compared to the FRW task) but instead may arise from recruitment confounds occurring between experiment one and experiment two. The participants in experiment

one were sourced from the '1,000 Elders Database' which is a bank of volunteers, typically ex-academics, who are regularly contacted to partake in research studies. Conversely, the participants from experiment two were predominantly community-sourced and anecdotally were less cognitively 'healthy' than the sample in experiment one, although no such objective measure to substantiate this claim was obtained. This may explain why the older adults in experiment one responded more similarly to the younger adults than the older adults in experiment two. In summary, there is some evidence to support the previous finding of a heightened Stroop effect with age, however, this conclusion is limited to the findings from experiment two only.

Interestingly, the delta plot, which is usually considered a more sensitive method than mean response times alone, revealed contrasting age-comparisons. In experiment one the younger adults displayed a linear relationship between the Stroop effect and response times that was not observed for the older adults. However, during experiment two, both the younger and older adults displayed a linear trend in the FRF and FRW tasks. The delta plots suggested differences between younger and older adults in experiment one, but not in either task during experiment two. The results from all three tasks were in line with previous findings and the Diffusion Model for Conflict Tasks (Ulrich et al., 2015), in that the delta plots demonstrated a linear relationship between the Stroop effect and response times for younger adults (Aschenbrenner and Balota, 2015, Christ et al., 2007, Pratte et al., 2010, West, 2003). However, there are comparatively fewer papers that have used delta plots to explore differences between age groups. Jackson and Balota (2013) also reported linear trends in their delta plots for both younger and older adults, however, they found divergence such that at the slower response speeds older adults displayed larger Stroop effects than younger adults, as per our own findings.

It has been suggested this last delta segment is an index of cognitive inhibition (Ridderinkhof, 2002), however, this explanation is not consistent with the Diffusion Model for Conflict Tasks, nor the positive

shape of the delta reported here (Gajdos et al., 2019). Instead, the last delta slope of the Stroop task likely represents greater accumulation of evidence from the task-irrelevant stimulus, or re-check stage of the task-relevant and task-irrelevant stimulus (Pratte et al., 2010). This may suggest that the divergence at the last delta segment between the age groups would represent a more cautious processing approach to avoid making mistakes when the correct response was not immediately obtained. Such a response strategy is consistent with the fMRI results of Milham et al. (2002) who reported increased ACC BOLD responses in older compared to younger adults, which they suggested represented a neural compensatory strategy to allocate more resources for detection of conflict or errors. The results from the error analysis a main effect of age in experiment two, but not one whereby older adults committed <1 more errors than younger adults. It is difficult to draw any conclusions from this due to the exceptionally low error rate.

Overall, there were no differences in the Stroop effect between younger and older adults during experiment one, however, a heightened Stroop effect in older adults during experiment two suggests age-related differences in impairment in cognitive inhibition in our community-based sample. Additionally, the shape of the delta plots indicates minimal differences in the mechanisms for processing Stroop stimuli, however, the pronounced divergence at the slowest response times for older adults may represent a more cautious processing strategy with heightened resources devoted to conflict detection.

3.4.2.2. Congruency-Sequencing Effects

FRF Tasks: Although in line with previous studies (Aschenbrenner et al., 2017), theoretically, it is perhaps surprising to report no age-related decline of the congruency-sequencing effect in the FRF tasks. The Conflict-Monitoring model (Botvinick, et al., 2001) has split the flexible modulation of behaviour into two processes: conflict detection, which has been localised to the anterior-cingulate

cortex (ACC); and upregulation of attentional resources, which is localised to the dorsolateral prefrontal cortex (DLPFC). Additionally, there are fronto-striatal loops that assist with response selection in cognitive tasks (Kaasin and Rinne, 2002, Milham et al., 2002, Redgrave et al., 2010, Ota et al., 2006, Tekin and Cummings, 2002). There is extensive literature citing age-related anatomical and functional decline in these structures and connective loops. The ACC is a renowned site for cognitive decline in healthy ageing that shows reduced grey matter volumes (Vaidya et al., 2007) that are accelerated compared to other (cingulate) regions (Mann et al., 2011). Pardo et al. (2007) correlated ageing with hypometabolism of glucose in the ACC, which they propose may underlie age performance differences in Stroop tasks. Further, the DLPFC is associated with a loss of dendrites and hence synaptic connections in healthy ageing (Fuster, 2015). Equally, age-related declines in brain dopamine (Berry et al., 2016) may impair cognitive performance (Cools and D'Esposito, 2011) perhaps more so for proactive control which relies on a phasic release of dopamine (Braver et al., 2009). Therefore, having established the congruency-sequencing effect reflects a top-down account (Section 3.4.1), both accounts of top-down conflict adaptation would predict an impairment with ageing.

Therefore, it was expected that these known anatomical deficits would be behaviourally reflected as an impaired congruency-sequencing effect in older adults. In contrast to hypothesis two, this was not the case. (Note, this study did not examine the ACC or DLPFC or dopamine levels of any participants directly and assumed that sampled participants would reflect the cognitive decline reported across the population.) The classification system introduced in Section 3.3.16. provided an additional method to explore the congruency-sequencing effect across age groups based upon their behavioural responses.

As shown in Figure 26, classifications one through three represent a positive congruency-sequencing effect and was present in 64% of younger and 69% of older adults. This shows that although the mean response times suggest no differences in the magnitude of the congruency-sequencing effect between

younger and older adults, a congruency-sequencing effect can be found more often in older than younger adults. When a congruency-sequencing effect was present (classifications one through three), post-congruent adaptations (classifications one and two) describe more than 95% of the data, illustrating its fundamental role in contributing to the congruency sequencing effect. This is especially prevalent in younger adults where the most common classification was class two, post-congruent adaptation only, and was displayed by a significantly greater percentage of younger than older adults (75% vs 53% of those displaying a congruency-sequencing effect). The most common classification for older adults was class one, adaptation to both congruent and incongruent trials, and this is also displayed by a significantly greater percentage of older compared to younger adults (65% vs 25% of those displaying a congruency-sequencing effect). These represent very important mechanistic differences between the two age groups' ability to adapt following conflict (an incongruent trial).

In summary, a greater percentage of older adults display a congruency-sequencing effect (class one through three), and of those who do, again, a large percentage of older adults display adaptation following congruent *and* incongruent trials, opposed to younger adults who rely predominantly on adaptation following only congruent trials. This is consistent with the reports that heightened ACC BOLD responses, reflective of conflict-monitoring, were observed during both congruent and incongruent Stroop trial for older adults, compared to during only incongruent trials for younger adults (Milham et al. 2002). This was combined with reduced DLPFC BOLD responses for older compared to younger adults (Milham et al., 2002). This represents a neural compensatory strategy in older adults that is consistent with the behavioural patterns revealed by the classification analysis. As such, this thesis proposes that the difference in classifications and the suggestion that older adults utilise information from congruent and incongruent trials to adapt their performance may reflect a compensatory strategy to accommodate declines in brain dopamine (Berry et al., 2016), ACC (Vaiyda

et al., 2007) and DLPFC functioning (Fuster, 2015) which would all impair conflict adaptation and would explain why older adults produce a larger congruency-sequencing effect than younger adults.

3.4.3. The Role of Feature-Repetitions

The third aim of this experiment was to compare the contributions of top-down and bottom-up influences of the congruency-sequencing effect. Although the results from the FRF tasks provide support for a top-down mechanism, note, however, that this is not a mutually exclusive explanation and that previous studies that have not control for such (feature-repetition) influences reported a much larger congruency-sequencing effect than those reported in our FRF tasks. West and Moore (2005), for example, failed to control for priming confounds in their Stroop task reported a congruency-sequencing effect of 68ms in younger adults. Hommel et al. (2004) brought to light that feature-repetitions can produce a congruency-sequencing effect without any top-down control, and as such, threaten the top-down accounts underlying the congruency-sequencing effect.

Experiment two compared the magnitude of the congruency-sequencing effect from a feature-repetitions free (FRF) and feature-repetitions with (FRW) task to contrast the contributions of top-down and bottom-up influences of the congruency-sequencing effect. As predicted, the congruency-sequencing effect was 37ms larger in the FRW than FRF task, replicating that feature-repetitions do indeed amplify the congruency-sequencing effect. This supports the conclusion from Hommel et al. (2004) in that feature-repetitions contribute to the congruency-sequencing effect. Importantly, there was a reliable congruency-sequencing effect in the FRF task that once again supports the top-down component of conflict adaptation. This highlights that whilst there is a top-down role of cognitive control underpinning the congruency-sequencing effect, if feature-repetitions are not adequately controlled for, they may mask any potential differences in top-down functioning, such as those predicted to occur with healthy ageing.

3.4.3.1. Post-Hoc Removal of Feature-Repetitions

Despite their known contribution, some studies have failed to control for feature-repetitions when reporting the congruency-sequencing effect (Bonnin et al., 2010, Fielding et al., 2005, West and Moore, 2005, Wylie et al., 2009a, Wylie et al., 2009b). Kerns et al. (2004) first addressed the potential confound of feature-repetitions by post-hoc removal of feature-repetitions from a standard Stroop test (in which feature-repetitions are abundant), and this approach has since become common practice (Aschenbrenner and Balota, 2015, Larson et al., 2016, Notebaert et al., 2006). Whilst Kerns et al. (2004) reported a reliable congruency-sequencing effect using this approach, Schmidt and De Houwer (2011) saw a reduction from 23ms to 2ms in their manual Stroop task. The discrepancies between such findings emphasises the difficulty in isolating the top-down component of conflict adaptation measured through the congruency-sequencing effect.

A novel critique of post-hoc removal of feature-repetitions is that the influence of the feature-repetitions on the remaining feature-alternation trials remained unknown and unaccounted for. To test this, post-hoc removal of feature-repetitions in the FRW task was performed (see Section 3.3.10.1.), and the resultant congruency-sequencing effect in the feature-alternation trials was compared to the congruency-sequencing effect yielded from the FRF task (which only included feature-alternation trials). As shown in Figure 20, the congruency-sequencing effect in the FRW task was 84ms larger for feature-repetition than feature-alternation trials, with the congruency-sequencing effect in feature-alternation trials at -17.5ms and 1ms for younger and older adults respectively. Importantly, the congruency-sequencing effect obtained after post-hoc removal of feature-repetitions yielded significantly different results to the FRF task which was specifically designed to not include any feature-repetitions (10ms and 17ms for younger and older adults, respectively). This highlights that post-hoc removal of feature-repetitions, such that has become common practice, is less than optimal for analysing the congruency-sequencing because remaining trials may be contaminated with carry-over

from the removed feature-repetitions. This emphasises that post-hoc removal of feature-repetitions from a standard conflict task may also underestimate the top-down contribution to cognitive flexibility and yield unreliable results compared to a feature-repetition free task.

3.4.3.2. Feature-Repetitions and Ageing

Failure to control for (West and Moore, 2005) or post-hoc removal (Aschenbrenner and Balota, 2015) of feature-repetitions has led to reports of a larger congruency-sequencing effect in older than younger adults. Aschenbrenner and Balota 2015 found a significantly larger congruency-sequencing effect in older adults and West and Moore (2005) reported congruency-sequencing effects of 38ms in older and 12ms in younger adults, although this difference did not reach significance. Considering the wealth of evidence suggesting age-related declines in DLPFC (Vaidya et al., 2007, Mann et al., 2011), ACC functioning (Fuster, 2015), and brain dopamine (Berry et al., 2016), on the surface, these findings seem counterintuitive. However, this likely reflects preserved or greater susceptibility to bottom-up processes with age (Andres et al., 2008, Bergerbest et al., 2009, Park and Reuter-Lorenz, 2009).

In line with notion of preserved bottom-up processing with age, the current study found that, although not statistically significant, the congruency-sequencing effect in the FRW task was 15ms greater for older than younger adults. To investigate this further and explore the influence of specific feature-repetitions, the response times for positive and negative priming trials were reported. As expected, positive-priming trials, those in which the task-relevant stimulus repeats from trial *n*-1 were shown to reduce response times on trial *n*, were 89ms ±6ms faster than the mean iI response time and negative-priming trials, where the task-irrelevant stimulus on trial *n*-1 repeats as the task-relevant stimulus on trial *n*, were 56ms ±4ms slower than mean iI response times. There was no interaction of priming and ageing. This suggests no differences in the between the older adults' ability to beneficially alter

performance when top-down control is not required, thus supporting preserved bottom-up processing (Andres et al., 2008, Bergerbest et al., 2009, Park and Reuter-Lorenz, 2009).

In support of the response time data, the classifications further suggest older adults possess preserved bottom-up functioning. In support of the heightened congruency-sequencing effect in the FRW compared to FRF task, there was also an increase in the percentage of participants producing a congruency-sequencing effect (classes one through three) such that 100% of younger adults and 93% of older adults produced a congruency-sequencing effect in the FRW task (compared to 64% and 69% of younger and older adults in the FRF task). In the FRW task, the Chi-Squared test revealed no main effect of age such that the distribution of classifications did not differ between younger and older adults, which once again, supports the preservation of bottom-up processing. It is interesting to note, that much like the FRF task, older adults did still preferentially produce a class one congruency-sequencing effect (58% of older adults who produced a congruency-sequencing effect) and younger adults a class two congruency-sequencing effect (62% of younger adults), although these differences were not significant.

In summary, when using the congruency-sequencing effect as an index of top-down cognitive control, it is vital to use a task specifically designed to account for feature-repetitions and that post-hoc removal is not an adequate control. Further, conflict adaptation is preserved in older adults, and likely reflects a greater reliance on an array of contextual information (bottom-up – if available – and post-incongruent adaptation) whereas younger adults predominantly rely on post-congruent adaptation to facilitate performance.

3.4.4. Limitations and Future Direction

The classification of the congruency-sequencing effect is a novel analytical tool to investigate the mechanisms underpinning the congruency-sequencing effect. This required an objective cut-off for each classification that was set to 5ms. This threshold was chosen because, upon visual inspection of the data, this provided the most appropriate classifications and best grouped similar data across participants. It is acknowledged that choosing a different threshold or including a greater number of categories may yield different results with regards to the distribution of classifications across participant groups. Five classifications were chosen to try to emphasise the important differences among the data, although, little explanatory differentiation is provided between class four (-5 to +5ms congruency-sequencing effect) and class five (<-5ms congruency-sequencing effect). Whilst the classifications can provide intel on the similarities or differences in processing across participants, it does not lead to a definitive mechanism or preferentially support one model of top-down control over the other. However, it does support fMRI data that suggests enhanced recruitment of the ACC to compensate for advanced decline of the DLPFC (Milham et al., 2002), basal ganglia, and fronto-striatal loops associated with healthy ageing. And as such, offers some explanatory power to the null differences reported across younger and older adults.

The FRF task provides evidence of top-down control of conflict adaptation, however, future studies should seek to provide causal evidence for the involvement of the DLPFC in producing the congruency-sequencing effect in a task free-from feature-repetition confounds (see Chapter Four).

3.7.0. Conclusion:

Unexpectedly, experiment one did not yield a larger Stroop effect in older compared to younger adults, however, the community-based sample in experiment two did. This is thought to reflect age-related deficits originating in the DLPFC that impair cognitive inhibition. The FRF tasks reported reliable congruency-sequencing effects in both experiments. This supports the use of a feature-repetition free task as an appropriate paradigm to explore top-down influences underpinning conflict adaptation. Despite reported age-related decline of the ACC and DLPFC in the literature, this did not behaviourally translate as impaired conflict adaptation as both FRF tasks reported congruency-sequencing effects of similar magnitudes for younger and older adults. However, an explorative analysis lead to a novel classification of congruency-sequencing effects which may represent subtle differences in conflict adaptation processing. Older adults may rely on adaptation post-congruent and post-incongruent trials, whereas younger adults predominantly rely on post-congruent adaptations only. Such compensatory behaviour may explain the null differences in the magnitude of the congruency-sequencing effect between younger and older adults.

The FRW task highlighted that feature-repetitions magnify the congruency-sequencing effect. The analysis reported that post-hoc removal of feature-repetitions is not an appropriate control for this confound and advocates the implementation of an FRF task. Response times and classification of the congruency-sequencing effect in the FRW task support a preservation of bottom-up processing with ageing. This supports the seemingly counterintuitive reports of larger congruency-sequencing effects in older adults when the task employed has not controlled for feature-repetitions (as per West and Moore, 2005).

Chapter Four: Using tDCS to Investigate the Involvement of the DLPFC in Cognitive Flexibility

4.0. Introduction:

Chapter Three established an appropriate behavioural paradigm to isolate the top-down component underpinning the congruency-sequencing effect. This provides support for top-down influences (either the Conflict-Monitoring model (Botvinick et al., 2001) or Repetition Expectancy Model (Egner, 2007), which suggests the congruency-sequencing effect is a result of cognitive adjustments by the DLPFC. The DLPFC is brain regions associated with accelerated age-related decline, thus it was expected that the adaptive behaviours produced by this region may be impaired compared to younger adults, however, there were no differences in the congruency-sequencing effect in the younger and older adults. This questions whether the top down-component of conflict adaptation demonstrated by the congruency-sequencing effect does in fact reflect activity of the DLPFC. Therefore, this chapter sought to measure causal involvement of the DLPFC in producing the congruency-sequencing effect through non-invasive brain stimulation.

4.1.1. Introduction to Non-Invasive Brain Stimulation

The effects of external electrical stimulation on the human body have been studied for over two millennia (see reviews by Sironi, 2011, Stagg and Nitsche, 2011). Dating as far back as 46AD it was reported that applying discharge from an electric ray on a human's head provided treatment for headaches and epilepsy (Sironi, 2011). Much later, in the late eighteenth century, Galvani famously discovered animal electricity when a pair of prepared frogs' legs with exposed nerves began vigorously contracting when touched with a metal lancet (Galvani, 1791). This led to his nephew, Aldini, performing pioneering work exploring the direct electrical stimulation of the cortex on decapitated

prisoners. In 1804, he concluded that electrical stimulation has value for the treatment of many neurological disorders (Aldini, 1804). In line with technological advances, the 1960s saw a surge of reinterest of Aldini's approach of applying electrical stimulation directly to the nervous system cortex. Electrical stimulation was applied directly to the spinal cord of a cat to record changes in, and to further understand the relationship between the size of the pre-synaptic potential and neurotransmitter release into the synaptic cleft (Eccles et al., 1962). Weak electrical stimulation, applied directly to the exposed rat cerebral cortex, was used to explore stimulation after-effects on cortical excitability (Bindman et al., 1962). Electrical stimulation of the exposed human cerebral cortex has also been performed; however, this was typically involved patients who were already undergoing neurosurgery (Celesai et al., 1967, Woolsey et al., 1979) so did not provide a means to investigate the cerebral cortex in healthy humans.

The 1980s saw the development of transcranial magnetic stimulation (TMS), which provides a means to non-invasively stimulate the intact human cerebral cortex. Copper wire coils placed parallel to the head induce a magnetic field to create an electric current which passes perpendicularly through, thus penetrating the skull and stimulating the tissue beneath (Klomjai et al., 2015). Single pulse TMS is often used in conjunction with motor evoked potentials (MEPs) to determine changes in corticospinal excitability pre and post intervention. Repetitive TMS (rTMS) applies trains of stimulation at high frequency (5-25Hz) to increase, or low frequency (<1Hz) to decrease, corticospinal excitability, often over several occasions to serve as a training intervention (Klonjai et al., 2015). For example, Kim et al. (2012) reported five days of rTMS applied to the DLPFC reliably reduced response times on incongruent Stroop stimuli in older adults, which they concluded to have demonstrated improved inhibitory control. A limitation of TMS is that it produces a noticeable cutaneous sensation through stimulation, which can be unpleasant. This, combined with the loud noise produced with each stimulation, makes it difficult to blind the participant or the researcher to sham conditions (Horvath et al., 2014).

4.1.2. Transcranial Direct Current Stimulation

4.1.2.1. Stimulating the Motor Cortex

An alternative form of non-invasive brain stimulation called transcranial direct current stimulation (tDCS) does not suffer from the same limitations of rTMS. During tDCS, a continuous electrical current passes between a positively (anode) and negatively (cathode) charged electrode where one or both electrodes are placed on the skull so that the current penetrates the brain regions below. Following the first modern studies employing tDCS, (Nitsche and Paulus, 2011, Priori et al., 2009), the last two decades has seen a surge of interest in the technique. A review by Horvath et al. (2015b) reported mixed findings regarding the applicability of tDCS to enhance cognitive capabilities, yet studies have reported a beneficial influence of tDCS to the DLPFC to improve working memory and cognitive inhibition (Bashir et al., 2019, Keeser et al., 2011), decision-making (Edgcumbe et al., 2019) and cognitive control (Gbadeyan et al., 2016a).

In a series of experiments, Nitsche and Paulus (2000) applied 1mA of current via electrodes attached over the motor cortex for up to five minutes. They used TMS to elicit motor evoked potentials (MEPs) from the hand muscles pre and post tDCS stimulation. They noticed that following anodal stimulation, where the current flows from the anode towards the cathode, MEP amplitudes were significantly higher than baseline. Likewise, following cathodal stimulation, where the current flows from the cathode to the anode, MEPs amplitudes were significantly smaller. They concluded that corticospinal excitability increases during anodal stimulation due to depolarisation of the resting membrane potential of the corticospinal neurons in the region below the anode. Conversely, during cathodal stimulation corticospinal excitability decreases due to hyperpolarisation of resting membrane potentials. Furthermore, Nitsche and Paulus, (2000) reported that longer durations (upwards of five minutes) of tDCS could prolong the time at which these changes in corticospinal excitability were observed. These findings have been replicated numerous times for both anodal and cathodal

stimulation (Horvath et al., 2015a) and tDCS has become a well-established method to non-invasively modulate corticospinal excitability.

4.1.2.2. Generalisability tDCS to Other Brain Regions

After establishing the neural underpinnings of tDCS, Antal et al. (2001) found good generalisability of their original findings from the motor cortex to performance changes co-occurring with stimulation of the visual cortex. However, this time, they did not seek to develop an external measure to validate that the same neural changes observed in the motor cortex were in fact driving the performances changes with stimulation of the visual cortex. This is an inherent limitation with the applicability of tDCS to brain regions other than the motor cortex. Although behavioural changes are the primary aim of stimulation, they offer only an indirect measure of levels of corticospinal excitability (Stagg and Nitsche, 2011). In the motor cortex, it is possible to use single pulse TMS to induce MEPs to objectively measure the corticospinal excitability before and after tDCS (Priori et al., 2009; Nitsche and Paulus, 2000). Heightened or reduced MEPs evoked by the same TMS stimulus represented proportionate increases or decreases in corticospinal excitability. However, other brain regions are not offered the affordance of such external validation. EEG has been used to measure acute changes in power output across different frequencies after receiving tDCS to the left DLPFC and primarily revealed increased delta power across the frontal cortex (Keeser et al., 2011). This suggests that EEG can be used to measure electrical changes resulting from tDCS to non-motor regions, although, the authors commented on time constraint of setting up EEG to record such acute changes.

4.1.2.3. Dorsolateral Prefrontal Cortex

Many studies have applied tDCS to the DLPFC to modulate inhibitory control, as reported through congruency effects (Angius et al., 2019, Frings et al., 2018, Huo et al., 2018, Loftus et al., 2015, Nejati et al., 2017, Zmigrod et al., 2016). However, a consistent finding is faster response times for both

congruent and incongruent trials with no modulation of the Stroop effect (Doruk et al., 2014, Frings et al., 2018, Hsu et al., 2015, Loftus et al., 2015). Interestingly, comparatively few studies have reported the sequential modulation of the Stroop effect: the congruency-sequencing effect (Baumert et al., 2020, Frings et al., 2018, Gbadeyan et al., 2019, Gbadeyan et al., 2016b).

The DLPFC is a key structure identified in the top-down processing of conflict adaptation implicated in proactive (Braver and Barch, 2002, De Pisapia and Braver, 2006) and reactive (Botvinick et al., 2001) control. Its role is to upregulate attentional control towards either the task-relevant or task-irrelevant stimuli. A proactive account states this occurs due to phasic dopamine released according to the predicted congruency of the upcoming trial whereas a reactive account states this occurs according to the congruency of the immediately preceding trial as detected by the ACC. Upregulation of the task-relevant stimuli occurs in anticipation of (proactive control), or due to having just experienced (reactive control), an incongruent trial so to minimise the interference from the task-irrelevant stimuli on the current trial. Equally, upregulation of the task-irrelevant stimuli occurs due to anticipation of, or having just experienced, a congruent trial so to maximise the facilitation from the task-irrelevant stimuli on the current trial. These attentional adjustments by the DLPFC are thought to underpin the congruency-sequencing effects and are thus a measure of conflict adaptation reported throughout this thesis. The General Introduction highlighted the key evidence for the involvement of the DLPFC where much of the evidence implicated the left DLPFC (Banich et al., 2000, Carter et al., 1998, MacDonald et al., 2000, Milham et al., 2001, Milham et al., 2003, Vanderhasselt et al., 2006a, see General Introduction) although there is also some support to implicate the right DLPFC (Kerns et al., 2004; Egner and Hirsch, 2005; Egner et al., 2008; Vanderhasselt et al., 2006b). Vanderhasselt et al. (2009) provides a brief review to suggest that right DLPFC is associated with reactive control and the left DLPFC with proactive control. However, this thesis will focus on evidencing involvement of the left DLPFC in conflict adaptation because that is the site suggested by much of the original research.

Note, most of this evidence was obtained through fMRI, which, however compelling, provides only correlational evidence. Therefore, causal evidence, such as that from non-invasive brain stimulation, should be obtained to confirm the proposed roles of the DLPFC.

Gbadyen et al. (2016) study sought to provide localised evidence of the DLPFC in the congruency-sequencing effect and to identify any lateralised differences between the left and right DLPFC. The congruency-sequencing effect was reliably larger under anodal tDCS of the DLPFC compared to sham stimulation, although this was not modulated by stimulation to the left compared to right hemisphere. Later studies do not provide compelling evidence for whether tDCS applied to the left (Baumert et al., 2020, Frings et al., 2018) or right (Gbadyen et al., 2019) DLPFC may be most effective at modulating conflict adaptation. This is in line with a meta-analysis that found no lateralised effect of tDCS applied to either the left or right DLPFC to modulate an array of cognitive functions (Dedoncker et al., 2016). In summary, there is more support for the role of the left DLPFC, which is widely accepted to underpin conflict adaptation and as such, will be the target stimulation site for this experiment.

4.1.3. Methodological Considerations of tDCS

4.1.3.1. Electrode Placement

The placement of electrodes in relation to each other is very important. As mentioned, current flows from the anode (cathode) to the cathode (anode), thus positioning of the second electrode influences the direction of current flow. Typically, studies have placed the second electrode on the contralateral region (Anguis et al., 2019, Loftus et al., 2015, Nejati et al., 2017, Zmigrod et al., 2016). This introduces a potential confound such that any behavioural changes could be attributed to the excitatory current under the anode or from negative, inhibitory effects of the cathode. Therefore, it is suggested that the second electrode be placed so to maximise current flow through the region of interest and be placed elsewhere (than the contralateral position) to remove such confounds (Thair et al., 2017). Further,

modelling computations (Miranda et al., 2006) suggest electrodes placed more than 5cm are less susceptible to shunting of the current across the scalp, thus resulting in greater penetration of the current to intended brain region (Nitsche and Paulus, 2011). For this reason, extracelaphic electrode montages whereby the reference electrode is placed on the deltoid (Huo et al., 2018) or neck (Baumert et al., 2020) are increasingly favoured to maximise the current directed to the region of interest.

4.1.3.2. Current Density

The current density is quantified as the surface area of the electrodes multiplied by the current output (mA/cm^2). In the reported tDCS studies this has ranged from 0.5mA (current density $0.056mA/cm^2$, Frings et al., 2018) to 2mA (current density $0.08mA/cm^2$, Huo et al., 2018). Current density is affected by stimulation duration. A meta-analysis reported higher current density applied over a longer duration positively influenced behavioural outcomes of stimulation to the DLPFC (Dedoncker et al., 2016). A drawback is that higher intensities may be subject to greater cutaneous sensation (Prior et al., 2009) which may be unpleasant for the participant. Therefore, within the tested safety parameters of tDCS (2mA applied for 20 minutes, Iyer et al., 2005), it is considered higher current applied for longer durations may be most effective at eliciting behavioural changes.

4.1.3.3. Stimulation Timings

If a low current density is applied for a short period of time, this will induce only weak changes in cortical plasticity that may not be sufficient to elicit detectable changes in the outcome behavioural measurement that outlast the stimulation duration. As such, offline stimulations, whereby behavioural assessments are performed pre- and post-stimulation, typically require a high current density. Further, offline stimulation studies, such as those deployed by Frings et al. (2018) may be subject to learning effects due to repetition of the task during pre- and post-stimulation testing (Thair et al., 2017). However, offline stimulation is advantageous for comparing the effects in situations the behavioural

measure cannot be performed during stimulation, for example, if the task cannot be performed stationary (such as walking) or if the task design restricts movements (is performed in a scanner) (Priori et al., 2009). Conversely, online stimulation, such as that used by Gbadyen et al. (2016; 2019) and Baumert et al. (2020) provides real-time information regarding changes in cortical excitability and are less reliant on higher current densities to elicit prolonged adaptations to the stimulation, thus is more favourable for static tasks such as the Stroop.

4.1.3.4. Control Stimulation

Horvath et al. (2014) proposes that participants can tell the difference between active and sham stimulation, so if participants noticed when they were receiving the 'real' stimulation, this may have influenced their performance. For this reason, an active stimulation control was used. Gbadyen et al. (2016; 2019) have used the motor cortex as a control stimulation site. With an extracephalic electrode montage, this would be a suitable control site because it is situated posterior to the DLPFC, thus the current will flow away from the DLPFC towards the reference electrode (typically on the neck or shoulder) and is less likely for current to spread to the DLPFC.

4.1.3.5. Feature-Repetitions

As demonstrated in Chapter Three, feature-repetitions play an important role in producing, and consequently magnifying, the congruency-sequencing effect. Of the studies using the congruency-sequencing effect to measure conflict adaptation, to best knowledge, no study has used an appropriate behavioural paradigm to remove the role of feature-repetitions (such as that described in Chapter Three). Frings et al. (2018) used a manual Stroop task consisting of only two-colours, which means that their task design must include feature-repetitions, however, their primary outcome measure was the basic Stroop effect, and their analysis of the congruency-sequencing effect was brief and supplementary. Baumert et al. (2020) made no acknowledgement of the role of feature-repetitions in

their four-choice manual Stroop task, thus it can be assumed no control analyses were conducted. Gbadyen et al. (2016; 2019) used a two-choice Flanker task such that it is not possible to remove feature-repetitions, but attempted to address this by post-hoc removal of *exact* feature-repetition trials (those which have a large influence on increasing response speed) in a separate analysis of the DLPFC groups. They reported a larger congruency-sequencing effect in repetition compared to alternation trials that did not interact with stimulation, thus concluding the congruency-sequencing effect results was not attributed to feature-repetitions and that anodal stimulation of the DLPFC heightens the congruency-sequencing effect compared to sham. However, the results from Chapter Three indicate that post-hoc removal of feature-repetitions is not equivocal to a priori-removal, therefore, Gbadyen's interpretation, whist seemingly intuitive, should be cautiously interpreted until validated by a study utilising a feature-repetition free task.

4.1.4. Aims and Hypotheses

In summary, tDCS is a method of non-invasive brain stimulation that was originally applied to the motor cortex to elicit measurable changes in TMS evoked MEPs, reflecting increased and decreased corticospinal excitability arising differentially from anodal and cathodal stimulation (Nitsche and Paulus, 2000). Only in the motor cortex can MEPs be used as an external validation of changes in corticospinal excitability; however, it is assumed the neuromodulation undergone in the motor cortex is generalisable to the rest of the cerebral cortex. TDCS has been used to explore cognitive inhibition and has been applied to the DLPFC which has reduced response times to Stroop stimuli without modulating the Stroop effect itself (Angius et al., 2019, Baumert et al., 2020; Huo et al., 2018; Frings et al., 2018).

Few studies have taken this opportunity to perform the analysis regarding the modulation of the Stroop effect according to the previous trial congruency (the congruency-sequencing effect) and thus

the role of the DLPFC in conflict adaptation (Baumert et al., 2020, Gbadyen et al., 2016; Gbadyen et al., 2019; Frings et al., 2018). Of those who have, none have used an appropriate behavioural paradigm such as the feature-repetition free (FRF) task employed in Chapter Three to remove the confounding influence of feature-repetitions.

Aim One: To use anodal tDCS to provide causal evidence for the involvement of the left DLPFC in conflict adaptation. To achieve this, online anodal tDCS will be applied to the DLPFC whilst participants perform the FRF Stroop task. A within-subjects design will be used whereby participants will also undergo anodal tDCS to the primary motor cortex (M1) which served as a control stimulation site.

Hypothesis One: A) The Stroop and B) congruency-sequencing effect will be observed during stimulation of the DLPFC and M1.

Hypothesis Two: Despite the differences in the proposed underlying mechanisms (proactive – in anticipation of; reactive – conflict driven), both top-down accounts of conflict adaptation would predict that anodal stimulation of the DLPFC will increase its functioning and allow for greater upregulation of the task-relevant /task-irrelevant stimuli. This would enlarge the congruency-sequencing effect compared to stimulation of M1 where no such modulations are predicted to occur.

Hypothesis Three: A) As per previous findings (Baumert et al., 2020, Doruk et al., 2014, Frings et al., 2018, Huo et al., 2018, Loftus et al., 2015), anodal tDCS to DLPFC will result in faster response times as compared to stimulation of M1, however, this will affect congruent and incongruent trials equally, and as such, B) no change in the Stroop effect is expected between stimulation of the DLPC and M1.

4.2.0. Methods:

4.2.1. Participants

Thirty-six participants aged 18-30 (20.7 ±3.2) years (23 female) were recruited from the School of Sport, Exercise and Rehabilitation Sciences at the University of Birmingham. Participants were offered course credit for their participation. In addition to the inclusion criteria in the General Methods, such as full colour-vision, etc., participants also completed a tDCS safety screening questionnaire to assess their eligibility (see Appendix). The study was approved by the University of Birmingham's STEM research ethics committee and all participants provided informed, written consent prior to taking part.

4.2.2. Stroop Task

The experiment was a cross-over within-subjects design whereby participants visited the laboratory on two occasions in a counterbalanced order. Participants performed the feature-repetition free (FRF) version of the Stroop task whilst receiving anodal tDCS stimulation to either the left DLPFC or the left primary motor cortex (M1). The Stroop task consisted of 400 trials split over 5 blocks, which lasted for 15 minutes. The task congruency was 50% and the 200 incongruent trials were equally distributed across all possible word-colour combinations to remove any potential contingency learning confounds associated with unequal presentation of specific word-colour pairings. Participants performed 10 practice trials without any stimulation prior to the main experiment. Visits were separated by 24 hours and were performed at the same time of day (between 8am and 6pm) for each participant. Each visit lasted approximately 45 minutes.

4.2.3. tDCS

4.2.3.1. Electrode Positioning

The 10/20 electrode placing system (Jasper, 1958) was used to identify the scalp locations for placing the stimulation electrodes on each participant. It uses measurements such as from the participants' nasion to inion, from their left to right pre-auricular and their head circumference to account for absolute differences in head size by identifying brain regions in accordance with their relative position to each other and bony landmarks (see Figure 28). Electrodes are placed in 10% increments apart and were identified by a letter and number pair. The letters refer to the lobe (except for the case of 'C' because there is no central lobe) of the cerebral cortex below and the numbers are split with even numbers on the right and odd numbers on the left hemisphere.

This system was used to identify the region of interest: the left dorsolateral prefrontal cortex (F3); and the control site: the left primary motor cortex (C3). An antiseptic wipe was used to clean the sites and remove any oils that may affect conductivity. To ensure close contact with the scalp, the hair was parted and a 5x5cm electrode, placed inside a saline soaked sponge, was placed centrally over the stimulation site, and secured to the head using elastic strapping. It was important the electrode sponges were not saturated to the point of dripping because wet hair can affect the spread and direction of the current (Horvath et al., 2014).

In line with safety guidelines (Iyer et al., 2005), anodal direct current stimulation was applied via a neuroConn (GmbH) stimulator at a constant current of 2mA, resulting in a current density 0.08mA/cm^2. During anodal tDCS, the current flows from the anode to the cathode electrode through the path of least resistance. This can sometimes include shunting across the more conductive cerebral spinal fluid without penetrating and stimulating the tissue below (Thair et al., 2017). To minimise this and maximise penetration of the current into the brain regions below the active electrode, it is suggested

to place electrodes further apart (Nitsche and Paulus 2011). Therefore, an extracephalic electrode montage was chosen whereby the cathode was placed on the contralateral (right) shoulder over the upper trapezius.

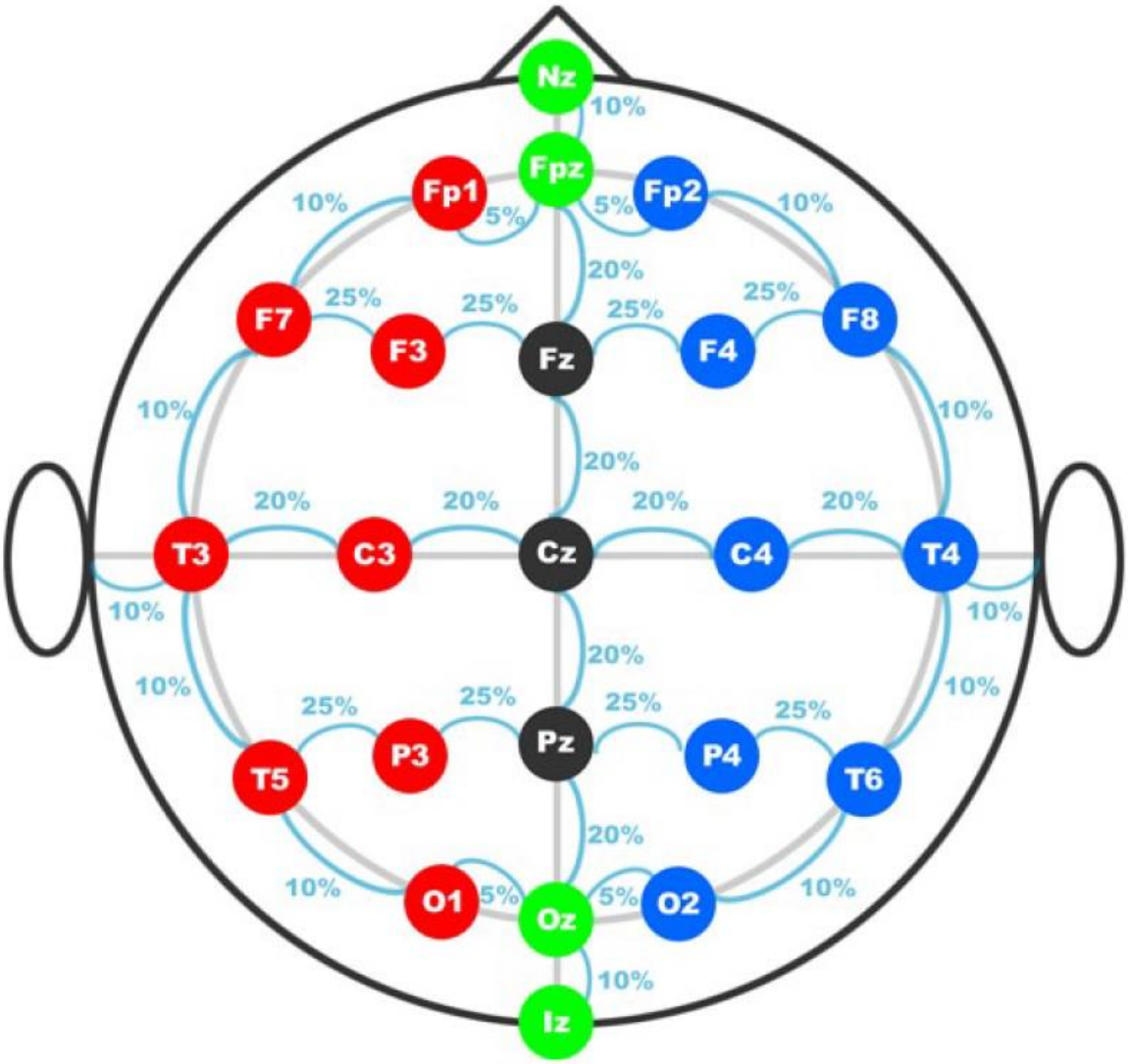


Figure 28. The 10/20 electrode placing system used to identify the two stimulation sites: the left dorsolateral prefrontal cortex (F3) and the left primary motor cortex (C3).

4.2.3.2. Electrode Modelling

Modelling software such as Simulation of Non-Invasive Brain Stimulation (SimNIBS) (Saturnino et al., 2019) simulates prospective electrode montages to explore the current distribution prior to testing. Note, in SIMNIBS, the shoulder is not included as a stored electrode position, however, it is possible to manually input co-ordinates to simulate current flow to this position. Figure 29 shows the current distribution of anodal tDCS applied to F3 with the cathode positioned on the shoulder. Warmer colours (yellow/ red) indicates higher current density under F3 that travels inferiorly towards the cathode. Minimal current spreads to C3 (the control site) and to the contralateral F4. This shows the proposed montage to be suitable to ensure the current is concentrated under F3.

A separate simulation was performed for C3, the output is displayed in Figure 29. The current spreads laterally and caudally towards the cathode, as indicated by the warmer colours in these regions. Importantly, during stimulation of C3 (the control site) there is minimal current under F3 (the investigated region) as denoted by the dark blue in this region, hence is a suitable control region. It should be highlighted that both simulations demonstrate an edge effect whereby the current is most concentrated at the lateral edge of the electrode. This can be circumvented through use of high definition tDCS, however, due to cost constraints, this was not possible, and it was accepted as a limitation of the technique.

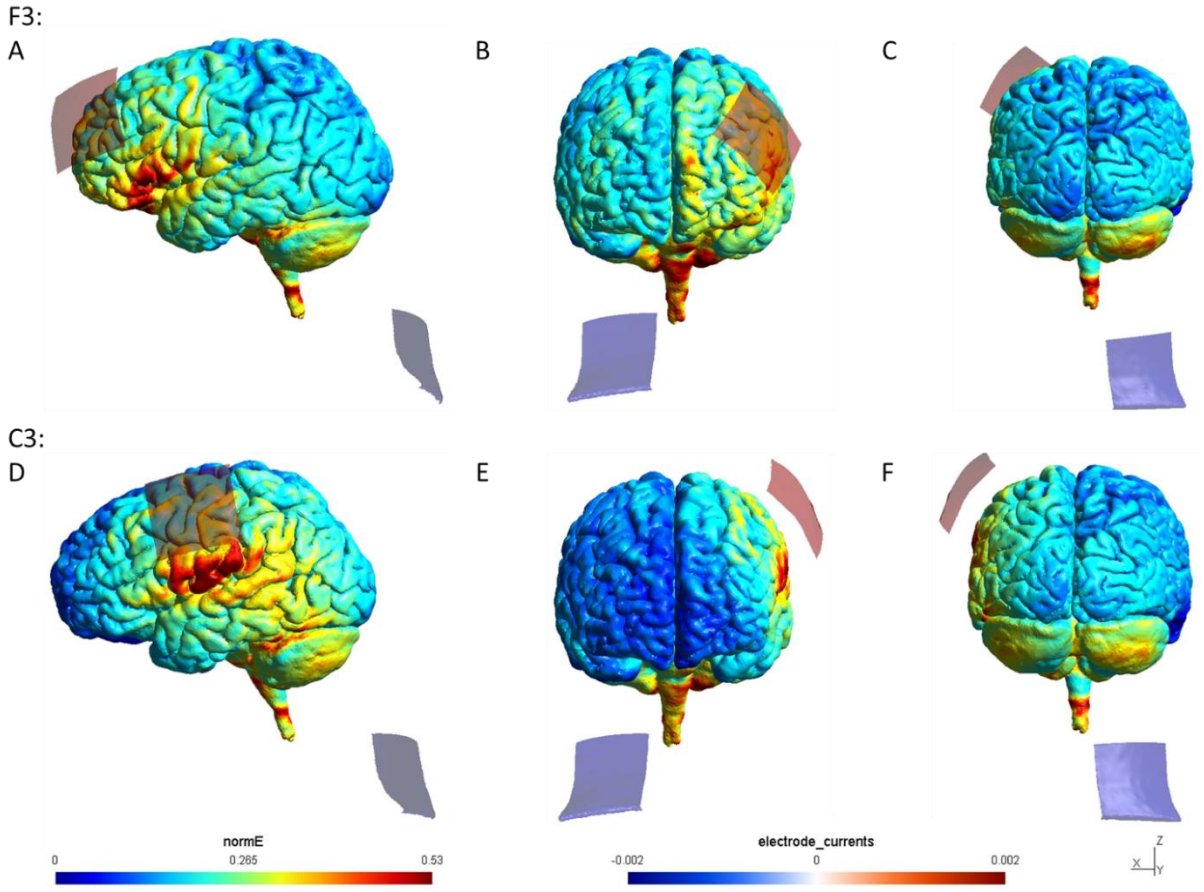


Figure 29. Electrode montage modelling to explore the strength of the electric field and current density prior to stimulation. The top three panels (A-C) display the output from the C3 simulation, and the bottom three (D-F) display the output from the F3 simulation. The leftmost panels (A and D) display the sagittal plane; the middle panels (B and E) display the frontal planes with the frontal lobes positioned anteriorly; the rightmost panels (C and F) display the frontal plane with the occipital lobes positioned anteriorly. The active electrode is shown by the transparent square, the reference electrode the grey/blue square positioned on the contralateral shoulder. The warmer colours towards the right of the spectrum highlight where the current is strongest, and the cooler colours where the current is weakest.

4.2.3.3. Anodal Stimulation

Once in both electrodes were in place, a 20 second impedance test (without stimulation) was performed to check the impedance remained below the recommended 5K Ω (DaSilva et al., 2011). If not, electrode was repositioned to ensure maximal contact with the scalp (Thair et al., 2017). Once satisfied, stimulation faded-in over 10 seconds and was applied for the duration of the Stroop task (15 minutes) and remained on for its entirety which included four 90 second breaks between blocks, before fading-out over 10 seconds. The impedance was continually observed throughout the task to ensure consistency across the session (Horvath et al., 2014). The impedance was recorded during the first 90 seconds and if it rose above this value mid-task, saline solution was added to the electrode sponge via a small, hosed bottle for precise application. If the impedance continued to rise such that the stimulation stopped, then the task was paused at the end of the block and the electrode repositioned before resuming stimulation. This happened on six occasions, of which three participants were removed from the analysis because more than 5% of trials were performed without any stimulation and the remaining three were included. This did not alter the results of any of the reported statistical analyses.

4.2.4. Data Analysis

Data analysis was performed as per the general methods; however, an overview is provided. The primary outcome measure was response times. From this, Stroop and congruency-sequencing effects are calculated. Response errors (<1% trials) were also recorded.

4.2.4.1. Participant Exclusions

Nine of the 36 participants were excluded from the final data analysis. Two participants were removed due to technical issues with the microphone. Two participants were removed as they had less than 80% of trials remaining for either dataset once all response errors, miss-trials and post-error trials were removed from the analysis. Two participants were removed because they did not show a reliable Stroop effect (-1ms and 1ms). A final three participants were removed as the stimulation stopped (due to high impedance) for a period covering more than half an experimental block (40 trials) on either visit. No participants were excluded due to adverse effects of the stimulation. In total, full datasets of 27 participants were analysed.

4.2.4.2. Response Times

A three-way RM ANOVA with PREVIOUS-CONGRUENCY, CURRENT-CONGRUENCY and STIMULATION-SITE (C3/F3) was performed.

Stroop: A main effect of CURRENT-CONGRUENCY shows a Stroop effect.

Congruency-Sequencing Effects: A reliable PREVIOUS-CONGRUENCY by CURRENT-CONGRUENCY interaction evidences a congruency-sequencing effect. Once established, this was calculated ((cI-cC)-(iI-iC)) and used as the dependent variable in separate ANOVAs to provide suitable post-hoc age and task comparisons. This also reduces the number of variables when performing multiple comparisons.

4.2.4.3. Power Analyses

Post-Hoc Power: As per the General Methods, a post-hoc power analysis for within-subject repeated measures ANOVA was performed to determine whether the study was adequately powered to observe a real difference in the magnitude of the congruency-sequencing effect between stimulation of F3 and C3, should one exist.

Smallest Effect Size of Interest: Further, the SESOI was calculated using the formulae provided in the General Methods from the data of Gbadyen et al. (2016). They also used M1 as a control stimulation site, however, they do not report the statistical analyses from this comparison (i.e., no PREVIOUS-CONGRUENCY, CURRENT-CONGRUENCY and STIMULATION SITE statistical comparison) and instead report only the between-subjects comparison of anodal and sham stimulation. Therefore, these values (anodal and sham comparison, $F(1,58)=9.53$, $p<.003$) are used to compute the SESOI.

Two One-Sided Tests of Equivalence: TOST of equivalence was used to interpret results smaller than the SESOI.

4.2.4.4. Time Course Analyses

Block-Wise: To compare the magnitude of the Stroop and congruency-sequencing effects across the experimental blocks, the main response time analysis was performed, with the addition of BLOCK (1-5) as a within-subjects variable.

Delta Plots: Delta plots were produced to compare the time-course of the Stroop effect across response times. Full details are provided in the general methods. Statistical analysis was as per the main response time data with the addition of QUINTILE (1-5) as a within-subjects variable.

4.2.4.5. Classifications

As with Chapter Three, congruency-sequencing effects were classified during stimulation at F3 and C3 to provide a more discreet measure of potential processing strategies utilised. To do this, if the gradient of the when the current trial is congruent (cC-iC) and when the current trial is incongruent (iI-cI) are each more than 5ms, it is assigned class one. If the gradient of the current congruent trial is more than 5ms but the current incongruent gradient is less than 5ms, participants are considered a class two. If the gradient of the current incongruent trial is more than 5ms but the current congruent trial is less than 5ms then participants are class three. Overall congruency-sequencing effects between -5 and +5ms are all class four, regardless of the gradients of the current and incongruent trials. Likewise, all congruency-sequencing effects less than -5ms are class fives, regardless of how it is derived from the current congruent or incongruent trials.

The percentage of participants reporting each classification are reported separately for C3 and F3 stimulation and compared using a Pearson's Chi-Squared test. Differences in the percentages of each

classification across both stimulation sites may suggest participants are using different processing strategies.

4.2.4.6. Order Effects

A RM ANOVA was performed to detect order effects and ensure there was no carry over effect from visit one to visit two. The Stroop effect was the dependent variable with STIMULATION (C3/ F3) as the within-subjects variable and ORDER (C3 First/ F3 First) as the between-subjects variable.

4.2.4.7. Response Errors

Errors on which participants stuttered or made an incorrect response were reported and underwent the same as the response time analysis to look for Stroop and congruency-sequencing effects.

4.3.0. Results:

4.3.1. Response Times

Figure 30 shows response times during F3 and C3. In contrast to hypothesis 3A, there was no main effect of STIMULATION-SITE $F(1,26)=0.04$, $p=.837$, $\eta_p^2=.00$ such that response times were not faster during stimulation of the DLPFC (566 ±14.8ms) than M1 (568 ±14.8ms).

Stroop Effect: As per hypothesis 1A, a main effect of CURRENT-TRIAL CONGRUENCY $F(1,26)=203.0$, $p<.001$, $\eta_p^2=.89$ revealed a significant Stroop effect whereby congruent trials were 85.9 ±6ms faster than incongruent trials (d=1.7, p<.001). Consistent with hypothesis 3B, there was no interaction between CURRENT-TRIAL CONGRUENCY and STIMULATION $F(1,26)=0.028$, $p=.869$, $\eta_p^2=.00$, thus the Stroop effect did not differ between stimulation of C3 (86 ±6ms) and F3 (86 ±6ms).

Congruency-Sequencing Effect: Figure 30B displays response times according to the trial sequence. Consistent with hypothesis 1B, a significant PREVIOUS-TRIAL by CURRENT-TRIAL interaction $F(1,26)=16.4$, $p<.001$, $\eta_p^2=.39$ shows the an overall congruency-sequencing effect across both C3 and F3. Congruent trials were 23.0 ±2ms faster when the previous trial was congruent (cC) than incongruent (iC) (d=2.9, p<.001). Similarly, incongruent trials were 10 ±2ms faster when the previous trial was congruent (cI) than incongruent (iI) (d=0.8, p<.001). In contrast to hypothesis two, there was not a three-way interaction of PREVIOUS-TRIAL, CURRENT-TRIAL and STIMULATION-SITE $F(1,26)=0.83$, $p=.371$, $\eta_p^2=.03$, indicating the congruency-sequencing effect did not differ between C3 or F3. Separate ANOVAs performed on F3 and C3 revealed significant PREVIOUS-TRIAL by CURRENT-TRIAL interactions

and there was a reliable congruency-sequencing effect of 11ms during stimulation of F3 $F(1,26)=6.65$, $p<.05$, $\eta_p^2=.20$; and 15ms during stimulation of C3 $F(1,26)=20.0$, $p<.001$, $\eta_p^2=.44$.

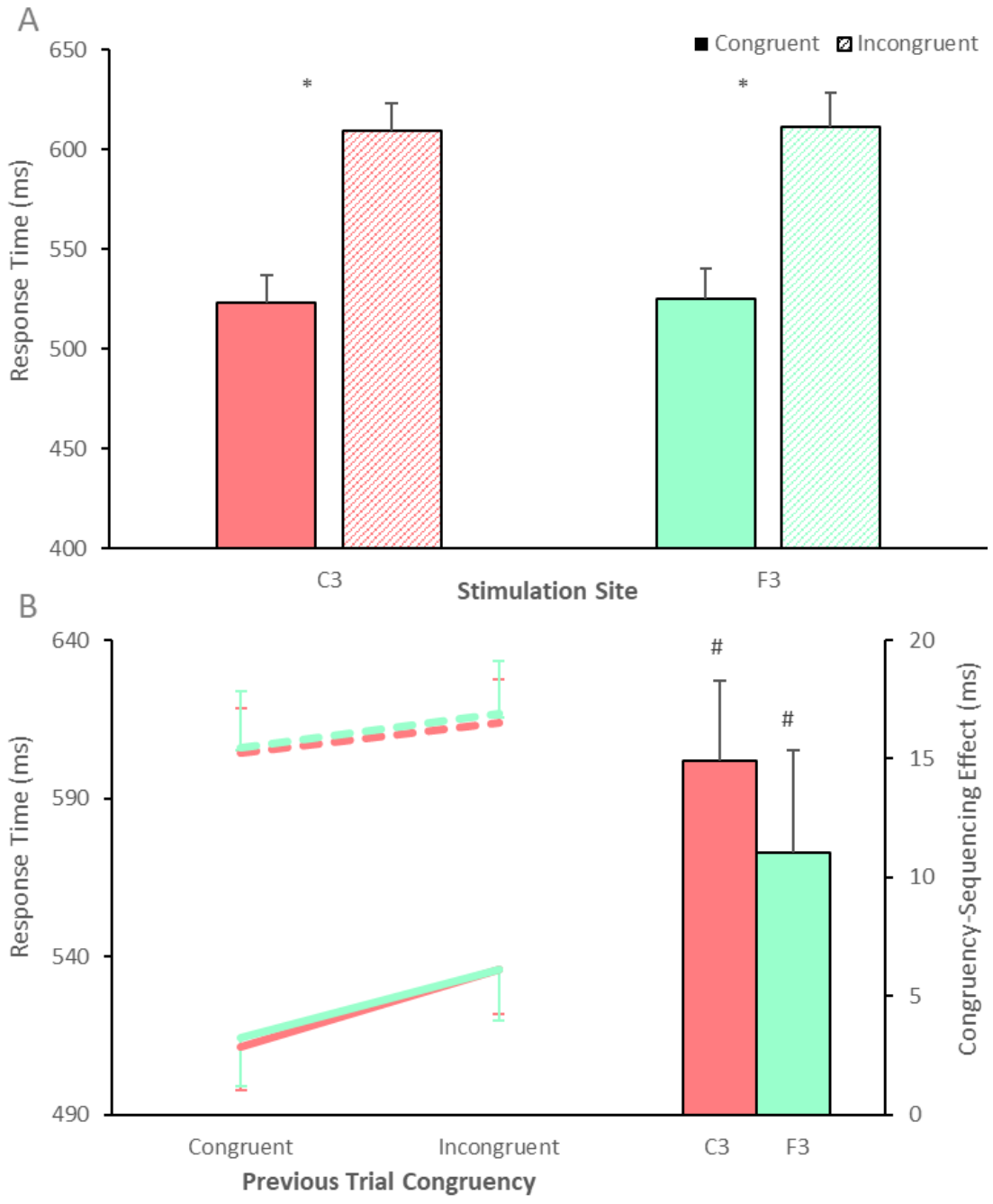


Figure 30. Response times during C3 (peach) and F3 (light green) stimulation. Panel A displays the response times for congruent (solid) and incongruent (hatched) trials to indicate the Stroop effect. Leftmost of panel B shows the response time for congruent (solid) and incongruent (dashed) trials in accordance to the congruency of the previous trial. The resultant difference is displayed as the congruency-sequencing effect on the right. The asterisks represent a significant Stroop effect and the hash a significant congruency-sequencing effect (p<.05). Neither effect differed according to stimulation site.

4.3.1.1. Power Analyses

Post-hoc Power: A post-hoc power analyses revealed that the obtained power of the PREVIOUS-CONGRUENCY, CURRENT-CONGRUENCY, by STIMULATION interaction (η_p^2=.03) was 0.17. This suggests the experiment was not adequately powered to detect the differences in the magnitude of the congruency-sequencing effect at the two stimulation sites.

Smallest Effect Size of Interest: Using the formulae provided in the General Methods, the SESOI was calculated as η_p^2 = 2.46. The three-way interaction of PREVIOUS-CONGRUENCY, CURRENT-CONRUENCY and STIMULATION-SITE revealed the η_p^2 = 0.03 and therefore, is not considered a meaningful difference.

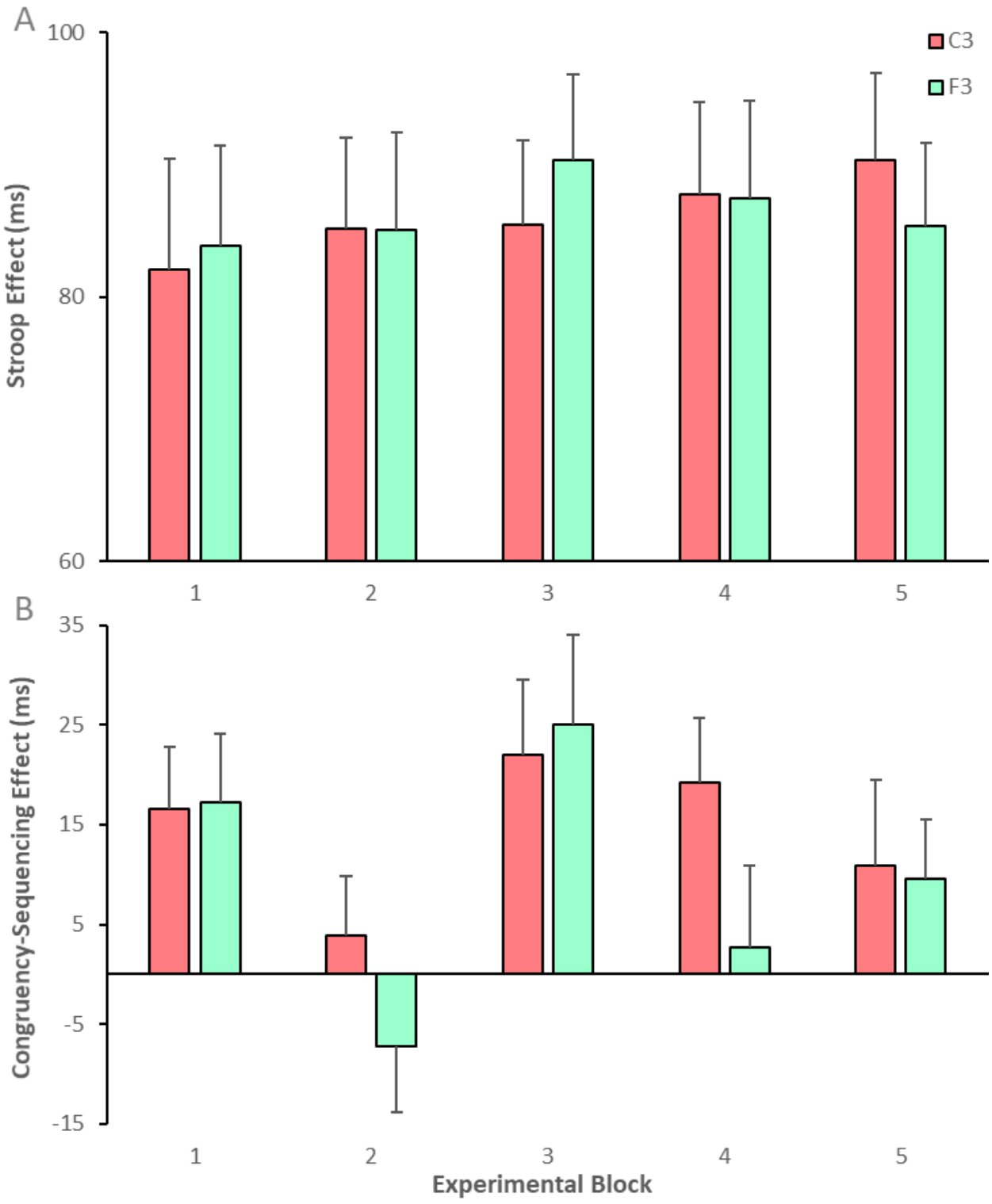
Two One-Sided Tests of Equivalence: The equivalence test was significant, t(48.97) = 8.339, p < .001, given equivalence bounds of -49.1 and 49.1ms and an alpha of 0.05. The mean congruency-sequencing effect obtained during stimulation of C3 (11ms) and F3 (15ms) lie within these boundaries. Therefore, the null hypothesis of no difference in the magnitude of the congruency-sequencing effect between stimulation of F3 and C3 can be accepted.

3.2. Block-wise Analysis

To explore whether the transcranial direct current stimulation affected performance differentially throughout the task, a block-wise analysis of the Stroop and the congruency-sequencing effect was performed.

Stroop Effect: Figure 31A shows the Stroop effect recorded during each of the five experimental blocks for both stimulation sites. The mean Stroop effect remained constant (between 83-88ms) across all blocks and stimulation conditions such that there was no main effect of BLOCK $F(2.9, 71.8\ (GG))=0.59$, $p=.611$, $\eta_p^2=.02$, nor an interaction of BLOCK by STIMULATION-SITE $F(3.1, 79.9\ (GG))=0.58$, $p=.632$, $\eta_p^2=.02$.

Congruency-Sequencing Effect: Figure 31B shows the congruency-sequencing effect during each of the five experimental blocks for both stimulation sites. A main effect of BLOCK $F(2.8, 71.7\ (GG))=3.3$, $p<.05$, $\eta_p^2=.11$ demonstrates the congruency-sequencing effect fluctuates throughout the experiment, with prominent differences occurring between blocks two (-2ms) and block three (24ms). The lack of STIMULATION-SITE by BLOCK interaction suggests the change in the congruency-sequencing effect across the blocks did not differ according to the site of stimulation (i.e., C3 or F3).



2304 *Figure 31. Stroop effect (panel A) and the congruency-sequencing effect (panel B) throughout the experimental blocks during*

2305 *tDCS stimulation of C3 (peach) and F3 (light green).*

3.3. Delta Plots

Figure 32A shows the Stroop effect according to response time. There was a significant main effect of response QUINTILE $F(1.43, 37.4\ (GG))=16.5$, $p<.001$, $\eta_p^2=.39$ such that, as predicted by the DMC (Ulrich et al., 2015), the Stroop effect increases from 69ms at the fastest response quintile (M=469ms) to 109ms at the slowest response quintile (M=687ms). This linear trend was observed in both C3 (t=6.4, $p<.001$) and F3 stimulation (t=8.4, $p<.001$), however, the non-significant QUINTILE by STIMULATION interaction ($F(1.65, 42.8\ (GG))=1.2$, $p=.332$, $\eta_p^2=.04$) shows the magnitude of the Stroop effect according to response time was unaffected by stimulation site.

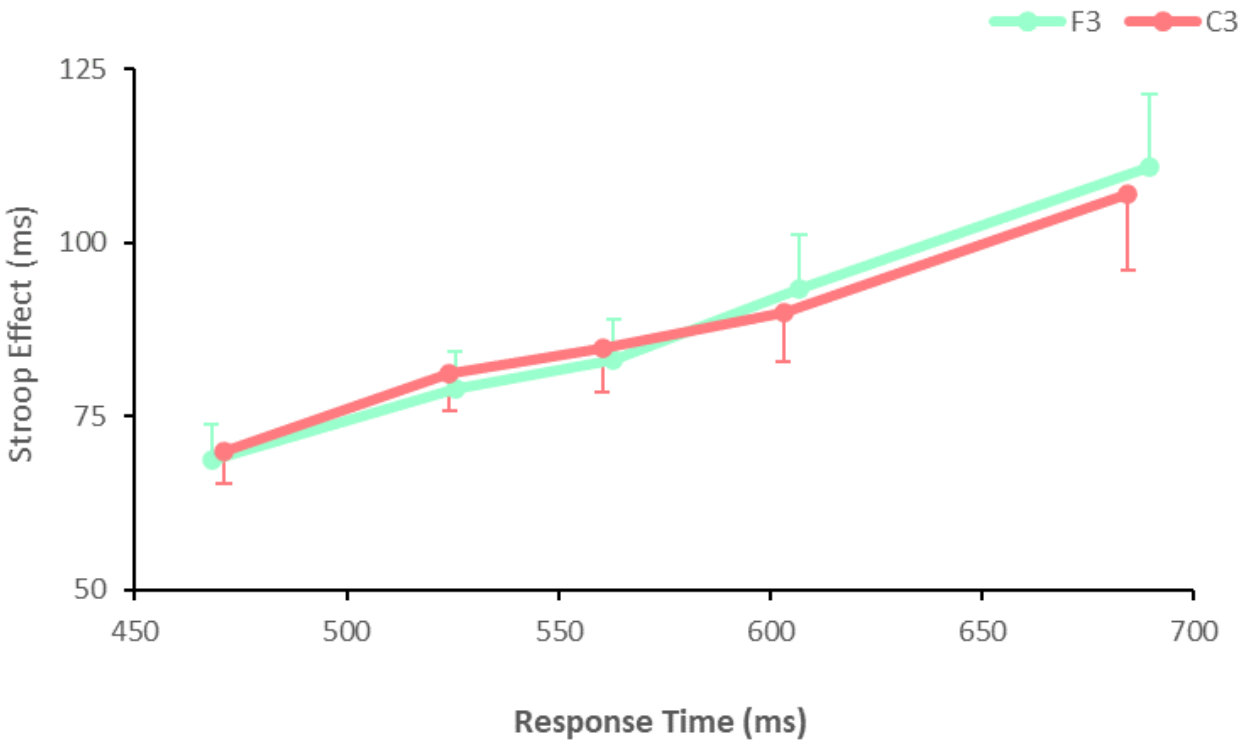


Figure 32. Delta plots reporting the magnitude of the Stroop effect according to response times during tDCS stimulation of C3 (peach) and F3 (light green).

3.4. Response Errors

Figure 33 shows there is a main effect of CONGRUENCY $F(1,26)=16.8$, $p<.001$, $\eta_p^2=.39$, participants made 0.28 ± 0.2 more errors on the incongruent compared to congruent trials. There was no main effect of STIMULATION $F(1,26)=1.5$, $p=.225$, $\eta_p^2=.06$ – the number of errors did not differ across stimulation sites. The PREVIOUS-CONGRUENCY by CURRENT-CONGRUENCY interaction was not significant $F(1,26)=3.6$, $p=.068$, $\eta_p^2=.12$ suggesting the congruency-sequencing effect was not reflected in the error data, however, it should be noted that error rates overall are very low.

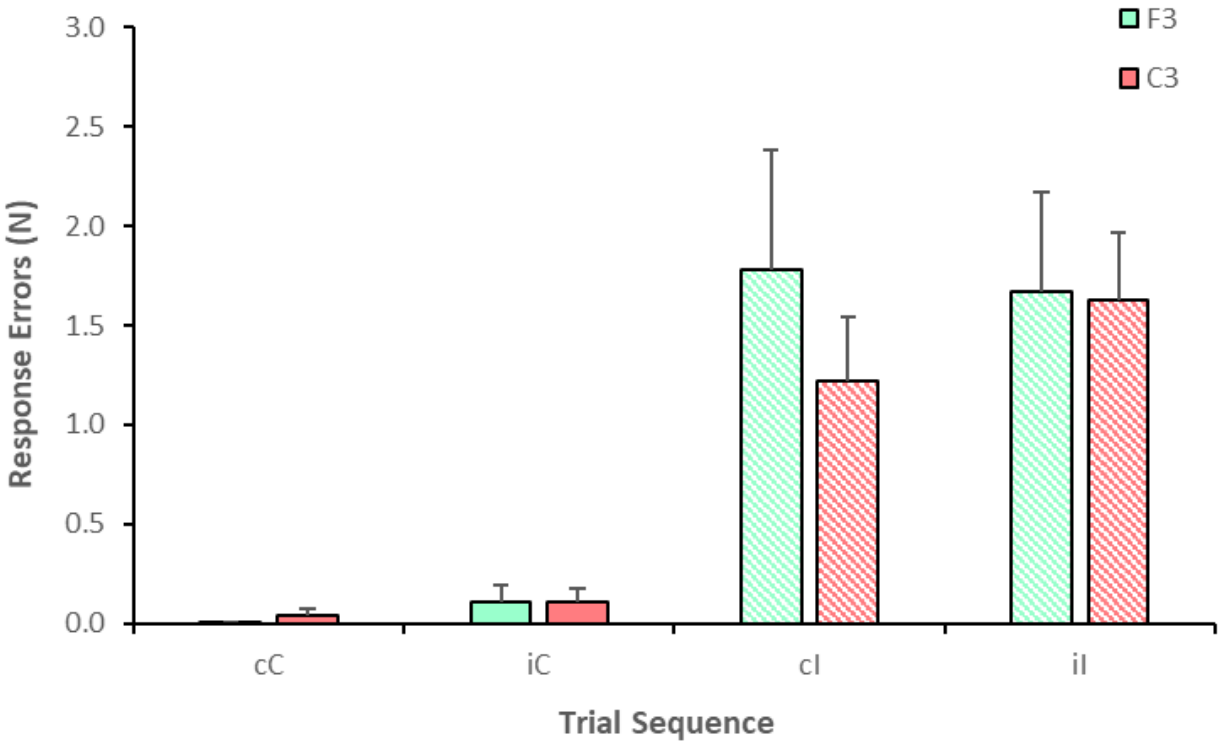


Figure 33. Response errors according to the trial sequence. The previous trial's congruency is denoted by lowercase letters (congruency= c; incongruent = i) and the current trial's congruency by capitalised letters. Current congruent trials (solid bars) are displayed on the left and current incongruent trials (dashed bars) on the right. The peach coloured bars represent data from C3 stimulation and the light green from the F3 stimulation.

3.5. Classifications

A full explanation of each of the classifications was provided in Chapter Three, but a brief overview is provided, also see Figure 26. Class one is the typically reported congruency-sequencing effect such that the participants are adapting after experiencing both congruent and incongruent trials. Class two is predominantly driven by adaptations occurring when the previous trial was congruent. Class three is infrequently reported and is driven by adaptations occurring to previously incongruent trials. Class four represents congruency-sequencing effects ranging from <5 to >5ms. Class five represents a maladaptive strategy such that the congruency effect is larger after a congruent trial.

As shown in Figure 34, the most frequent classification was class two (56% and 45%), followed by class one (18% and 22%) for stimulation of C3 and F3, respectively. This mirrors the behavioural data obtained from the FRF tasks obtained in Chapter Three: Most frequently younger adults change their performance in accordance to previously congruent trials (class two), with fewer participants adapting differentially to both previously congruent and incongruent trials (class one). This also explains why the mean response data reported in Figure 30B looks the way it does, with both the current congruent and current incongruent lines increasing but off-parallel to each other, opposed to the typical congruency-sequencing effect whereby congruent and incongruent trials respond in opposite directions depending on whether the previous trial was congruent or incongruent. One person (4%) showed a class three congruency-sequencing effect that was not replicated in F3 stimulation. Class four represents 'non-adapters', that is, those who display a congruency-sequencing effect between -5 and +5ms and class five is those who display a negative congruency-sequencing effect that is considered to represent a detrimental adaptation. During stimulation of C3, only 22% of participants displayed either a class four or five congruency-sequencing effect, whereas during F3 stimulation, this represented 33% of participants. This may evidence that tDCS of the left DLPFC *impaired* conflict adaptation. However, the Pearson's Chi-squared test showed no differences between the response

distributions during C3 and F3 stimulation $\chi 2$ (12) = 9.0, p =.703. This indicated that the pattern of responding and underlying mechanisms utilised to produce the congruency-sequencing effect may be similar during stimulation of both F3 and C3.

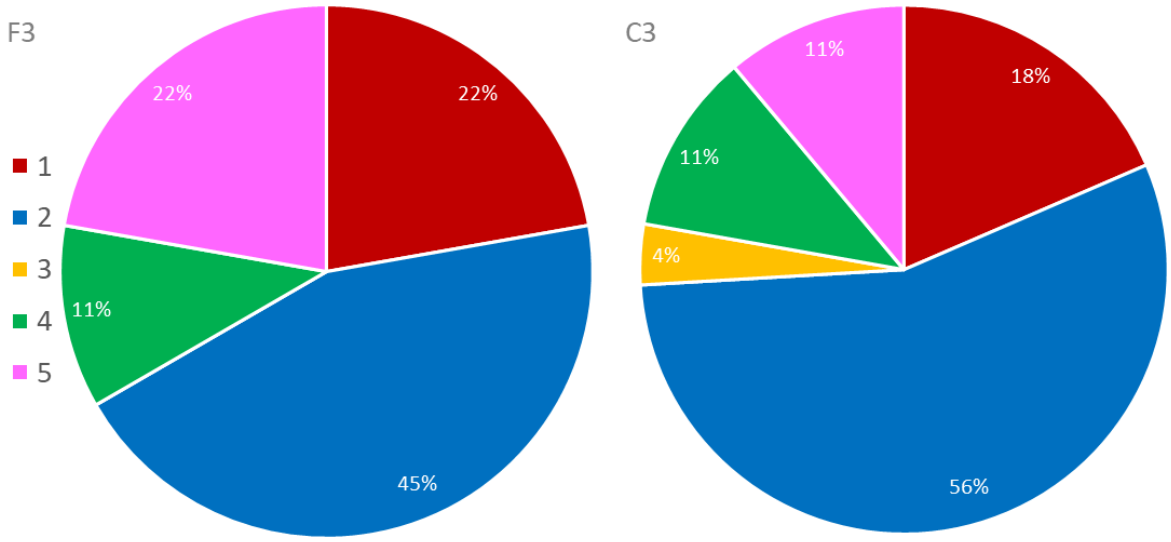


Figure 34. The percentage of participants displaying each congruency-sequencing effect classification during stimulation of F3 (left) and C3 (right).

3.6. Order Effects

A control analysis was performed to ensure there were no order / carry over effects. The Stroop effect was compared for C3 and F3 depending on where stimulation (C3 or F3) was received first. This reported no main effect of ORDER $F(1,26)=1.48$, $p=.235$, $\eta_p^2=.01$ nor a significant interaction between the STIMULATION-SITE and ORDER $F(1,26)=0.2$, $p=.632$, $\eta_p^2=.00$.

4.4.0. Discussion:

The aim of this chapter was to provide causal evidence for the involvement of the dorsolateral prefrontal cortex in producing the congruency-sequencing effect observed in conflict tasks. To do this, anodal transcranial direct current stimulation was used to increase the cortical excitability of the DLPFC. This was proposed to increase its ability to appropriately upregulate attentional resources to the task-relevant or task-irrelevant stimuli based on either the conflict experienced on the previous trial (reactive) or the pre-empted upcoming congruency based upon global cues (proactive control), thus resulting in a larger congruency-sequencing effect compared to stimulation of the motor cortex, which served as a control site. The motor cortex was selected as the control site due to its known responsiveness to tDCS but does not contribute to the Stroop nor congruency-sequencing effect. In contrast to our predictions, the magnitude of the congruency-sequencing effect did not differ between stimulation of the DLPFC and M1.

4.4.1. Stroop Effect

4.4.1.1. Mean Response Times

It was predicted that a Stroop effect would be observed during stimulation of both the DLPFC and M1 (Hypothesis 1A) and will not differ in magnitude (Hypothesis 3B). As predicted, there were significant Stroop effects of the same size during stimulation of the DLPFC (86 ±6ms) and M1 (86 ±6ms). These magnitudes are very consistent with the 88ms Stroop effect obtained during the FRF task in Chapter Three.

The lack of an effect of stimulation on the Stroop effect is consistent with other studies who have used either tDCS (Anguis et al., 2019; Baumert et al., 2020; Huo et al., 2018) or rTMS to target the DLPFC (Vanderhasselt et al., 2007, Vanderhasselt et al., 2006, Wagner et al., 2006). This does not necessarily

indicate that the stimulation had no effect on behaviour. It has been interpreted that the DLPFC positively affects both congruent and incongruent response times, therefore, the resultant difference (the Stroop effect) is unchanged (Vanderhasselt et al., 2006). This is consistent with Baumert et al. (2020) and Huo et al. (2018) who reported faster response times arising from stimulation of the DLPFC.

Considering these findings, Hypothesis 3A stated that overall response times to both congruent and incongruent trials would be faster during stimulation of the DLPFC than M1. In contrast, mean response times were not faster during stimulation of the DLPFC (566 ±15ms) than M1 (568 ±15ms). Therefore, this explanation does not fit with the results of the present study where the response times are reliably consistent (<3ms different) between stimulation of the DLPFC and M1, nor the results of Anguis et al. (2019). This may suggest a lack of, or unspecific effect of stimulation that did not differentially affect the DLPFC compared to stimulation of M1 (or sham in the case of Anguis et al., 2019), but this will be discussed in conjunction with the results in Section 4.4.4.

4.4.1.2. Delta Plots

Whilst the mean response times suggest no differential influence of stimulation to the DLPFC compared to M1, delta plots can be used to provide a more sensitive measure to explore changes in congruency effects across response times (DeJong et al., 1994, Balota et al., 2011, Gajos et al. 2019, Pratte et al., 2010). If the pattern of responding differs between two (stimulation) groups, this can infer different processing strategies implemented at the cognitive level which may go undetected by response times alone (Balota et al., 2011). The Diffusion Model for Conflict Tasks (Ulrich et al., 2015) proposes that the delta plots from Stroop tasks typically increase with slower response times. Thus, deviation from this expected linear response or lateral shifts in the size of the Stroop effect at faster/slower response times may suggest altered functioning of the DLPFC with anodal stimulation. Consistent with the Diffusion Model for Conflict Tasks and the results of Chapter Three, the Stroop

effect increased as the response times slowed. Importantly, this did not differ for C3 or F3 stimulation. As such, it can be surmised that the Stroop effect was not differentially affected by stimulation at either stimulation site.

4.4.2. Congruency-Sequencing Effects

4.4.2.1. Mean Response Times

The primary role of the DLPFC in a Stroop task is conflict adaptation. Whilst the Stroop effect is concerned only with the congruency of the current trial, the role of the DLPFC is to utilise information about the congruency of either the immediately previous trial (reactive control) or global trial history (proactive control) to modulate performance on trial *n*, hence producing the congruency-sequencing effect (Banich et al., 2000, Carter et al., 1998, Kerns et al., 2004, MacDonald et al., 2000, Milham et al. 2001). As such, unmodulated response times or Stroop effects are not cause for concern because the primary expected outcome of tDCS to the DLPFC was amplification of the congruency-sequencing effect. Anodal stimulation has been shown to increase cortical excitability of the motor cortex (Nitsche and Paulus, 2000) and has since been applied to modulate excitability in other brain regions such as the visual cortex (Antal et al., 2001) and the DLPFC (Bashir et al., 2019, Gbadeyan et al., 2016a). Although not directly measured, it was expected that anodal stimulation to the left DLPFC would increase cortical excitability (Doruk et al, 2014, Frings et al., 2018, Gbadyen et al., 2016, Loftus et al., 2015, Zmigrod et al., 2016) that would be measurable through a heightened congruency-sequencing effect (Gbadyen et al., 2016).

In support of Hypothesis 1B, a significant congruency-sequencing effect was observed at both simulation sites. This was not reflected in response errors such there were not fewer error on iI than cI trials, although this is likely due to extremely low error rates across the task (<1%). Importantly, in contrast to our main prediction (Hypothesis 2), the congruency-sequencing effect was not significantly

larger with the DLPFC stimulation (11ms) compared to M1 (15ms). This may suggest that tDCS of the left DLPFC elicited no measurable changes in conflict adaptation.

Although consistent with Baumert et al. (2020) who also applied anodal stimulation of the left DLPFC, these findings contrast with Gbadyen et al. (2016) who claimed modest increases in the congruency-sequencing effect with anodal stimulation of both the left and right DLPFC. However, a key difference is that Gbadyen et al. performed anodal and sham stimulation of the DLPFC and M1 and that the reported effect was based on a comparison between anodal versus sham stimulation of the DLPFC. Indeed, a comparison of the congruency-sequencing effects they obtained during anodal DLPFC stimulation (22ms) and anodal M1 stimulation (24ms) would have led them to the same conclusion as the current findings i.e., that stimulation of the DLPFC did not modulate conflict adaptation. It is also of interest, that Gbadyen et al. (2016) used different participants to compare stimulation sites but performed anodal and sham stimulation within-subjects. Horvorth et al. (2015) proposes that participants can tell the difference between active and sham stimulation, so if participants noticed when they were receiving the anodal stimulation, this may have influenced their performance. In summary, there is some evidence to suggest the congruency-sequencing effect can be modulated by tDCS, although the effects may be small and not measurable under all conditions (such as between-subjects designs or through active control stimulation). For this reason, a more intricate measure, such as the novel classification system introduced in Chapter Three, may provide an insight into subtle influences of stimulation.

4.4.2.2. Classifications

The previous chapter introduced an exciting classification system to discern differences in the congruency-sequencing effect that may be obscured by mean response time measures and may represent different mechanisms of DLPFC functioning. The most frequent of which were class one,

where there is adaptation to previously congruent *and* incongruent trials; and class two which suggests adaptation only when the previous trial was congruent. This highlights the congruency-sequencing effect is a crude measure of adaptation driven by the DLPFC. To more subtly investigate whether stimulation to the DLPFC differentially influenced the congruency-sequencing effect compared to M1 stimulation, the congruency-sequencing effect was categorised as class one through five, as detailed in Chapter Three.

Importantly for this study, class two was most frequent (56% and 45%) and class one next most (18% and 22%) during *both* C3 and F3 stimulation and did not differ from each other. This suggests that the way in which the DLPFC is adapting (in response to congruent and/or incongruent trials) did not change with anodal stimulation compared to M1. Despite the lack of stimulation effect, the classification distribution very closely mirrors the pattern of classifications obtained from younger adults in Chapter Three. This emphasises that most younger adults are in fact adapting, that is showing an altered Stroop effect, when the previous trial was congruent (class two). This challenges the previously accepted view that the congruency-sequencing effect reflects adaptation to incongruent trials. In fact, less than one person displayed a congruency-sequencing effect that is driven based upon adaptation only to the previous incongruent trial (class three). However, that is not to say that participants cannot adapt to previous incongruent trials because ~1/5 participants display the typical conflict adaptation pattern where there is differential adaptation to both previous congruent and incongruent trials (class one). This classification system highlights that the way of viewing the congruency-sequencing effect as a reduced Stroop effect following an incongruent trial may not be the most appropriate because it appears that conflict adaptation may derive from a larger Stroop effect from a previously congruent trial. This important differentiation may have theoretical implications for how the automaticity of stimuli is interpreted.

4.4.3. Longevity of Stimulation

Nitsche and Paulus (2000) reported a dose effect such that longer stimulation duration enhanced the longevity at which changes in corticospinal excitability were observed. As such, during an online task, it may be prudent to compare the magnitude of the Stroop and congruency-sequencing effects according to experimental block. A block-wise analysis of the congruency-sequencing effect (see Chapter Three) has not been previously been reported in the tDCS literature but was first used by Mayr et al. (2003) in a Flanker task. They reported a large decrease in the congruency-sequencing effect from 68ms in the first ~180 trials, to 4ms during the final ~700 trials. As highlighted in General Introduction, Flanker tasks are subject to feature-repetitions, therefore, they may play a role in producing a block-wise effect. The Stroop task used in the current experiment had all feature repetitions removed and therefore, these could not account for any changes in the Stroop or congruency-sequencing effect that were observed across blocks. The block-wise analysis of the FRF tasks performed in Chapter Three will therefore serve as a baseline in the absence of stimulation effects. Here, the congruency-sequencing effect remained constant throughout the experiment and did not change across blocks. This contrasts the results of this stimulation study that found although the Stroop effect remained constant (between 83 and 88ms) throughout the experiment during both C3 and F3 stimulation, the congruency-sequencing effect, was not. It was smallest during block two (trials 81 – 160; 3.5 – 5.5 minutes) and subsequently rebounded to its highest values during block three (trials 161 – 240; 7 – 9 minutes) for both C3 and F3 stimulation, although this fluctuation was only significant during F3. This suggests the stimulation may not be providing a constant influence on the behavioural outcome measure. Note, each block was very similar to one another in that the trial sequence (cC, iC, cI, iI) was the same but the exact stimulus (word-ink pairs) were substituted during each block. It is not considered that this will contribute to the fluctuations in the congruency-sequencing effect reported in this chapter because this task was the exact same as that used in Chapter Three which reported no main effect of block.

As mentioned in the Section 4.2.3.3, stimulation ceased for more than 5% of trials for a total of three participants. As such these participants were removed, and no analysis was performed on their datasets from either stimulation visit. Stimulation ceased mid-block for a further three participants but for less than 5% of trials and were included in the analysis and did not alter the non-significance of the congruency-sequencing by stimulation interaction. Therefore, it is considered high resistance causing the stimulation to cut out did not contribute to the fluctuations in the congruency-sequencing effect across experimental blocks.

To circumvent any differences between stimulation duration it may be prudent to limit analysis to the later experimental blocks only. However, this also did not suggest any differences in the congruency-sequencing effect across blocks (3-5) according to stimulation site. As such, it appears the stimulation affected the congruency-sequencing effect differentially throughout the experiment (as revealed by a main effect of BLOCK and through comparison with Chapter Three) but not differentially according to stimulation site.

4.4. An Effect of Stimulation?

The results presented here provide limited evidence that anodal tDCS to the DLPFC increased cortical excitability to improve DLPFC functioning, as seen by no change to the size of the congruency-sequencing effect as compared to M1 stimulation. The SESOI revealed that when comparing the difference in the congruency-sequencing effect across stimulation sites, a partial eta squared greater than 2.46 would indicate a significant difference, which is far greater than the 0.03 reported in the present study. The TOST suggested that this would represent a difference exceeding 49ms, which is far greater than the difference of only 4ms reported here. Therefore, it is concluded with confidence that there was no meaningful difference between the size of the congruency-sequencing effect at C3 or F3.

This leaves three possible conclusions for the null results to be considered: 1) stimulation was ineffective at increasing cortical excitability of DLPFC; 2) stimulation was effective at increasing cortical excitability but this did not lead to a change in function of DLPFC; 3) stimulation was effective at increasing cortical excitability, and this did lead to a change in function but the DLPFC does not play a role in conflict adaptation.

As detailed in the introduction, tDCS was originally applied to M1 to increase the excitability of the motor cortex (Nitsche and Paulus, 2000). Stimulation to M1 offers the affordance that tDCS can be used in conjunction with TMS evoked MEPs to objectively validate changes in cortical excitability of the region. However, no such standardised external measure is available to test whether the principles observed in the motor cortex can be generalised to other brain regions to modulate cortical excitability. The lack of a standardised external validation measure is less of a contentious issue when the findings reveal the expected pattern of results (improved performance with anodal and decreased performance with cathodal stimulation), however, it makes null results difficult to interpret.

Previous studies (Baumert et al., 2020, Doruk et al., 2014, Frings et al., 2018, Huo et al., 2018, Loftus et al., 2015) have reported that anodal stimulation to the DLPFC has reduced response times and thus provides an indirect measure of stimulation that is not dependent on the primary outcome measure (e.g. the Stroop effect can be larger/ smaller irrespective of response times). However, these faster response times were only reported through offline studies, and not in studies using online stimulation studies such as the present study, Anguis et al. (2019) and Baumert et al. (2020), all of whom did not report faster response times with stimulation to the DLPFC. Therefore, faster response times may represent a learning effect from pre- to post-stimulation rather than reflect a way to indirectly measure cortical excitability. Further, a review by Horvath et al. (2015b) of single session tDCS studies found reliable effects of M1 on modulating excitability but reported no reliable effects regions elsewhere at

moderating cognition. Therefore, it appears that anodal stimulation may not have modulated the cortical excitability of the DLPFC.

In addition to mean response time measures, additional more sensitive measures have been used. For example, delta plots to determine the functioning of the DLPFC according to response times; block-wise analyses to explore the function of the congruency-sequencing effect across the experimental blocks; and congruency-sequencing effect classification to investigate the situations in which conflict adaptation arises. These more subtle measures detected no such changes between stimulation of DLPFC to M1, nor between the behavioural-only findings of Chapter Three which participants did not undergo and stimulation. Further, stimulation of comparable current intensity and stimulation (2mA for 20 minutes) to the DLPFC has improved cognitive performance in the stop signal task and a working memory task detected through mean response times (Bashir et al., 2019). However, it has been suggested that cognition relies on a greater interplay with connecting brain regions, therefore, changes in excitability may be less predictable than the motor cortex (Tremblay et al., 2014). Therefore, it is likely that these additional analyses provide sensitive enough measures to detect meaningful changes in cortical excitability were any present.

To differentiate between explanation one that proposes stimulation did not modulate cortical excitability and explanation two that proposes a generalised effect of stimulation regardless of stimulation site and explanation three, a sham condition (which was not performed) was needed. This could have provided a within-subjects comparison to compare the size of the congruency-sequencing effect with and without stimulation. However, Horvarth et al. (2014) advises against sham conditions because participants can tell the difference between the cutaneous stimulation received. In the absence of a sham condition, the results of Chapter Three provide a between-subjects comparison of the congruency-sequencing effect observed during stimulation to the DLPFC (11ms) and no stimulation

(11ms). This suggests the most likely of the three explanations is explanation one: that anodal tDCS did not modulate the cortical excitability of the DLPFC, and hence was unable to increase its attentional up regulatory function of conflict adaptation and thus did not increase the magnitude of the congruency-sequencing effect nor result in any sensitive measures of conflict adaptation. The results of the current study, cannot, however, rule out explanation three as a possible reason for the null results. But given the wealth of neuroimaging (Botvincik et al., 1999; MacDonald et al., 2000;) and EEG data (Clayton and Larson, 2011, Yeung et al., 2004), this seems unlikely.

4.4.5. Limitations and Future Direction

A limitation of this study is that it did not include any such external validation of changes in corticospinal excitability during stimulation of M1 through MEPs as first described by Nitsche and Paulus (2001), nor through measuring changes in power output via EEG after stimulation of the DLPFC as per Keeser et al. (2011). This would have provided more definitive explanatory power between the three possible explanations for the null results.

Future studies should seek to use a feature-repetition free task such as that described in the last two chapters to eradicate the confound of feature-repetitions whilst isolating the top-down component of conflict adaptation because Chapter Three demonstrated the incomparability of using an FRF task compared to post-hoc removal of feature-repetitions. This could be used in conjunction with high density tDCS (as per Gbadyen et al., 2016) to concentrate the current density to the DLPFC and a ring cathode around the DLPFC would minimise any shunting of the current to other brain regions.

4.5.0. Conclusion:

Congruency-sequencing effects were observed during stimulation of both the primary motor cortex and the dorsolateral prefrontal cortex and were of a similar magnitude to those reported in the Chapter Three where participants performed the same Stroop task without stimulation. In contrast to the main hypothesis, the congruency-sequencing effect was not larger during stimulation of the DLPFC compared to M1. This finding is in line with others (Baumert et al., 2020, Frings et al., 2018, Gbadyen et al. 2019) who have used tDCS to target the DLPFC to modulate the congruency-sequencing effect. The possible explanations for this have been discussed and whilst a lack of external validation measure in the current experiment means it is not possible to rule out that the DLPFC was modulated by the stimulation but does not play a role conflict adaptation, this explanation was considered unlikely due to the wealth of previous research that implicates the DLPFC (Botvinick et all., 1999, Botvinick et al., 2001, Carter and van Veen, 2007, Kerns et al., 2000, MacDonald et al., 2000). Instead, it is concluded that the stimulation had no effect on DLPFC functioning as revealed through no differences between crude (congruency-sequencing effect) nor discrete (delta plots, classifications) measures of conflict adaptation.

Chapter Five: Dissociating Proactive from Reactive Top-Down Control Processes

5.1.0. Introduction:

The General Introduction introduced three possible accounts underpinning the congruency-sequencing effect (see Figure 5). The feature-integration account posits that stimulus-response pairings form an episodic memory and that repetition of one or both stimulus components (task-relevant or task-irrelevant) can alter response times to mimic the same behavioural pattern as the congruency-sequencing effect through bottom-up influences. Chapter Three investigated the role of feature-repetitions and reported that whilst they can indeed heighten the magnitude of the congruency-sequencing effect, once removed from the task design, the congruency-sequencing effect still prevails. Thus, one of the two top-down accounts, either proactive or reactive control, must be responsible for the conflict adaptation measured through the congruency-sequencing effect. The experiments described in this chapter used a behavioural paradigm containing training and test phases to try and discern whether proactive or reactive control strategies are most dominant.

5.1.1. Overview of Proactive and Reactive Accounts

Both proactive and reactive control processes are top-down mechanisms that utilise the dorsolateral prefrontal cortex to optimise performance in conflict tasks (Braver et al., 2007, Carter and van Veen, 2007, De Pisapia and Braver, 2006, Paxton et al., 2008). In the context of a Stroop task, the Conflict-Monitoring model (Botvinick et al., 2001) suggests reactive control occurs as a transient activation of the DLPFC that occurs *after* the stimulus presentation. For this reason, reactive control is often considered a '*late-correction'* mechanism (Jacoby et al., 1999a). Involvement of the DLPFC is triggered by competing responses co-activated by the task-relevant and task-irrelevant stimulus (such as on an

incongruent trial) or through an erroneous response selection, both of which are detected by the ACC. As stated, these adjustments occur *after* stimulus presentation in response to the previously experienced conflict. After a congruent trial, attentional control is upregulated towards the task-irrelevant stimulus, whereas after an incongruent trial, attentional control is upregulated towards the task-relevant stimulus. As such, performance is benefitted when the congruency repeats from trial *n*-1 to trial *n* (cC and iI trials) compared to when the congruency alternates (iC and cI trials), thus producing a congruency-sequencing effect.

Conversely, the repetition expectancy explanation (Gratton et al., 1992; Egner, 2007) outlines a proactive control strategy that includes an anticipatory, '*early-selection*' mechanism (Jacoby et al., 1999a) that adjusts the attentional weighting of the task-relevant/ task-irrelevant stimulus *before* stimulus presentation. Context-specific information refers to any source of information which biases performance (Braver et al., 2007) and could relate to: the task instruction (i.e., the task-relevant stimulus); the most informative source of information (i.e., task-relevant stimulus in a mostly incongruent task, or the task-irrelevant stimulus in a mostly congruent task); or the congruency of the previous trial. Such information is used to predict the congruency of the upcoming trial and appropriately weight attention towards the context-specific information via the DLPFC. Note, the term 'context-specific' and not task-relevant nor task-irrelevant stimuli were used to recognise that it is not always the task-relevant (imperative) stimulus that serves as the most informative. Take for example, a Stroop task with a high proportion of congruent trials, there would be advanced context-specific cues suggesting the upcoming trial will be congruent, thus, there is greater weighting of the task-irrelevant stimulus. Equally, in a Stroop task with a high proportion of incongruent trials, the task-relevant (imperative) stimulus provides context-specific information that will receive the greatest attentional weighting from the DLPFC.

Predominantly, proactive control strategies are long term and take into consideration the contextual cues on a global (all trial history) level (Braver et al., 2007) to allow sufficient time for phasic dopaminergic learning to occur. However, there are others (Duthoo and Notebaert, 2012, Egner, 2007) who refer to proactive control in a short-term way and expect the congruency will always repeat from trial *n* to trial *n*+1. This was the interpretation first put forward by Gratton et al. (1992) in the originally reported the congruency-sequencing effect. Behaviourally, this would not be distinguishable from a reactive control strategy, because both would yield a congruency-sequencing effect of the same magnitude, but a short-term proactive strategy would derive from the participant's expectation and a reactive strategy would derive from the previously experienced conflict. For the remainder of this introduction, proactive control will be considered from a global perspective such that contextual cues accumulated over a long-term history will inform the prediction of the upcoming congruency, however, the implications for a short-term proactive control strategy will be returned to in the discussion.

In the reactive control mechanism, recruitment of the DLPFC is triggered via the ACC, while in the proactive mechanism, recruitment of the DLPFC relies on gated release of midbrain dopamine (Braver and Cohen, 1999, D'Ardenne et al., 2012). Proactive control suggests that when the gate is open, control towards context-specific information is maintained, whereas when it is closed, interference to such information is blocked. Therefore, responses are faster when participants correctly anticipate the congruency of the upcoming trial and can use such information to implement attentional adjustments via the DLPFC to minimise interference and maximise facilitation, and thus produce a congruency-sequencing effect. As such, both top-down accounts of cognitive control would predict a congruency-sequencing effect from a standard Stroop task with minimal scope for differentiating the two accounts. The remainder of this introduction will report first an alternative laboratory tasks used to investigate proactive and reactive control before returning to specific manipulations within Stroop tasks.

5.1.2. Dual Mechanisms of Control

Proactive and reactive control processes are not mutually exclusive accounts of cognitive control. That is, evidence for one does not refute the other. Braver et al. (2012) put forward the dual mechanisms of control model that proposes both proactive and reactive control processes are used to minimise conflict. This is consistent with their example of how conflict is minimised in an everyday setting. Figure 35 displays an example of how someone avoids forgetting they need to go shopping after work. The bottom row demonstrates how the goal is actively maintained until the end of the day and that in the face of a conflicting event (the meeting after work), the individual still maintains their goal of going shopping. Conversely, the top row suggests that it is only upon presentation of the shopping list in the car that the individual remembers their intended goal, which was subject to distraction in the form of a meeting after work. Both forms of cognitive control are used throughout the day to minimise or prevent conflict in everyday life. The cognitive load required to maintain such information throughout the entire day is far greater than the retrieval of such information at a time-relevant point (the end of the day) and may be why one strategy may be favoured over the other.

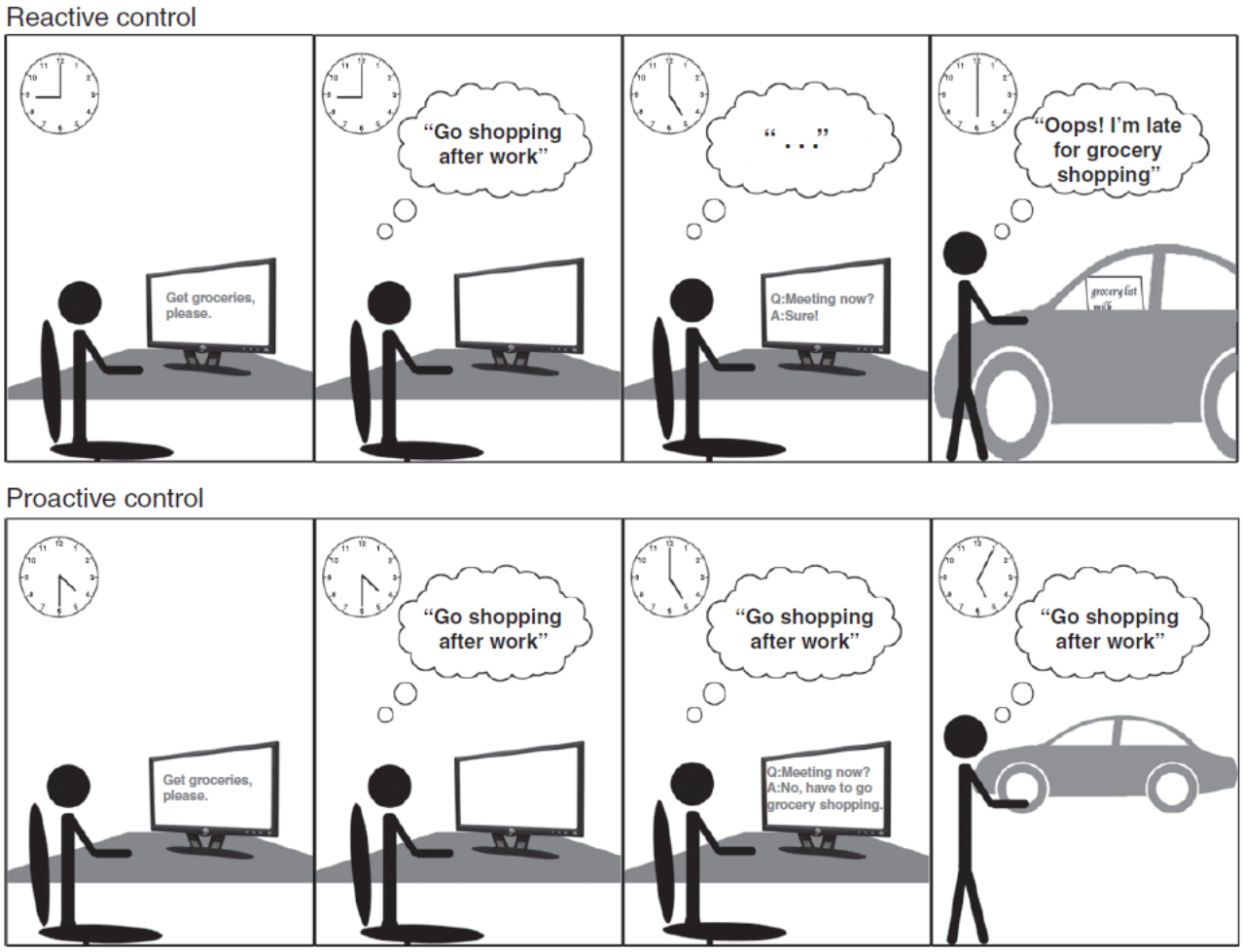


Figure 35. An example from Braver et al. (2012) to demonstrate proactive and reactive control processes in a daily setting where an individual must remember to go shopping after work. The top row shows that the individual is only prompted that they need to go grocery shopping when they see the list in their car. This is an example of reactive control – correction mechanisms (i.e., going shopping) are only implemented after conflict has arose (attending a meeting instead of going shopping). Whereas the bottom row shows the individual has actively maintained their desire to go shopping which prevented distractions, such as after work meetings, to enable them to reach their goal. This is an example of proactive control – maintenance of the goal has minimised distraction (attending a meeting) before the event (the end of the day when they need to go shopping).

The most compelling evidence supporting the dual mechanisms of control model comes not from the congruency-sequencing effect, but through performance in a continuous performance task (Rosvold et al., 1956), the AX-CPT developed by the Braver research group. Each trial consists of a cue, followed by a delay period, and finally a probe (see Figure 36). Participants are required to press button two when presented with an AX cue-probe pair and button one when presented with any other sequence (AY, BX, BY cue-probe pairs where B is any letter other than A, and Y is any letter other than X), see Figure 36). Importantly, the cue, 'A', is paired with the probe, 'X', on a high proportion of trials. Therefore, participants using a proactive control strategy can maintain the context-specific information during the delay period and can prepare a target-response when presented with the cue A and a non-target response to the cue B. Participants using a proactive strategy perform better on BX trials, but worse on AY trials (where the target-response had been incorrectly prepared). Whereas participants using a reactive control strategy do not prepare a response in advance of the probe and retrieve the contextual cue only when the probe appears, leading to worse performance on BX but better performance on AY trials. In general, most participants utilised a proactive strategy (Braver et al., 2005, Paxton et al., 2008). Paxton et al. (2008) has shown participants exhibiting a behavioural proactive strategy elicit increased BOLD activity in the prefrontal cortex at the time of the cue and reduced BOLD activity when the probe is presented. Whereas participants using a reactive strategy showed increased BOLD activity of the DLPFC during the probe and reduced BOLD activity during the cue. Thus, despite utilising the same brain region, proactive and reactive control strategies can be temporally differentiated.

Additionally, task manipulations can modify the strategy used *within* individuals. In a study by Braver et al. (2009), participants completed the AX-CPT twice, once to serve as a baseline and a second which introduced a monetary penalty for poor performance. Compared to baseline, there was reduced BOLD activity in the DLPFC during presentation of the cue and delay period (suggesting less proactive

response preparation) and increased BOLD activity in the DLPFC during the probe presentation (suggesting reactive retrieval of the cue). This, coupled with behavioural changes in the task performance, indicates the monetary penalty forced a shift towards a reactive strategy within participants. To induce an increased proactive control strategy within participants, Gonthier et al. (2016) informed participants of the increased probability of AX cue-probe pairing. Compared to baseline, participants committed more errors on AY trials (those at detriment from proactive preparation of an AX pairing) and were 36ms faster to respond to BX trials (those where proactive control reduces conflict when presented with an X probe that does not require a target response). This indicates increased utilisation of a proactive control strategy within participants.

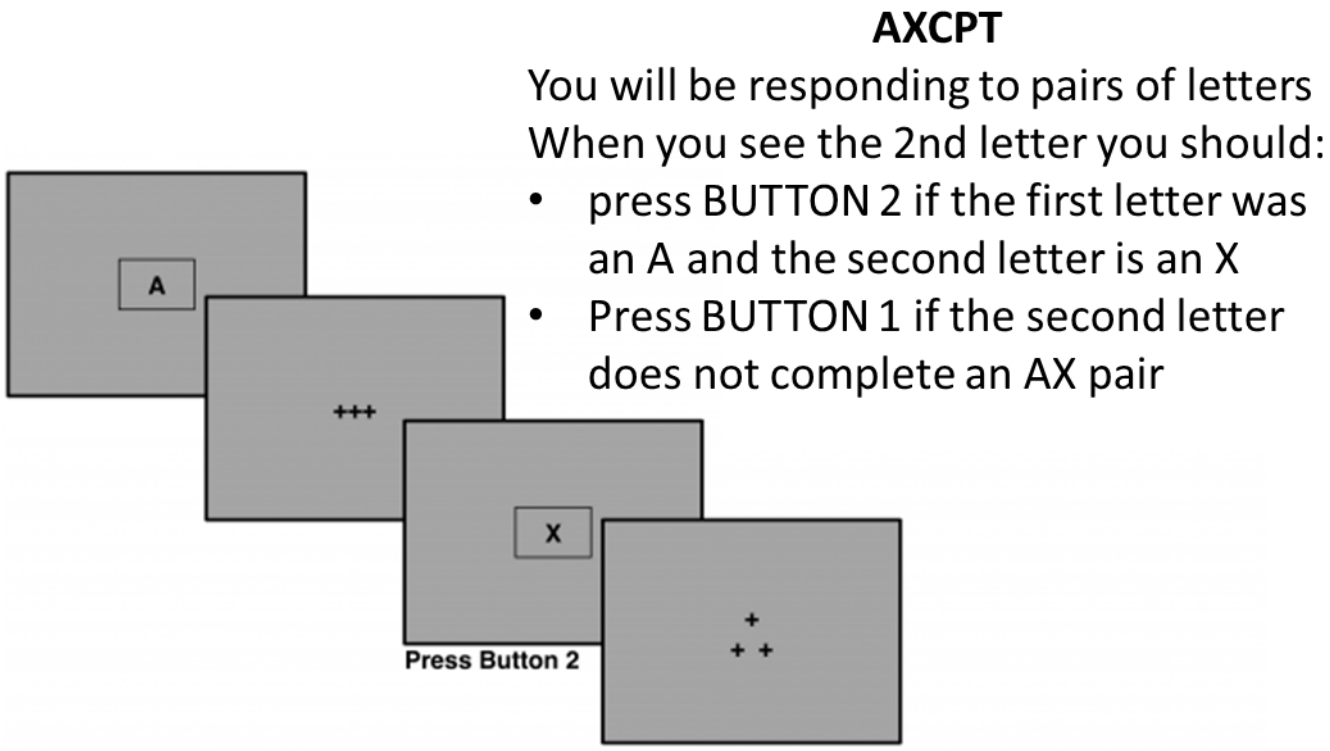
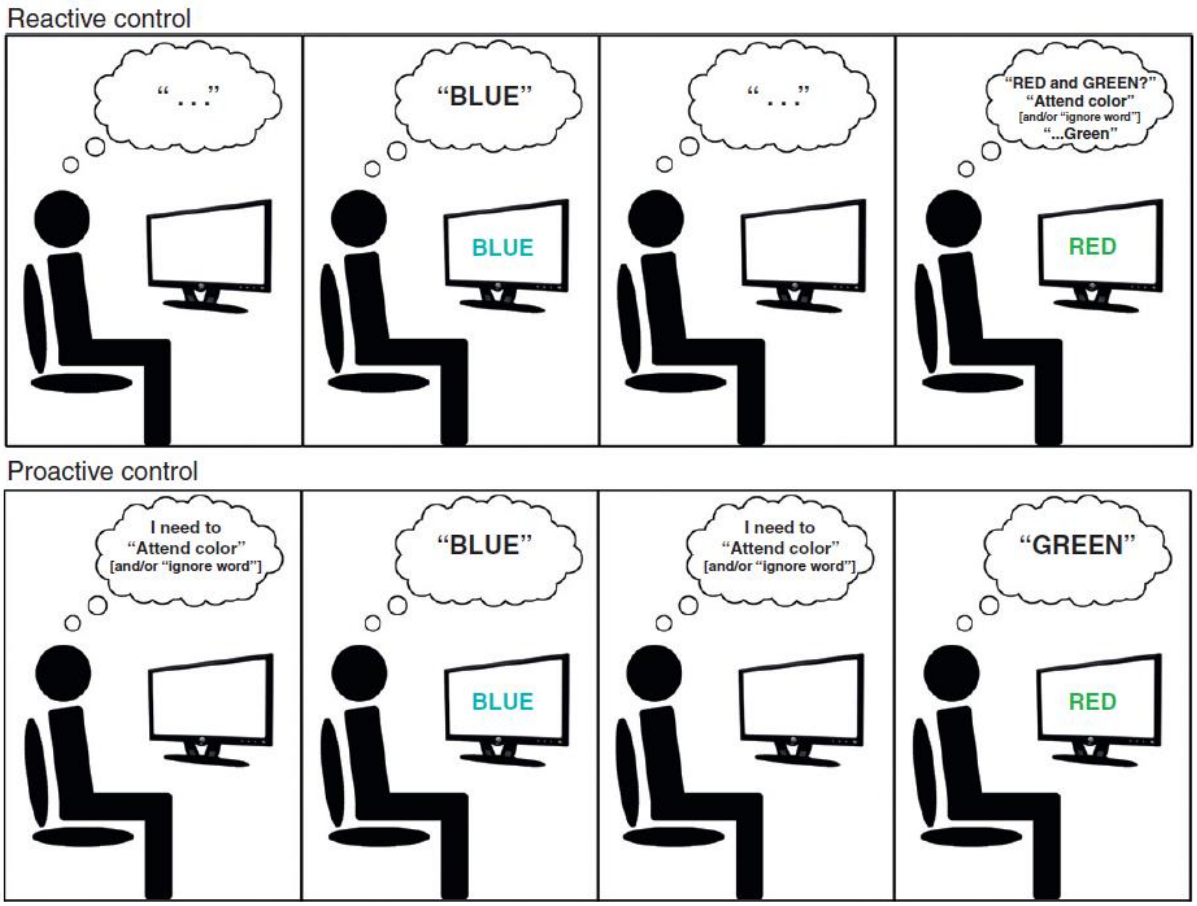


Figure 36. An example from Braver et al. to indicate the protocol of the AX-CPT task. Participants are presented with a cue (A or B) followed by a delay period, and then a probe (X or Y). Participants are instructed to make a target response if the probe and cue form an AX pair and a non-target response for any other probe-cue pair.

Taken together, the results from Braver et al. (2009) and Gonthier et al. (2016) provides evidence for both proactive and reactive processes and that task manipulations can elicit changes in processing strategy that are measurable through altered neural dynamics and behavioural performance. It also suggests that younger adults default towards a proactive strategy (Braver et al., 2005) and only stray towards a reactive strategy when there is a penalty for incorrectly pre-empting the response (Braver et al., 2009). However, this evidence comes from an AX-CPT task where there is a contextual cue on *each trial* to provide a strong source to base expectations upon and to time-lock neural activity to dissociate proactive and reactive control strategies. Whilst there appears to be a clear preference for participants to use a proactive control strategy in AX-CPT, it could be that this is driven by the inclusion of a contextual cue. In a task that does not have such a basis on which form firm expectations but still requires top-down control, participants may preference a different strategy. Therefore, it is of interest to investigate whether proactive, reactive control, or perhaps even a combination of the two prevail in a task such as the Stroop (see Figure 37) where there are less explicit contextual cues available. Such findings would provide a more ecological comparison to Braver et al.'s shopping list example displayed in Figure 35 whereby participants may or may not be provided with contextual prompts (invitations to a meeting after work) to preferentially utilise either a proactive or reactive control strategy.



2726 *Figure 37. An example from Braver et al. (2012) to demonstrate how both proactive and reactive control strategies are used*
2727 *during a Stroop task. The top row shows a reactive strategy whereby the participant retrieves the task instruction upon*
2728 *stimulus presentation and does not prepare the response in advance. Conversely, the bottom row displays a proactive strategy*
2729 *in which the task instruction is maintained between stimuli.*

5.1.3. Stroop Task Manipulations

The next section of this introduction will discuss commonly used Stroop task manipulations and their potential caveats before introducing a novel strategy by Duthoo and Notebaert (2012). As discussed in the General Methods, the overall task-congruency is a very important consideration. A high proportion of congruent trials (where conflict is infrequently experienced) will result in a larger Stroop effect than tasks on which the proportion congruency is lower (where conflict is frequent) (Lindsay and Jacoby, 1999). This finding is known as a list-wide proportion congruence (LWPC) effect and is thought to reflect a proactive control strategy where greater weighting is given to the context-specific (most frequently informative) stimulus *in advance* of stimulus presentation. Here, participants would be able to use the advanced knowledge of the overall likelihood of a congruent or incongruent trial to upregulate control towards the task-relevant (in anticipation of an incongruent trial) or task-irrelevant stimulus (in anticipation of a congruent trial) and thus provides a paradigm for exploring proactive control within a Stroop task.

A similar manipulation, the item-specific proportion congruency (ISPC) effect is used to measure the extent to which a reactive control strategy is used (Jacoby et al., 2003). Here, specific stimulus-response pairs are frequently presented in either their congruent or incongruent colour with smaller Stroop effects reported for mostly incongruent pairs. The reason this is considered to reflect a reactive control strategy is because there are no advanced cues to indicate whether the upcoming trial will be congruent or incongruent, therefore, the mechanisms underpinning the reduced Stroop effect on incongruent stimulus-response pairs can only be implemented after stimulus presentation and not in advance.

The Stroop effects arising from the LWPC and the ISPC manipulations are well documented, however, few studies have compared the magnitude of the congruency-sequencing effect under such

conditions. Those who have (Aschenbrenner and Balota, 2019, Crump et al., 2018) failed to report a significant interaction of the LWPC effect and the congruency-sequencing effect (Blais et al., 2014, Crump et al., 2018) nor the ISPC and the congruency-sequencing effect (Aschenbrenner et al., 2019, Crump et al., 2018). This implies neither the LWPC (thought to reflect proactive control) nor the ISPC (thought to reflect reactive control) effects represent the same process as the congruency-sequencing effect. However, as emphasised in Chapter Three, there is good evidence that the congruency-sequencing effect reflects a top-down control strategy and is not confounded with bottom-up influences. It is, therefore, prudent to consider whether the list-wide and item-specific proportion congruency effects do indeed reflect proactive and reactive control.

Schmidt and Besner (2008) propose that proportion congruency effects (LWPC and ISPC) are derived from a form of contingency learning where participants respond faster to more frequently presented stimuli. When they reanalysed the data of Jacoby et al. (2003), who first reported the ISPC effect, they found that trials were faster (and the Stroop effect 24ms smaller) on high-contingency trials (that is, congruent stimuli from pair-one and incongruent stimuli from pair-two) than low-contingency trials (incongruent stimuli from pair-one and congruent stimuli from pair-two). As such, they proposed that Jacoby et al.'s ISPC effect could be explained entirely in terms of contingency effects as opposed to top-down reactive control. Extrapolation of this finding suggests that the LWPC could also reflect a form of contingency learning whereby participants learn that colours are most frequently presented in their congruent colour and can respond faster on congruent trials without necessarily engaging top-down control strategies.

5.1.4. An Alternative Approach

Duthoo and Notebaert (2012) attempted to disentangle proactive and reactive control processes using an innovative Stroop paradigm. Importantly, it does not centre around item-specific or list-wide proportion congruency manipulations vulnerable to contingency-biases and does not require cues (that feature in the AX-CPT) to elicit proactive control. The experiment consisted of two tasks (the repetition and alternation task) which both contained training and test phases. In the training phase, the likelihood of the congruency-level repeating or alternating from one trial to the next was manipulated. In the repetition task, there was a 70% probability that a congruent trial would proceed a congruent trial and that an incongruent trial would proceed an incongruent trial. Equally, in the alternation task, there was a 70% probability that a congruent trial would proceed an incongruent and that an incongruent trial would proceed a congruent trial. This congruency-level manipulation was designed to alter participant's expectations and allow a proactive strategy to develop whereby participants would be able to anticipate the congruency of the upcoming trial. Importantly, the objective task-congruency was maintained at 50% during the training phase, therefore, Duthoo and Notebaert's (2012) design fosters a proactive control strategy with minimal confounds from contingency-biases and thereby addresses the main limitation of the proportion congruency manipulations. Both the repetition and alternation tasks are interspersed with test phases. The task-congruency of the test phases were also set to 50% but, unlike the training phases, did not include a congruency-level manipulation, therefore, there was an equal probability of the congruency repeating from one trial to the next.

Based upon a short-term interpretation of proactive control, Duthoo and Notebaert predicted that in the training phases, participants would anticipate a congruency-level repetition. Therefore, they predicted a larger congruency-sequencing effect in the repetition training phase compared to the alternation training phase would occur because of the increased frequency of repetition expectations

(cC and iI) trials being met. The increased frequency of cC and iI trials in the repetition training phase would magnify the congruency-sequencing effect, and the increased frequency of iC and cI trials in the alternation training phase would diminish it. If participants utilised a proactive strategy throughout the task, it was expected that the differential influences of training on the congruency-sequencing effect (larger and diminished congruency-sequencing effects in the repetition and alternation training phases, respectively) would also carry through to the test phases. However, if participants preferentially respond transiently to the immediate trial history (i.e., reactive control), it was expected that the congruency-sequencing effect would display a large divergence from the training phase (i.e., a reduced congruency-sequencing effect in the repetition test phase and a heightened congruency-sequencing effect in the alternation test phase). Additionally, the congruency-sequencing effect would be of a comparable magnitude between the repetition and alternation test phases.

As expected, Duthoo and Notebaert reported a larger congruency-sequencing effect in the repetition training than the alternation training phase. This is predicted by both a proactive and reactive account and is not informative for disentangling the two accounts. The 'critical determinant' of whether participants are using a proactive or reactive strategy is the transfer of the magnitude of the congruency-sequencing effect from the training to the test phases. Duthoo and Notebaert reported no transfer of the training effect and the magnitude of the congruency-sequencing effect did not differ between the repetition or alternation test phases. The similarities between the two test phases highlights that the immediate trial history was pertinent to determining the magnitude of the congruency-sequencing effect, above and beyond that of the global trial history, therefore, this suggests participants preferentially engaged a reactive control strategy.

Their novel approach has not since been replicated, therefore, this current study aimed to use the same testing paradigm but with a different analytical stance. Duthoo and Notebaert included all the

training trials in their analysis, which may not be problematic if viewing proactive control as a short-term mechanism. However, when considered as a long-term accumulation of the global trial history, such is the generally accepted view, it is questionable whether participants would have sufficient experiences of the training phase manipulations in the first block (80 trials) to appropriately predict the congruency of the upcoming trial. For this reason, the present study proposes to discard such (120) trials to provide participants with exposure to the training phase manipulations. Further, the test phases (40 trials) are embedded in between the training phases. Duthoo and Notebaert suggest a transfer of the magnitude of the congruency-sequencing effect between the training and test phase may be crucial for differentiating proactive from reactive control processes. Figure 38A highlights the directional findings from both a proactive strategy: the training phase will differentially influence participants in the repetition/alternation task which results in a heightened/diminished congruency-sequencing effect. A directional transfer of the magnitude of the congruency-sequencing effect from the training phase to the unmanipulated test phase will suggest minimal impact in the change of probability of a congruency-level repetition/ alternation, therefore, the global trial probability prevails as the key determinant of the magnitude of the congruency-sequencing effect. This is represented by a small convergence of the magnitude of the congruency-sequencing effect from the training to test phases but additionally that the test phases still differ. Figure 38B also displays the expected pattern of results from a reactive perspective. This explanation once again anticipates that the repetition and alternation training phases display a differential training effect, but this time that there is a large divergence in the magnitude of the congruency-sequencing effect from the training to test phase. Additionally, note that the magnitudes of the congruency-sequencing effect between the repetition and alternation test phase are the same, to represent the removal of the training manipulation.

A further novel aspect of this thesis is the use of the classification system to look for differences in the distribution pattern between the training and test phases to infer whether there was a transfer. For

example, if a greater proportion of participants produce a congruency-sequencing effect (class one to three) in either the training or test phase, this would further support evidence of a transfer effect and that participants were using a reactive control strategy. Finally, to aid the comparison of the congruency-sequencing effects obtained within test phases, identical test phase sequences will be used in the repetition and alternation tasks at each block. As such, a block-wise comparison can directly compare the magnitude of the congruency-sequencing effect at each block, which is a more discrete measure than relying solely on the mean value calculated from all test phase trials, as per Duthoo and Notebaert (2012).

5.1.5. Aims and Hypotheses

Aim One: To decipher between whether participants use a proactive or reactive control strategy. To address this aim, there are three key results to consider, with the evidence described from both a proactive and reactive perspective.

Result One: Is there a differential effect of training on the magnitude of the congruency-sequencing effect in the repetition and alternation task?

Proactive Hypothesis: The congruency-sequencing effect will be larger in the repetition training compared to alternation training phase. Remington (1969) reported that participants expect responses to repeat, therefore, after a congruent trial, it is predicted that participants will expect another congruent trial, and visa-versa for incongruent trials. The distribution of the congruency-sequencing effect classifications will differ in the repetition and alternation training phases to represent the differential effect of the congruency-level manipulations.

Reactive Hypothesis: The cumulated sequences of cC and iI trials will also affect response times such that the reactive account would predict the congruency-sequencing effect would be larger in the

repetition training compared to alternation training phase. Importantly, the reactive account would not support the finding of a congruency-sequencing effect in the alternation task because the high-frequency of iC and cI trials are those where the cognitive adjustments implemented by the DLPFC do not benefit performance (upregulation of the task-irrelevant stimulus after experiencing a congruent trial and upregulation of the task-relevant stimulus after experiencing an incongruent trial).

Result Two: Does the magnitude of the congruency-sequencing effect transfer from the training to the test phase?

Proactive Hypothesis: The magnitude of the congruency-sequencing effect in the repetition test phase will be marginally smaller than in the repetition training phase to reflect the reduced reliability of the congruency-level repetition (change from 70% in the training phase to 50% in the test phase, see Table 14).

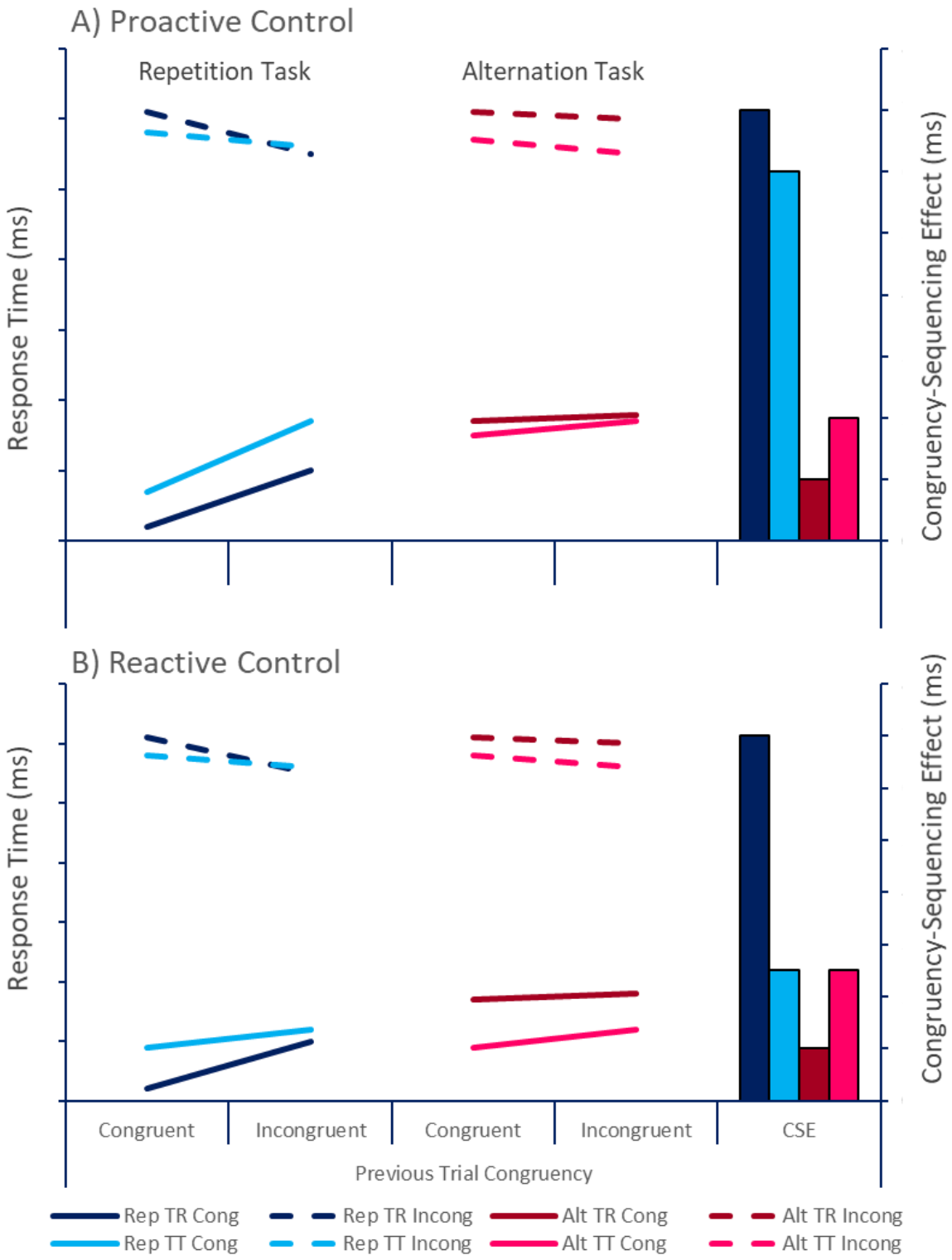
The magnitude of the congruency-sequencing effect in the alternation test phase will be larger than in the alternation training phase to reflect the increase in congruency-level repetitions (cC and iI trials) from the training to test phase. Importantly, in both tasks, this transfer will represent only a marginal difference in the magnitude of the congruency-sequencing effect, see Figure 38A.

Reactive Hypothesis: There is no transfer, that is, there is a large divergence in the magnitude of the congruency-sequencing effect reported in the training to the test phase. Statistically this will emerge as a PREVIOUS-CONGRUENCY by CURRENT-CONGRUENCY by PHASE interaction for both the repetition and alternation task, see Figure 38B. This would reflect the immediate trial history as a more pertinent factor than the global trial history.

Result Three: Are the magnitudes of the congruency-sequencing effects in the test phases of the repetition and alternation task the same as each other?

Proactive Hypothesis: The test phases are not the same because the test phase only represents a marginal change in the global probability, therefore, has a minimal effect on the magnitude of the congruency-sequencing effect. As such, the congruency-sequencing effect will be larger in the repetition test phase than the alternation test phase.

Reactive Hypothesis: The removal of the congruency-level manipulation from the training to test phases results in congruency-sequencing effects of comparable magnitude in the repetition and alternation test phases. This iterates the importance of the previous trial congruency over and above the global trial history. Further, because the current study will ensure the test phases are identical at each block, it is expected the congruency-sequencing effect to be comparable at each block stage as well as the mean magnitude.



2895 *Figure 38. Depiction of the predicted pattern of results from the perspective of a proactive (panel A) and reactive strategy*
2896 *(panel B). The solid lines represent when the current trial is congruent and the dashed line, incongruent. The shades of blue*
2897 *refer to the repetition task and the red the alternation task where in both instances the darker shades refer to the training*
2898 *phase and the lighter the test phase. The resultant congruency-sequencing effect is plotted as a column chart on the far right.*
2899 *See in-text for why each strategy would predict such a pattern of results.*

5.2.0. Methods:

5.2.1. Participants

One hundred and three adults aged 18 - 24 (M = 21 years) were recruited from the School of Sport, Exercise and Rehabilitation Sciences at the University of Birmingham. Participants were randomly assigned to either the repetition (n=51) or alternation (n = 52) task. All participants provided written informed consent and all studies were performed in accordance with the Declaration of Helsinki.

5.2.2. Task Design and Procedure

Participants completed either the repetition or alternation task, both of which followed the same task design. Each task consisted of trials constituting a training phase (600 trials), interspersed with a test phase (200 trials). This was split over five blocks of 80 training trials, 40 test trials, followed by a further 40 training trials, as shown in Figure 39.

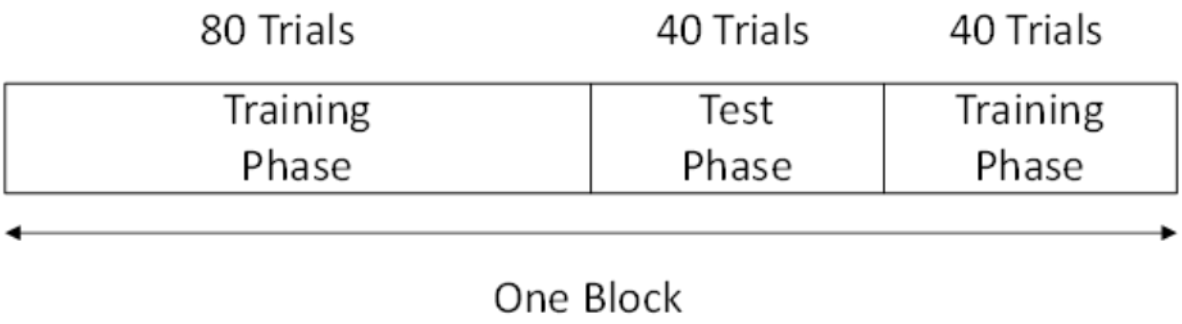


Figure 39. The task design of each block for both the repetition and alternation task. Both begin with 80 training trials, 40 training trials, followed finally by a further 40 training trials.

5.2.2.2. Training Phases

Training phases were used to differentially alter the magnitude of the congruency-sequencing effect. To do this, the likelihood of the congruency of the previous trial either repeating or alternating on the subsequent trial was manipulated. Importantly, this was not achieved by altering the percentage of congruent or incongruent trials, which remained at 50% throughout the task, but by the repetition or alternation of the previous trial's congruency.

The congruency-sequencing effect is calculated as the Stroop effect when the previous trial was congruent subtracted from the Stroop effect when the previous trial was incongruent ((cI-cC)-(iI-iC)). Therefore, the increased frequency of congruency-level repetitions (cC and iI trials) in the repetition task was thought to result in faster response times and thus increase the magnitude of the congruency-sequencing effect. Conversely, the frequency of the congruency-level alternations (iC and cI trials) in the alternation task was thought to diminish the congruency-sequencing effect.

Repetition Task: In the repetition training phase, there was a 70% chance that after a congruent trial, another congruent trial would be presented immediately after. Likewise, after an incongruent trial, there was a 70% chance of another incongruent trial appearing on the subsequent trial. This resulted in strings (never exceeding five) of either congruent (cC) or incongruent (iI) trials. Table 7 details how 70% of trials were congruency-repetitions (cC and iI) compared to 30% of congruency-alternation (iC and cI) trials whilst a 50% task congruency was maintained. The right-hand side of Table 7 shows the careful consideration of ensuring each trial sequence contained an equal number of each task-relevant stimuli colours, to eradicate any possible influences of colour on response times that was highlighted during pilot studies conducted prior to beginning the studies described within this thesis. This is elaborated in Table 9 to demonstrate that the contingency bias of presenting specific words in specific colours was also considered. For example, the word blue is not presented in a colour (other than itself

– a necessity of 50% task congruency) more frequently than any other colour. This prevents priming of word-colour combinations that may lead to faster responses without top-down influences.

Alternation Task: In the alternation training phase, there was a 70% chance that an *incongruent* trial would follow each congruent trial and vice versa. Table 8 demonstrates that this resulted in strings (never exceeding five) of iC and cI trials, such that these congruency-alternation trials contribute to 70% of the overall training trials compared to 30% of congruency-repetition trials (cC and iI). As with the repetition training phase, the right-hand side of Table 8 demonstrates that care was taken to ensure each trial sequence consisted of the same number of trials where the task-relevant stimuli was each colour. Table 9 demonstrates that additionally, the contingency bias was addressed so that no colour was presented more frequently in an incongruent colour more frequently than any other incongruent colour.

Note, in both the training phases the task congruency was 50% and the task contingency was as per Table 9, thus, the only difference between the repetition and alternation tasks is the proportion of congruency-repetition trials (cC and iI) compared to congruency-alternation (iC and cI) trials.

			Number of trials on which the participants say…				
	Total (N)	**Total (%)**	**Red**	**Blue**	**Yellow**	**Green**	**Pink**
Congruent	300	50	60	60	60	60	60
Incongruent	300	50	60	60	60	60	60
cC	210	35	42	42	42	42	42
iC	90	15	18	18	18	18	18
cI	90	15	18	18	18	18	18
iI	210	35	42	42	42	42	42
Repetition	420	70	84	84	84	84	84
Alternation	210	30	32	32	32	32	32
TOTAL	**600**		**120**	**120**	**120**	**120**	**120**

*Table 7. Task design and trial distribution for the **training phase of the repetition task** (600 trials). The overall task-congruency is 50%, yet the likelihood of congruency-repetitions (cC and iI) trials is 70%.*

			Number of trials on which the participants say…				
	Total (N)	**Total (%)**	**Red**	**Blue**	**Yellow**	**Green**	**Pink**
Congruent	300	50	60	60	60	60	60
Incongruent	300	50	60	60	60	60	60
cC	90	15	18	18	18	18	18
iC	210	35	42	42	42	42	42
cI	210	35	42	42	42	42	42
iI	90	15	18	18	18	18	18
Repetition	210	30	32	32	32	32	32
Alternation	420	70	84	84	84	84	84
TOTAL	**600**		**120**	**120**	**120**	**120**	**120**

*Table 8. Task design and trial distribution for the **training phase of the alternation task** (600 trials). The overall task-congruency is 50%, yet the likelihood of congruency-alternations (iC and cI) trials is 70%.*

Stimulus	N	Stimulus	N	Stimulus	N	Stimulus	N	Stimulus	N
RED	**60**	**BLUE**	15	**YELLOW**	15	**GREEN**	15	**PINK**	15
RED	15	**BLUE**	**60**	**YELLOW**	15	**GREEN**	15	**PINK**	15
RED	15	**BLUE**	15	**YELLOW**	**60**	**GREEN**	15	**PINK**	15
RED	15	**BLUE**	15	**YELLOW**	15	**GREEN**	**60**	**PINK**	15
RED	15	**BLUE**	15	**YELLOW**	15	**GREEN**	15	**PINK**	**60**

Table 9. Addressing the contingency bias in the training phases of both the repetition and alternation training tasks. The task-congruency is 50%, therefore, every colour is presented in its own colour on of the trials, but on the incongruent trials, no word is presented more frequently in any given incongruent colour Thus, the contingency bias is minimised.

2.2.3. Test Phases

Nested half-way through each block (after 80 training trials), participants seamlessly transitioned into a test phase. As with the training phase, the task-congruency was maintained at 50%, however, the likelihood of the congruency of the previous trial repeating from trial *n* to trial *n*+1 changed to 50%. Thus, after a congruent trial, there was equal probability of the subsequent trial being either congruent or incongruent. Note, this is the same design as the FRF task used in Chapter Three and Four.

A key result is whether the magnitude of the congruency-sequencing effect elicited in the manipulated training transferred to the unmanipulated test phase. The test phase represents an objective change (decrease from the repetition training phase and increase from the alternation training phase) in the frequency of congruency-level repetitions. If participants utilise a proactive strategy, this shift represents a very minor change in the global probability of congruency-level repetition/ alternations across the entire experiment (see Table 14). Therefore, it is expected to elicit a very minor change (decrease in the repetition task and increase in the alternation task) in the magnitude of the congruency-sequencing effect from the training to the test phase. However, if participants utilise a reactive strategy, this objective difference in congruency-level repetitions/ alternations will manifest as a large difference in the magnitude of the congruency-sequencing effect to reflect the importance of previous trial congruency over and above the global trial history and may also be coupled with a shift in distribution of the congruency-sequencing effect classifications. Further, because the test sequences are identical in the repetition and alternation tasks, the magnitudes of the congruency-sequencing effects would also match if using a reactive but not necessarily a proactive account.

			Number of trials on which the participants say…				
	Total (N)	**Total (%)**	**Red**	**Blue**	**Yellow**	**Green**	**Pink**
Congruent	100	50	20	20	20	20	20
Incongruent	100	50	20	20	20	20	20
cC	50	15	10	10	10	10	10
iC	50	15	10	10	10	10	10
cI	50	15	10	10	10	10	10
iI	50	15	10	10	10	10	10
Repetition	100	50	20	20	20	20	20
Alternation	100	50	20	20	20	20	20
TOTAL	**200**		**40**	**40**	**40**	**40**	**40**

*Table 10. The task design and trial distribution of the **test phases** (200 trials) of both the repetition and alternation tasks. Note, the congruency is 50%, with a 50% congruency repetition from one trial to the next.*

Stimulus	**N**	**Stimulus**	**N**	**Stimulus**	**N**	**Stimulus**	**N**	**Stimulus**	**N**
RED	**20**	**BLUE**	5	**YELLOW**	5	**GREEN**	5	**PINK**	5
RED	5	**BLUE**	**20**	**YELLOW**	5	**GREEN**	5	**PINK**	5
RED	5	**BLUE**	5	**YELLOW**	**20**	**GREEN**	5	**PINK**	5
RED	5	**BLUE**	5	**YELLOW**	5	**GREEN**	**20**	**PINK**	5
RED	5	**BLUE**	5	**YELLOW**	5	**GREEN**	5	**PINK**	**20**

Table 11. Addressing the contingency bias in the test phases of both the repetition and alternation training tasks. The task-congruency is 50%, therefore, every colour is presented in its own colour on of the trials, but on the incongruent trials, no word is presented more frequently in any given incongruent colour Thus, the contingency bias is minimised.

2.2.4. Task Overview

As displayed in Figure 39, the test phases were nested in each block, after 80 training trials and preceded by 40 more training trials. After each block, the participants had a self-paced break. Therefore, the task design of the entire experiment is displayed in Table 12 for the repetition task and Table 13 for the alternation task.

			Number of trials on which the participants say…				
	Total (N)	**Total (%)**	**Red**	**Blue**	**Yellow**	**Green**	**Pink**
Congruent	400	50	80	80	80	80	80
Incongruent	400	50	80	80	80	80	80
cC	260	32.5	52	52	52	52	52
iC	140	17.5	28	28	28	28	28
cI	140	17.5	28	28	28	28	28
iI	260	32.5	52	52	52	52	52
Repetition	520	65	104	104	104	104	104
Alternation	280	35	56	56	56	56	56
TOTAL	**800**		**160**	**160**	**160**	**160**	**160**

Table 12. An overview of the entire repetition task (including the training and test phase). Note, the overall repetition of the experiment has decreased to 65% due to the inclusion of the test phase with only 50% repetition.

			Number of trials on which the participants say…				
	Total (N)	Total (%)	Red	Blue	Yellow	Green	Pink
Congruent	400	50	80	80	80	80	80
Incongruent	400	50	80	80	80	80	80
cC	140	17.5	28	28	28	28	28
iC	260	32.5	52	52	52	52	52
cI	260	32.5	52	52	52	52	52
iI	140	17.5	28	28	28	28	28
Repetition	280	35	104	104	104	104	104
Alternation	520	65	56	56	56	56	56
TOTAL	800		160	160	160	160	160

Table 13. An overview of the entire alternation task (including the training and test phase). Note, the overall alternation of the experiment has decreased to 65% due to the inclusion of the test phase with only 50% alternation.

Block/ Phase	Total Trials (N)	Phase Probability Congruency-level repetition/ alternation	Global Probability Congruency-level repetition/ alternation
B1 TR (80)	80	70%	70%
B1 TT (40)	120	50%	63%
B1 TR (40)	160	70%	65%
B2 TR (80)	240	70%	67%
B2 TT (40)	280	50%	64%
B2 TR (40)	320	70%	65%
B3 TR (80)	400	70%	66%
B3 TT (40)	440	50%	65%
B3 TR (40)	480	70%	65%
B4 TR (80)	560	70%	66%
B4 TT (40)	600	70%	65%
B4 TR (40)	640	70%	65%
B5 TR (80)	720	70%	66%
B5 TT (40)	760	50%	65%
B5 TR (40)	800	70%	65%

Table 14. Demonstration of the change in global trial probability of a congruency-level repetition/ alternation throughout the experiment. Each training phase represents a 70% probability and each test phase a 50% probability of a congruency-level repetition (cC/ iI trial) or alternation (iC or cI) trial and how this is affected throughout the experiment with regards to the global probability (far right column). The leftmost column details the experimental block number (B1-5), the order of the training (TR) and test (TT) phase, and the number of trials (N) in each phase.

5.2.3. Data Analysis

Data analysis was performed as per the general methods, but a brief overview is provided below. The main outcome measure is response times, from which the Stroop and congruency-sequencing effects are calculated.

5.2.3.1. Trial Exclusions

Block One: This experiment utilised a training phase to induce a proactive control strategy. It could be considered that during the initial block, limited exposure to this manipulation may not have been sufficient to induce the desired expectations. Therefore, the entire first block (training and test phases) were discarded and not included in any analyses.

'40 Training Phase' Trials: Each block was comprised of 80 training trials, followed by 40 test trials, and a further 40 training trials. The 40 training trials after the test phase revealed the magnitude of the congruency-sequencing effect was not consistent with the magnitude observed during the training phases of the 80 trials. These differences are reported in Section 5.3.3. Thus, the final 40 trials of blocks two through five are also excluded and therefore, all analyses on the training phase are derived from the initial 80 training trials on blocks two through five and the test phase analyses also only used data from blocks two through five.

Total Trials: As fully detailed in the general methods, response errors, miss trials and post-error exclusions were excluded. Any participants who did not have at least 80% of trials that were analysed (384) remaining after all exclusions were also removed. This resulted in the removal of three participants from the repetition task and two participants from the alternation task.

5.2.3.2. Participant Exclusions

Stroop Effect: Participants who reported a Stroop effect of less than 20ms in both the test and training phase or a negative Stroop effect in either phase were removed. This excluded one participant from the repetition task and two participants from the alternation task. In total, analyses were performed on 47 and 48 participants in the repetition and alternation tasks, respectively.

5.2.3.3. Response Times

A four-way RM ANOVA with PREVIOUS-CONGRUENCY (congruent/ incongruent), CURRENT-CONGUENCY (congruent/ incongruent), PHASE (training or test) as within-subjects factors and TASK (repetition/ alternation) as a between subjects factor was performed.

A main effect of CURRENT-CONGRUENCY within this RM ANOVA would reveal the presence of a Stroop effect. A previous-congruency by current-congruency interaction shows a congruency-sequencing effect. If established, the congruency-sequencing effect will be calculated ((cI-cC)-(cI-iI)) separately in each task and used as the dependent variable to compare across tasks and phases to minimise the number of comparisons and to allow for appropriate post-hoc comparisons.

5.3.3.4. Power Analyses

Post-Hoc Power: As per the General Methods, a post-hoc power analysis was performed to determine whether the study was adequately powered to observe a real difference in the magnitude of the congruency-sequencing effect between the repetition and alternation task, should one exist.

5.2.3.5. Classifications

The congruency-sequencing effects were classified during the training and test phases of the repetition and alternation tasks to provide a more discreet measure of potential processing strategies utilised. To do this, if the gradient of the when the current trial is congruent (cI-cC) and when the current trial is incongruent (iI-cI) are more than 5ms each, it is assigned class one. If the gradient of the current congruent trial is more than 5ms but the current incongruent gradient is less than 5ms, participants are considered a class two. If the gradient of the current incongruent trial is more than 5ms but the current congruent trial is less than 5ms then participants are class three. Overall congruency-sequencing effects between -5 and +5ms are all class four, regardless of the gradients of the current and incongruent trials. Likewise, all congruency-sequencing effects less than -5ms are class fives, regardless of how it is derived from the current congruent or incongruent trials.

The percentage of participants placed in each classification are reported separately for the test and training phase of the repetition and alternation task. The percentage of each classifications were compared using a Pearson's Chi-Squared test. Similarities in the percentages of each classification from the training to test phase would suggest a transfer and that the global probability of congruency-level repetition/ alternations are driving the magnitude of the congruency-sequencing effect. Whereas differences between the training and test phase would suggest the previous trial history is driving the congruency-sequencing effect and the shift from the manipulated to training phased to unmanipulated test phase is coupled with a change in distribution of the classifications. This analysis is used as a more discrete measure of the mean response times but is not a stand-alone analysis.

5.2.3.6. Time Course Analyses

Block-Wise: To compare the magnitude of the Stroop and congruency-sequencing effects across the experimental blocks, the main response time analysis was performed, with the addition of BLOCK (2-5) as a within-subjects variable. Again, this is a supplementary to the mean response times.

5.2.3.7. Response Errors

Errors on which participants stuttered or made an incorrect response were reported and underwent the same response time analysis to look for Stroop and congruency-sequencing effects.

5.3.0. Results:

5.3.1. Response Times

Figure 40 displays the response times and congruency-sequencing effects for the repetition (panel A) and alternation task (panel B). See that the results are plotted from both a reactive (left) and proactive (middle) perspective with the resultant congruency-sequencing effect on the right. It shows there was no effect of TASK on the response times from the repetition or alternation task $F(1,93)=0.20$, $p<.05$, $\eta_p^2=.00$.

Stroop Effect: A main effect of CURRENT-TRIAL CONGRUENCY reveals a significant Stroop effect $F(1,93)=412$, $p<.001$, $\eta_p^2=.82$. Congruent trials were 90 ±4ms faster than incongruent trials (d= 2.1, $p<.001$). CURRENT-TRIAL CONGRUENCY was unchanged across PHASE $F(1,93)=0.44$, $p=.509$, $\eta_p^2=.00$; TASK $F(1,93)=0.53$, $p=.469$, $\eta_p^2=.00$; and did not interact with TASK and PHASE $F(1,93)=0.12$, $p=.714$, $\eta_p^2=.00$, demonstrating the Stroop effect was stable across all conditions.

Congruency-Sequencing Effect: An interaction of PREVIOUS-TRIAL and CURRENT-TRIAL CONGRUENCY $F(1,93)=30.7$, $p<.001$, $\eta_p^2=.25$ highlights an overall congruency-sequencing effect. Congruent trials are 25 ±2ms faster when the previous trial is also congruent (cC), compared to incongruent (iC) (d= 1.7, $p<.001$). Incongruent trials are 16 ±2ms faster when the previous trial is congruent (cI) compared to incongruent (iI) (d=1.0, $p<.001$). PREVIOUS and CURRENT-TRIAL CONGRUENCY further interacted with TASK $F(1,93)=4.8$, $p<.05$, $\eta_p^2=.05$; and PHASE $F(1,93)=5.2$, $p<.05$, $\eta_p^2=.05$; but there was not a significant four-way interaction of PREVIOUS-TRIAL CONGRUENCY, CURRENT-TRIAL CONGRUENCY, PHASE and TASK $F(1,93)=3.9$, $p=.885$, $\eta_p^2=.00$.

5.3.1.1. Repetition Task

Figure 40A shows the response times from the training (dark blue) and test (light blue) phases. There was a main effect of PHASE $F(1,46)=21.4$, $p=<.001$, $\eta_p^2=.32$ such that the response times in the training phase were 15 ±3ms faster than in the test phase ($d=0.68$, $p<.001$).

Congruency-Sequencing Effect: An interaction of PREVIOUS and CURRENT-TRIAL CONGRUENCY highlights a significant overall congruency-sequencing effect $F(1,46)=32.4$, $p<.001$, $\eta_p^2=.41$. Congruent trials were 29 ±2ms faster when the previous trial was congruent (cC) compared to when it was incongruent (iC) ($d=1.9$, $p<.001$). Incongruent trials were 16 ±2ms faster when the previous trial was congruent (cI) compared to incongruent (iI) ($d=7.1$, $p<.001$). Thus, demonstrating there was an overall significant congruency-sequencing effect of 9ms in the repetition task.

To determine whether the congruency-sequencing effect reported in each phase of the repetition task reached significance, separate ANOVAs as per Section 5.2.3.3. were performed.

Training Phase: The PREVIOUS-TRIAL by CURRENT-TRIAL CONGRUENCY interaction indicates the 18 ±3ms congruency-sequencing effect was significant $F(1,46)=31.5$, $p<.001$, $\eta_p^2=.41$.

Test Phase: Likewise, a significant PREVIOUS-TRIAL by CURRENT-TRIAL CONGRUENCY interaction indicates the 9 ±4ms congruency-sequencing effect was significant $F(1,46)=5.8$, $p<.05$, $\eta_p^2=.11$.

The three-way PREVIOUS by CURRENT-TRIAL CONGRUENCY by PHASE interaction will determine whether there was a difference (or transfer) between the congruency-sequencing effect reported in the training and test phases. In the repetition task, this approached, but did not reach significance

$F(1,46)=3.4$, $p=.073$, $\eta_p^2=.07$. This demonstrates there was a transfer in the magnitude of the congruency-sequencing effect from the repetition training to the repetition test phase. As per 'result two' in Section 5.1.5, this would support a proactive account such that the global trial history is a more pertinent contributor to magnitude of the congruency-sequencing effect than the immediate trial history. The classifications (see Section 5.3.2.) will offer a more discrete measures to supplement this result.

5.3.1.2. Alternation Task

Figure 40B shows the response times from the training (dark red) and test (light red) phases. Unlike the repetition task, there was no effect of PHASE $F(1,47)=2.3$, $p=.139$, $\eta_p^2=.05$ on the responses times.

Congruency-Sequencing Effect: The PREVIOUS by CURRENT-TRIAL CONGRUENCY interaction highlights a significant overall congruency-sequencing effect $F(1,47)=5.2$, $p<.05$, $\eta_p^2=.10$. Congruent trials were 22 ±2ms faster when the previous trial was congruent (cC) compared to when it was incongruent (iC) ($d=1.4$, $p<.001$). Incongruent trials were 16 ±2ms faster when the previous trial was congruent (cI) compared to incongruent (iI) ($d=7.0$, $p<.001$). Thus, demonstrating there was a significant congruency-sequencing effect of 4ms in the alternation task.

To determine whether the congruency-sequencing effect reported in each phase of the alternation task reached significance, separate ANOVAs as per Section 5.2.3.3. were performed.

Training Phase: A significant PREVIOUS-TRIAL by CURRENT-TRIAL CONGRUENCY interaction indicates the 10 ±3ms congruency-sequencing effect was significant $F(1,47)=8.5$, $p<.05$, $\eta_p^2=.15$.

Test Phase: In contrast, there was not a significant PREVIOUS-TRIAL by CURRENT-TRIAL CONGRUENCY interaction which demonstrates the 2 ±4ms congruency-sequencing effect in the alternation test phase was not significant $F(1,47)=0.1$, $p=.71$, $\eta_p^2=.00$.

The three-way PREVIOUS by CURRENT-TRIAL CONGRUENCY by PHASE interaction will determine whether there was a difference between the congruency-sequencing effect reported in the training and test phases. Considering the difference in magnitude between the training and test phase, it is surprising this three-way interaction did not reach significance $F(1,47)=2.0$, $p=.162$, $\eta_p^2=.04$. Again, this may support that there was a transfer of the magnitude of the congruency-sequencing effect from the training to the test phase, which would be consistent with a proactive account. But again, it is important to consider more discrete measurements, specifically, the distribution of classifications across the training and test phases (see Section 5.3.2.).

5.3.1.3. Between Task Comparisons

This section pertains to the comparisons between the magnitude of the congruency-sequencing effect in the training and test phases between the repetition and alternation task. For this reason, the congruency-sequencing effect (established as statistically significant in all but the alternation test phase) was used as the dependent variable. There was a main effect of TASK $F(1,93)=4.8$, $p<.05$, $\eta_p^2=.05$ such that the congruency-sequencing effect was 8 ±3ms larger in the repetition than the alternation task.

Training Phases: Duthoo and Notebaert predicted that if participants use a proactive strategy, the training phases would differentially alter the congruency-sequencing effect such that it would be larger

in the repetition training phase than in the alternation training phase. There was not a significant PHASE by TASK interaction $F(1,93)=0.0$, $p=.89$, $\eta_p^2=.00$ and the post-hoc analyses show there was no significant difference between the 18ms and 10ms congruency-sequencing effect reported in the repetition and alternation training phases, respectively ($p=0.72$, $d=0.16$). Reported as 'result one' (as fully outlined in Section 5.1.5) this may not support the use of a proactive control strategy in both tasks. However, an alternative interpretation of this will be covered in the discussion.

Test Phases: There was no PHASE by TASK interaction and the post-hoc analysis revealed the congruency-sequencing effect did not differ between the repetition (9ms) nor alternation test phases (2ms) ($p=1.00$, $d=0.14$). The reactive account would suggest that regardless of the training phases, due to the importance of only trial *n*-1, the size of the congruency-sequencing effect in the test phases will be the same. Before concluding a reactive account, the classification distribution and block-wise analyses provides insights into the differences of the test phase to rebut that a reactive account was used in the repetition and alternation tasks.

Summary: The key finding is that there was no effect of phase in neither the repetition nor alternation task, which indicates there was a transfer in the magnitude of the congruency-sequencing effect from the training to test phases. This strongly implicates that a proactive account was used in both tasks. In contrast, the comparison of the test phases found no effect of task, which would lend support that the local trial congruency prevailed over the global influence of the training, thus a reactive account may have been used. However, in the next sections, the block-wise analysis will emphasise the differences in the test phases and cast doubt over use of a reactive strategy.

5.3.1.4. Power Analyses

Post-hoc Power: A within-subjects repeated measures ANOVA post-hoc power analysis revealed the observed power of the three-way interaction between PREVIOUS-CONGRUENCY, CURRENT-CONGRUENCY and PHASE (η_p^2=.05) was 0.9. This suggests the experiment was adequately powered to detect the differences in the magnitude of the congruency-sequencing effect between the training and test phases.

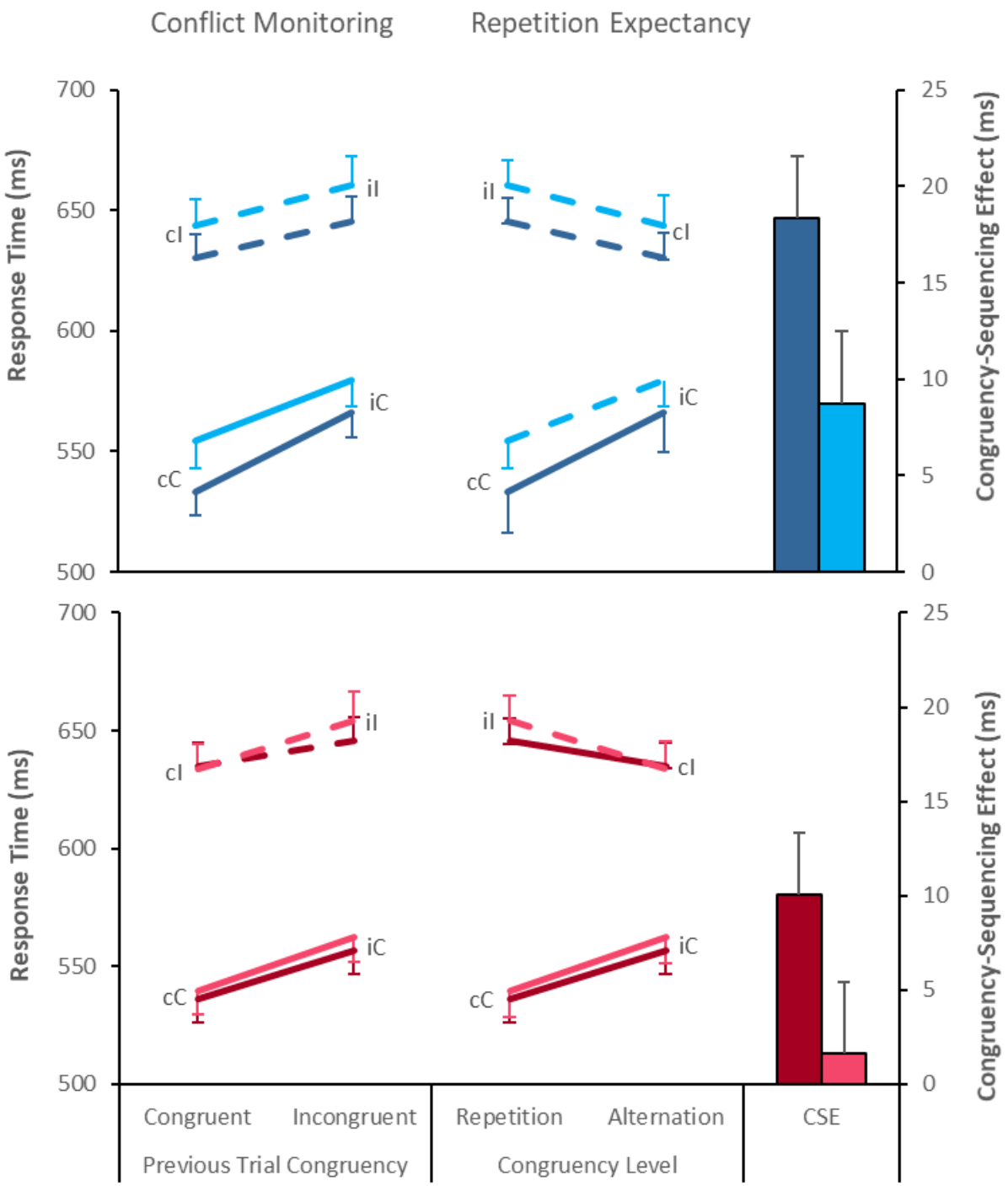


Figure 40. Response times from the repetition (panel A) and alternation (panel B) tasks. The darker shades refer to the training phase and the lighter shades the test phase. Solid lines represent when trial n is congruent and dashed lines, incongruent. The response times are displayed from the conflict monitoring perspective (left) and the repetition expectancy account (right). Data points are labelled according to the trial sequence (cC, iC, cI, iI). Note, when the current trial is incongruent, the data points are switched so that iI is presented on the right from the conflict monitoring perspective (previous trial incongruent) but on the left from the repetition expectancy perspective (the congruency level has repeated). The resultant congruency-sequencing effect (CSE) is plotted as a column chart on the far right.

5.3.2. Classifications

Chapter Three identified a classification system to try to differentiate processes underlying the congruency-sequencing effect. For example, class one represented when a participant adapted to both congruent and incongruent trials, thus, cC trials were faster than iC *and* iI trials were faster than cI. This produces the typical conflict adaptation graph referred to throughout the thesis. However, our studies typically report participants who adapt only post-congruent trials (class two). In this instance, a congruency-sequencing effect arises because of a reduced Stroop effect following an incongruent trial, but not due to iI trials being faster than cI trials. Class three follows the same principle as class two, but instead is when participants adapt only to post-incongruent trials (iI are faster than cI trials) but not post-congruent trials (cC are not faster than iC trials). This is an infrequently reported classification but is included for completion. Classes one through three are all when participants display a positive congruency-sequencing effect of at least 5ms. Class four is participants who display a congruency-sequencing effect of between -5 and +5ms. Class five represents participants who show a congruency-sequencing effect less than -5ms. In this instance, it can be considered participants are adapting, but in a way that perhaps does not benefit performance.

Each participant is classified according to the above system and a percentage of total participants displaying each classification is displayed in Figure 41. Earlier chapters suggest this may be a more subtle means to measure changes in processing strategy that may not be reflected through mean response times alone. Therefore, differences in the percentage of classifications in the training and test phases across each task may indicate similarities/ differences in conflict control strategies.

Repetition Task: In the training phase (Figure 41A), most participants (55%) displayed a class two congruency-sequencing effect. The next most common is class one (19%). Combining these classifications together, almost three-quarters (74%) of participants display a positive congruency-

sequencing effect, compared to the test phase (53%). It is also greater than the percentage of participants reported in Chapter Three (49%) where there was no expectancy manipulation implemented. Like the repetition training phase, class two was most common (42%), followed by class one (11%) during the repetition test phase. Despite these differences, the Pearson's Chi-Squared test revealed there was no effect of PHASE in the repetition task $\chi 2$ (3) = 4.9, p =.182 (Cramer's V = .228). This complements the non-significant effect of PHASE reported on the mean response times and suggests a transfer from the training to the test phase in the repetition task, thus supporting a proactive account.

Alternation Task: There are subtle differences in the pattern of classifications between the training and test phase, for example, the percentage of class one reduces from 17% in the alternation training to 6% in the alternation test phase. Also, there was an increase from 33% to 40% of class twos in the training to test phase. However, the Pearson's Chi-Squared test revealed there was no effect of PHASE $\chi 2$ (4) = 3.1, p =.541 (Cramer's V = .180). This may suggest that there are only subtle differences in the alternation training and test phases, which would be consistent with a proactive control strategy and mirror the transfer reported in the mean response times in Section 5.3.1.2.

Training Phases: The Pearson's Chi-Squared revealed there was no difference in the distribution of the classifications between the training phases of the repetition or alternation task: TASK $\chi 2$ (4) = 6.9, p =.141.

Test Phases: The next step is to compare the classifications from the test phases of the repetition and alternation task. The assumption being that the if the classifications arising from two test phases are the same, then a reactive control strategy must dominate to eradicate the influence of the training phases. The Pearson's Chi-Squared test revealed a non-significant effect TASK $\chi 2$ (4) = 2.7, p =.607 (Cramer's V = .169) which suggests there were no differences between the classification distribution

between the test phases of the repetition and alternation task and may lend support towards a reactive account. However, as mentioned, the key comparison is that of the block-wise analysis.

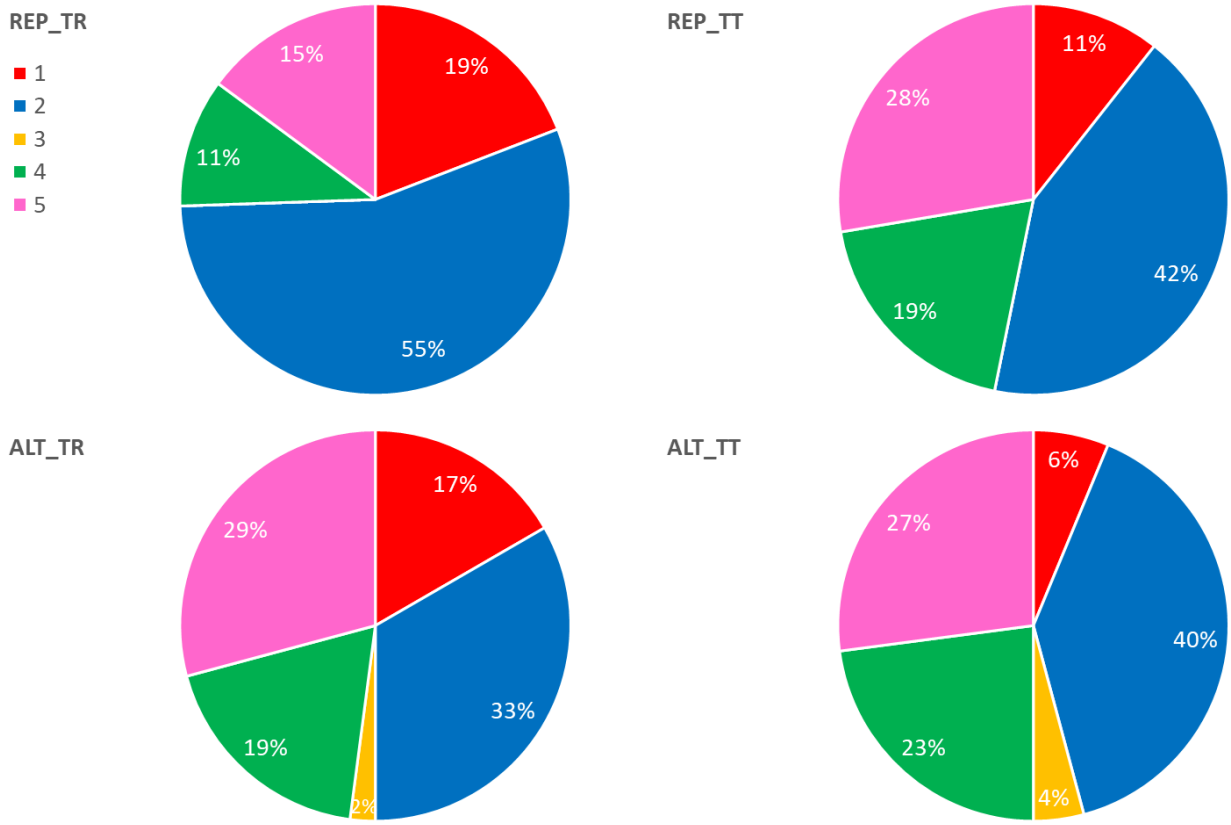


Figure 41. Classifications (1-5) of the congruency-sequencing effect from the repetition (top) and alternation (bottom) tasks for both the training (left) and test (right) phases.

5.3.3. Block-Wise

Figure 42 shows the congruency-sequencing effect from all data (panel A) and that which was analysed throughout this results section (panel B) plotted for each experimental block. As per the methods, the first block was excluded because it was not deemed the training would have developed sufficiently to alter participants' expectations. Also displayed in panel A are the 40 training trials that occurred last in each block.

Congruency-Sequencing Effect: There was an overall main effect of BLOCK $F(3,279)=2.6$, $p<.05$, $\eta_p^2=.03$ such that the congruency-sequencing effect started at 13ms in block two, reduced to 2.2ms in block three, increased to 8ms in block four, before increasing to its largest value of 16ms in the final block. There was no interaction of BLOCK and TASK $F(3,279)=0.8$, $p=.506$, $\eta_p^2=.01$, which suggests the congruency-sequencing effect did not differ across block throughout the two tasks. Whilst not statistically different from one another, the congruency-sequencing effect differs by as much as 8 ±11ms in block two (= 0.07, $p=1.00$) and 15 ±11ms in block four ($d=0.14$, $p=1.00$). This casts doubt over the use of a reactive control strategy. There was also a significant three-way interaction of BLOCK, TASK and PHASE $F(3,279)=3.0$, $p<.05$, $\eta_p^2=.03$, however, there were no significant post-hoc comparisons.

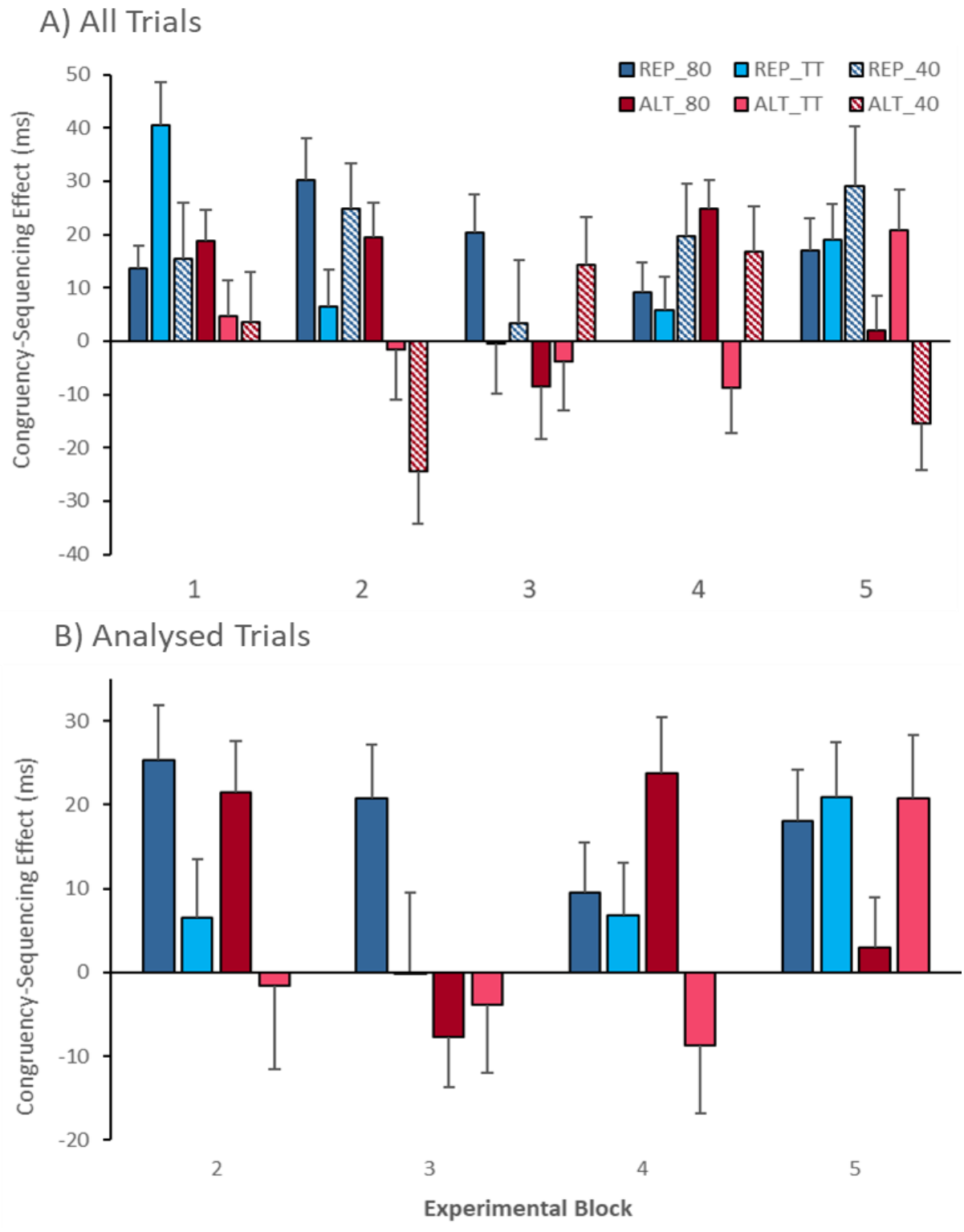


Figure 42. The congruency-sequencing effect from all data (blocks 1-5; panel A) and the data included throughout the results section (blocks 2-5; panel B). Results are displayed for the repetition (blue) and alternation (red) task whereby the darker shades refer to the training and the lighter shades the test phase. It is important to note that panel A includes additional hashed bars to display the excluded 40 training trials.

5.3.5. Response Errors

Figure 43 displays the response errors across the repetition and alternation tasks. There was no main effect of TASK $F(1, 93)=0.01$, $p=911$, $\eta_p^2=.02$, such that participants did not elicit more errors in either the repetition or alternation task. There was a main effect of CURRENT-TRIAL CONGRUENCY $F(1, 93)=110.2$, $p<.001$, $\eta_p^2=.54$. Participants made 2 ± 0 more errors on incongruent than congruent trials ($d=1.1$, $p<.001$). There was a main effect of PHASE $F(1, 93)=81.4$, $p<.001$, $\eta_p^2=.54$. Participants made 0.8 ±0.1 more errors during the training than the test phase ($d=.93$, $p<.001$). There was a PREVIOUS by CURRENT-TRIAL CONGRUENCY interaction $F(1, 93)=16.1$, $p<.001$, $\eta_p^2=.15$ reflecting a congruency-sequencing effect. Further, the four-way interaction with PREVIOUS-TRIAL, CURRENT-TRIAL CONGRUENCY, PHASE and TASK $F(1, 93)=48.3$, $p<.001$, $\eta_p^2=.34$.

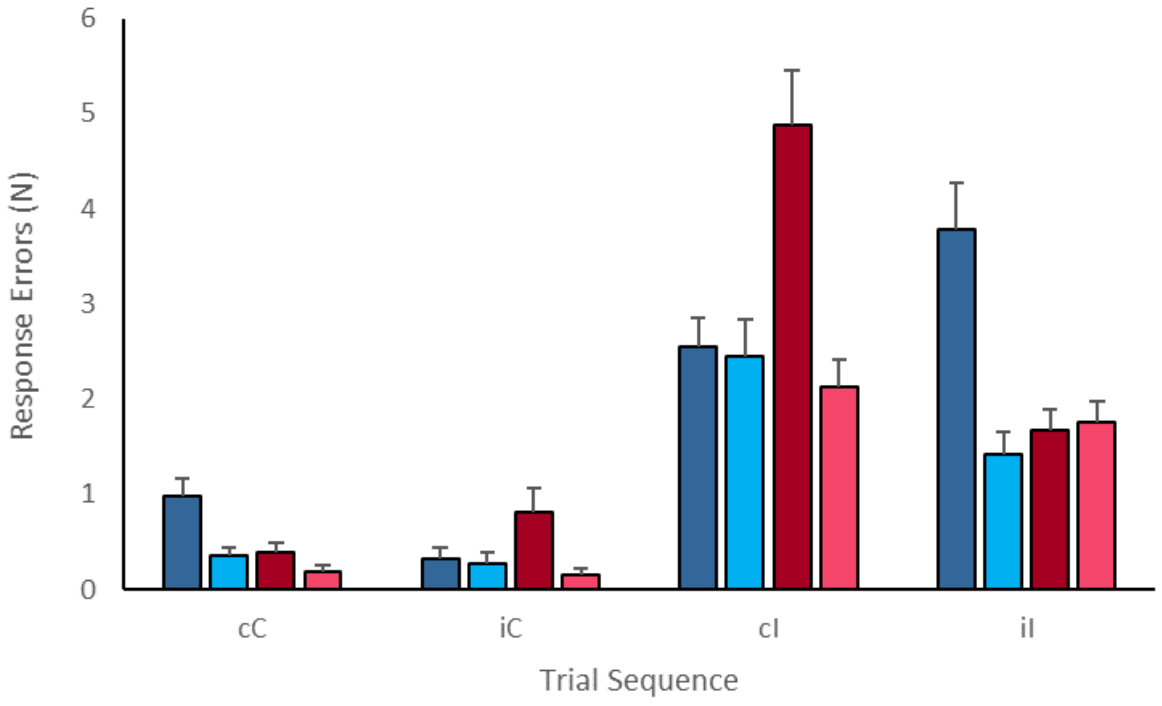


Figure 43. The number of response errors according to trial sequence from the repetition (blue) and alternation (red) task. Darker shades refer to the training phase and lighter shades the test phase.

5.4.0. Discussion:

This study sought to decipher proactive from reactive control strategies underpinning conflict adaptation using a behavioural paradigm described by Duthoo and Notebart (2012). It used a training phase to alter participants' expectations regarding the congruency of the upcoming trial. Essential to this manipulation was the prediction that the repetition training phase would elicit a differential congruency-sequencing effect than the alternation training phase. The critical determinant of whether participants used proactive or reactive control is whether the size of the congruency-sequencing effect in the training phases transfer into an unmanipulated test phase where there is equal probability of the upcoming trial being either congruent or incongruent. A transfer in the magnitude of the congruency-sequencing effect would suggest participants utilise a proactive control strategy, whereby they consider the global probability of the congruency-level repetition/ alternations whereas a reactive strategy would anticipate a divergence in the magnitude of the congruency-sequencing effect between the test and training phases whereby the local, immediate trial congruency bears greater influence than the global probability of congruency-level repetitions/ alternations.

5.4.1. Training Phases

Crucial to the study was to create an environment during which participants could anticipate the congruency of the upcoming stimuli by using context-specific information. This was achieved by creating training phases during which there was a bias in congruency-level repetitions (C, C, C, I, I, I, C) and alternations (I, C, I, C, I, C, I, I) whilst the object task-congruency was maintained at 50%. Remington (1969) reported that participants tend to expect congruency-level repetitions even when probabilistically unlikely. Citing the work of Remington (1969) Duthoo and Notebaert state that *"participants tend to expect that a particular stimulus condition on a given trial will be repeated on the next one … so even when congruent (C) and incongruent (I) trials are objectively equally likely to be presented, subjects still predict that the trial following a congruent one will be another congruent trial,*

whereas incongruent trials are expected to be followed by incongruent ones". According to this interpretation, when these expectations were met (cC and iI trials), the control adjustments implemented by the DLPFC (upregulation of the task-irrelevant stimulus in anticipation of another congruent trial and upregulation of the task-relevant stimulus in anticipation of an incongruent trial), would facilitate performance. Conversely, on congruency-level alternations (30% of trial in the repetition task, and 70% of trials in the alternation task), when the participants' expectations are not met (iC and cI trials), such adjustments in control serve to reduce facilitation on the iC trials and maximise interference on the iI trials.

The results of the current study revealed a large congruency-sequencing effect of 18ms in the repetition training phase. Surprisingly, a significant congruency-sequencing effect of 10ms was also reported in the alternation training phase. This was not shown to demonstrate a significant difference (p=.73). As such, it is considered the training did not differentially alter the magnitude of the congruency-sequencing effect and contrasts Duthoo and Notebaert. The implications of such will be discussed in Section 5.4.5, however, in brief, this would not support the short-term proactive account proposed by Duthoo and Notebaert and displayed in Figure 38. Additionally, this nullifies the predictions proposed in Section 5.1.5., and instead, the key results will be highlighted by examining each task in isolation.

5.4.2. Repetition Task

The presence of a significant congruency-sequencing effect in the repetition training phase, by itself, does not support either a proactive or reactive account. Instead, Duthoo and Notebaert suggest the investigation of a potential transfer of the differential effect of the training to the test phase could *"critically differentiate between conflict adaptation and the repetition expectancy account".* If the magnitude of the congruency-sequencing effect during the training phase (which was expected to

operate differentially in the repetition and alternation tasks) transferred into the test phases, this would suggest that global contextual cues served as a more dominant influence that local cues (previous trial congruency) and that a proactive control strategy was also used in the test phase, see Figure 38A.

In the repetition task, the congruency-sequencing effect reduced from 18ms in the training to 9ms in the test phase. Despite this, the three-way interaction of PREVIOUS-CONGRUENCY * CURRENT-CONGRUENCY * PHASE only approached significance (p=.073) which suggests the congruency-sequencing effect in the training phase is not distinct from the congruency-sequencing effect in the test phase, and therefore, likely represent a proactive control strategy. Further, the distribution of classifications revealed no differences between the repetition training and test phases, and, mirroring the response time result, further support the use of a proactive control strategy in the repetition task.

5.4.3. Alternation Task

Returning to Duthoo and Notebaert's interpretation of Remington (1969), they predicted that participants could anticipate congruency-level repetitions, but they did not consider that participants may predict congruency-level alternations. As such, they predicted a diminished congruency-sequencing effect in the alternation training phase. In contrast to this, the alternation training phase yielded a significant congruency-sequencing effect of 10ms. Duthoo and Notebaert may take the stance that, although statistically significant, a congruency-sequencing effect of 10ms does indeed reflect a diminished congruency-sequencing effect. Two counter arguments to this are put forward: 1) the magnitude of the congruency-sequencing effect in the alternation training phase is not statistically smaller than that in the repetition training phase (18ms); 2) the 10ms congruency-sequencing effect reported is of the same magnitude of that reported in Chapter Three where there were no congruency-level manipulations. Therefore, it can be considered that the 10ms congruency-sequencing effect in

the alternation training phase is a meaningful find. Next it should be considered which control strategy underpins such finding.

As foreshadowed in the General Introduction, there is some disagreement between the interpretation of proactive control put forward by this thesis and that of Duthoo and Notebaert. They interpret Remington (1969) such that participants always predict congruency-level repetitions, even when unlikely (such as the alternation training phase). This interpretation can be considered a 'short-term' proactive control strategy that operates somewhat similarly to a reactive control strategy. Both implement attentional adjustments that benefit a congruency-level repetition with the subtle difference being that a reactive strategy is conflict-driven and does so based upon the previously *experienced* congruency and short-term proactive strategy does so in *anticipation* of a congruency-level repetition. With both strategies adjusting performance to benefit a congruency-level repetition, neither account would support a congruency-sequencing effect in the alternation training phase. However, generally, proactive control is considered to operate on a more global level that absorbs contextual cues from across the entire trial sequence. As such, when considered from a long-term proactive perspective, it could be that the participants were able to predict not only congruency-level repetitions (in the repetition training phase), but also congruency-level alternations (in the alternation training phase). As such, the DLPFC could implement the same anticipatory control mechanisms (upregulation of the task-irrelevant stimulus in anticipation of another congruent trial and upregulation of the task-relevant stimulus in anticipation of an incongruent trial) to produce a congruency-sequencing effect in the alternation training phase by predicting the congruency-level alternations. Therefore, the finding of a congruency-sequencing effect in the alternation training phase supports a proactive control strategy, and specifically one that operates on a global, long-term scale.

If participants utilise a proactive control strategy in the alternation task it is expected that there will be only a small divergence in the congruency-sequencing effect in the alternation test phase, but specifically, it is expected the magnitude of the congruency-sequencing effect in the alternation test phase to be *smaller* than in the alternation training phase. This is because in the training phase participants are predicting a congruency-level alternation (70% of trials), which then become less frequent in the alternation test phase (50% of trials). The congruency-sequencing effect did indeed reduce in the alternation test phase and was 2ms. Because this did not reflect an interaction of PREVIOUS-CONGRUENCY * CURRENT-CONGRUENCY * PHASE (p=.162) this would suggest there was a transfer from the training to the test phase. This would, therefore, support the use of a proactive control strategy throughout the alternation task.

Further evidence for the use of a proactive control strategy throughout the alternation task is provided from the distribution of the congruency-sequencing effect classifications. In the alternation training phase, 52% and in the alternation test phase, 50% of participants produced a congruency-sequencing effect (summation of classifications 1-3). Furthermore, a similar percentage of participants produce a class one (17% and 6%), class two (33% and 40%) and class three (2% and 4%) in the training and test phases, respectively. This would provide additional support of a proactive strategy was used during the training and test phase of the alternation task.

5.4.4. Test Phases

Key evidence in Duthoo and Notebaert's conclusion of a reactive control strategy was the comparison of the test phases between the repetition and alternation task. During the test phases of both tasks, half the trials were congruent, with equal probability of the congruency of trial *n* repeating to trial *n*+1. If participants were using a reactive (or short term proactive) strategy in both tasks it is expected that the magnitude of the congruency-sequencing effect would be the same because the immediate trial

history would be more pertinent than the global trial history. To aid with such comparisons, the present study carefully designed the trial sequence such that the test phases were identical across both the repetition and alternation tasks so to minimise the influence of any other factors on the response times. Similarities in the test phases would contradict the above findings and lend support the use of a reactive control strategy in both tasks, whereas any differences would support the use of long-term proactive strategies in both tasks.

The present study reported a congruency-sequencing effect of 9ms and 2ms in the repetition and alternation test phases, respectively. Such did Duthoo and Notebaert, the present study did not report a reliable difference in the congruency-sequencing effect in the test phases from the repetition and alternation task (p=1.00). In isolation, this may be seen to support a reactive control strategy. The classifications mirror the response time results and show there is good concordance across the two tasks such that 53% and 50% of participants produced a congruency-sequencing effect (class one through three) during the repetition and alternation training phases, respectively. Generally, the contribution of the congruency-sequencing effect (percentage of each classification) is also similar across the two test phases. As such, the classification analysis supports the interpretation from the mean response times that the test phases represent a reactive control strategy.

As outlined, the sequences in the test phase blocks are identical. Therefore, it is also prudent to compare the magnitude of the congruency-sequencing effect at each block. This provides a 'real-time' comparison of the magnitude of the congruency-sequencing effect that is less vulnerable to extreme values that may obscure the reported mean value. A reactive account would anticipate that the magnitude be identical at each time-point to reflect eradication of the congruency-level manipulations from the training phases. The post-hoc comparisons reveal there are no significant differences between the test phases at any of the blocks. Despite this, there are large differences in the

magnitudes reported, for example during block four, the magnitude of the congruency-sequencing effect from the repetition test phase is 5.7ms and -8.8ms in the alternation test phase. This demonstrates that although they are not statistically significantly different, they are quite clearly not identical. Therefore, although the statistical analyses suggest the test phases do not differ, they are not, as a reactive account would predict, identical, and therefore, likely do not reflect a reactive control strategy in either the repetition or alternation task.

Whilst there are some discrepancies in the comparison of the test phases between the repetition and alternation tasks, overall, it is considered that the magnitude of the congruency-sequencing effects in the test phases are not identical, such was a key prediction of the reactive control strategy. Therefore, it is concluded that a reactive strategy was not used during the repetition and alternation task. This compliments evidence concerning the transfer of the magnitude of the congruency-sequencing effect reported above which concluded both tasks elicited a proactive control strategy.

5.4.5. Comparison with Duthoo and Notebaert

A key difference between Duthoo and Notebaert and the present study is the interpretation of proactive control. Typically, proactive control is considered to represent a sustained, anticipatory control mechanism, whereas reactive control is considered a transient mechanism (Braver, 2012, Torres-Quesada et al., 2014). Whilst in their introduction, Duthoo and Notebaert state this viewpoint, their interpretation of their own findings is not consistent with these views. The fundamental difference stems from their interpretation of Remington (1969). His results of demonstrate the response times on trial *n* for response repetitions and alternation back to trial *n*-4. Trials were fastest when all response were repetitions (aaaaA) and slowest when there was an alternation after a string of repetitions (bbbbA) however, trials where there are high frequency response alternations (ababA) were not in the slowest quartile of responses. Therefore, this thesis considers that whilst there may be

a cost associated with a response alternation, this may be experienced to a lesser extent when responses alternate frequently than when they do not.

Duthoo and Notebaert, however, interpreted such findings that participants always expect congruency-level repetitions. This would constitute a trial-to-trial repetition-expectancy (short-term) interpretation of proactive control. Behaviourally, this would present the same as a reactive control strategy but differ through the driver: reactive control is conflict-driven and induced based on the previously experienced conflict, but short-term proactive control would always assume a congruency-level repetition (both would elicit a congruency-sequencing effect of the same magnitude). This is inconsistent with the predominant interpretation of proactive control that suggests contextual cues are accumulated over the global trial history to predict the upcoming trial. This is an important difference because a short-term interpretation of proactive control would not predict a congruency-sequencing effect in the alternation training phase, whereas a long-term proactive control strategy would suggest participants could anticipate the alternation sequence (iC and cI trials) to produce a congruency-sequencing effect, such as was reported in the current study. For example, after a congruent trial, the DLPFC would upregulate attentional control towards the task-relevant stimuli in anticipation of an incongruent trial. Equally, after an incongruent trial, attention control would be upregulated by the DLPFC towards the task-irrelevant stimuli in anticipation of a congruent trial. Such adjustments in control would produce a congruency-sequencing effect in the alternation training phase. A limitation of the present study is that the current design would only differentiate between a long term and short-term control strategy, so if proactive control can also operate in a short-term manner it would not be possible to differentiate between this and reactive control.

To further support their conclusion that participants used reactive control processes during the repetition and alternation task, Duthoo and Notebaert performed sub-analyses on trial sequences

which included a repetition on trial *n*-2 and alternation on trial *n*-3 (iccC; iccI; ciiC; ciiI). They reported no differences in the response times between the repetition and alternation task to further support a reactive control strategy. The present study was designed to ensure there were equal number of repetitions in the repetition task as there were alternations in the alternation task by limiting the number of consecutive congruency-level repetitions/ alternations (which did not exceed five). As such, there are fewer than 10 iccC trials in the alternation and iccI trials in the repetition training phases. Therefore, such analysis was not deemed appropriate on what Duthoo and Notebaert themselves admit is a very limited number of trials.

On the surface, it is not necessarily clear why the results of the present study may differ to that of Duthoo and Notebaert when the experimental designs were so similar. What did differ, however, was the analysis. The current study reasoned that a proactive control strategy would accumulate contextual cues in the training phase to determine the frequency of congruency-level repetitions or alternations. As such, during the first block, participants may not have received sufficient exposure to these cues for them to serve as informative. Therefore, the trials in the initial testing block (80 training phase, 40 test phase, 40 training phase) were excluded from all analyses in both tasks.

Additionally, the final 40 training phase trials were also excluded because the magnitude of the congruency-sequencing effect appeared to display drastic rebounds that do not reflect the magnitude of the 80 training trials or the test phase of each block. For example, Figure 42A shows all trials across blocks. In block two of the alternation task, the congruency-sequencing effect in the 80-trial training phase was 19ms, which reduced to -1.6ms in the test phase and was further attenuated to -24ms in the 40-trial training phase. Further, in block three of the alternation task, the magnitude of the congruency-sequencing effect was -9ms in the 80 training phase, which increase to -4ms in the test phase and increase all the way to 14ms in the 40 training phase. Duthoo and Notebaert did not report

the block-wise analysis, so it is unclear whether they displayed any such fluctuations and whether such exclusions were necessary from their dataset.

5.4.6. Proactive or Reactive Control?

Based upon the evidence discussed, namely the significant congruency-sequencing effect in the alternation training phase that would not be predicted by a reactive nor short-term proactive strategy, it is considered that the participants used a long-term proactive control strategy throughout the alternation task. This is further evidenced via the transfer (non-significant PREVIOUS-CONGRUENCY*CURRENT-CONGRUENCY*PHASE interaction) and the non-significant differences in the distribution of classifications between the alternation training and test phases. The repetition task displayed the same pattern of results to that of the alternation task: a no differences between the training and test phases on between the magnitude of the congruency-sequencing effect nor the distribution of classifications. Therefore, it is concluded that there is evidence for use of proactive control in the repetition task also.

The comparison of the test phases shows similarities between the repetition and alternation task. Whilst this could be seen interpreted to support a reactive account, this is inconsistent with the results proposed above. Therefore, it is instead proposed that a proactive control strategy was used in both tasks.

The results of the current study directly contrast the results of Duthoo and Notebaert (2012). A possible explanation for this could be that the analytical approach adopted by the current study excluded the initial block of testing where a long-term proactive control strategy may not have received sufficient exposure to the task manipulation to effectively influence the congruency-

sequencing effect. Duthoo and Notebaert did not exclude any trials from their analyses, and as such, it is possible participants could have been utilising a proactive control strategy but any evidence of proactive control later in the experiment would be diluted by the inclusion of earlier experimental blocks.

5.4.7. Comparison to Wider Literature

The results of the current study support a proactive control mechanism. This is consistent with results from behavioural and imaging data from other paradigms (Gonthier et al., 2016, Paxton et al., 2008). Evidence from this Chapter's Introduction demonstrated that the AX-CPT can produce both proactive control processes (Braver et al., 2009), however, this task is reliant on a cue to implement a proactive control strategy, whereas the evidence from the current Stroop task demonstrates that this can be induced without such a cue. This is important for the generalisability of findings to real-world examples, such as the example of the shopping list provided in this introduction (see Figure 35). Previously the view of proactive control, active maintenance of a goal such as to remember to go shopping after work, relied upon a prompt (such as the after-work meeting proposal depicted in panel 3 of Figure 37), however, the results from the current study removes the dependence of the prompt from proactive control. That is, even without the question "Meeting now?" in Figure 37, the individual would still remember to go shopping after work.

Braver et al. (2012) suggest use of proactive or reactive control represents a trade-off between the costs and benefits of the two strategies. Proactive control is very resource-intensive – it requires constant maintenance of stimuli via dopamine release and reduces the capacity for other information to influence behaviour (Braver et al., 2009). Perhaps the necessity to override automatic an habitual

responses from the task-irrelevant stimuli required the devotion of many attentional resources and is why a proactive control strategy prevailed in this task.

5.5.0. Conclusion:

In summary, it is considered the significant congruency-sequencing effect in the alternation training phase is of a comparable magnitude to that reported in Chapter Three where there was no congruency-level manipulation. This is not supported by the reactive account, which would predict that the abundance of iC and cI trials would diminish the congruency-sequencing effect. Further, there was close concordance with the pattern of classifications between the alternation training and alternation test phase that would lead to conclude that a proactive strategy was used during the alternation task.

Based on the same pattern of results, it is suggested that participants also used a proactive control strategy in the repetition task as well. Further, when comparing the test phases, a reactive account would suggest the magnitude of the congruency-sequencing effect would be identical, however, the results from the block-wise analysis reveal this was not the case. Therefore, this provides further evidence to support that younger adults preferentially engage a proactive control strategy in a Stroop task. This is consistent with the data from an AX-CPT task suggesting younger adults most frequently use a proactive control strategy (Braver et al., 2005).

Chapter Six: General Discussion

The main aim of this thesis was to use the congruency-sequencing effect as a behavioural marker of conflict adaptation to investigate the processes that allow for successful behaviour (performance) after experiencing response conflict. The initial literature search revealed three accounts that may underpin the congruency-sequencing effect: Feature-Integration (Hommel, 1998; Hommel et al., 2004); Conflict Monitoring (Botvinick et al., 2001); and Repetition Expectancy (Gratton et al., 1992; Egner, 2007), (see Figure 5). The Conflict Monitoring and Repetition Expectancy account are both top-down accounts that implicate the DLPFC as instrumental in up-regulating attentional resources to the task-relevant or task-irrelevant stimuli but differ in how the DLPFC is recruited. In contrast, the Feature-Integration account proposes that the congruency-sequencing effect arises as a consequence of similarities and repetitions of certain stimuli features from one trial to the next. Consequently, it was pertinent to first exclude this potential explanation from confounding any investigations into the top-down role of conflict adaptation.

6.1. Chapter Three

To investigate the use of the congruency-sequencing effect as a behavioural index of conflict adaptation, two Stroop tasks were designed. The with feature-repetition task was as per a standard Stroop task whereby feature-repetitions occurred on most (70%) of trials. The second was the feature-repetition free task which was created by specifically designing a trial sequence such that no stimulus feature (task-relevant nor task-irrelevant) repeated from one trial to the next. The FRW task demonstrated that, as per other reports in the literature (Aschenbrenner and Balota, 2015, Aschenbrenner and Balota, 2017, Duthoo et al., 2014; Duthoo and Notebaert), feature-repetitions can produce a congruency-sequencing effect. Importantly, the FRF task revealed a reliable, albeit smaller

congruency-sequencing effect. This shows that, in the absence of feature-repetitions, a congruency-sequencing effect is still produced, indicative of a top-down component.

A crucial finding from the second experiment was that the post-hoc removal of feature-repetitions from the FRW task that is often used by researchers (first championed by Kerns et al., 2004) is not comparable to the magnitude of the congruency-sequencing effect reported in a pure FRF task. As such, whilst it is more convenient to use a conflict task to explore congruency-sequencing effects, this thesis recommends that it is imperative to steer away from such temptation and to instead invest the time to design an appropriate task that does not contain any feature-repetitions so to eradicate the influence of the (post-hoc) removed feature-repetition trials on the remaining feature-alternation trials.

A further prediction of Chapter Three was that if the congruency-sequencing effect is reflective of a top-down component, as the results have revealed, this should be accompanied by an age-related decline. Therefore, it was predicted that older adults would display a diminished congruency-sequencing effect. Interestingly, this was not the case and the reports of age-related DLPFC decline did not translate to age-related deficits in conflict adaptation. In fact, in the older adults displayed a larger congruency-sequencing effect than the younger adults, particularly in the FRW tasks, although this difference was not statistically significant. Whilst counterintuitive to our predictions, this is consistent with others (e.g. West and Moore, 2005) who have used standard Stroop tasks (equivocal to the FRW task) and reported heightened congruency-sequencing effects in older compared to younger adults. From this, it is concluded that compared to younger adults, older adults displayed heightened conflict adaptation (see also the end of Section 6.2).

6.2. Classifications of Conflict Adaptation

When analysing the data from the first two experiments (Chapter Three) it became clear that whilst a reliable congruency-sequencing effect was reported, it was brought about in an unexpected fashion. That is, instead of producing the typical pattern of results (faster iI than cI trials), the congruency-sequencing effect emerged because when the previous trial was incongruent, the Stroop effect (iI-iC trials) was smaller than when the previous trial was congruent (cI-cC trials). Interestingly, this pattern was also reported in the FRW task, so is not unique to only the FRF task. Further, the pattern of responding reported in this thesis can also be observed in other studies (Duthoo and Notebaert, 2012; Duthoo et al., 2014). This inspired the question *'are all congruency-sequencing effects the same?'*. To delve further into this, a novel five-point classification system was devised. This included three classes for participants who displayed a congruency-sequencing effect according to whether they exhibited post-congruent adaptation (class two), post-incongruent adaptation (class three), or both (class one). The final two classes differentiated 'non-responders' from those who displayed a negative congruency-sequencing effect (a heightened Stroop effect after an incongruent trial) which is a form of adaptation, but one that would allow greater interference from the task-irrelevant (distractor) stimulus, and thus could be considered detrimental to performance.

Based upon the mean results originally reported by Gratton et al. (1992) (faster cC than iC and faster iI than cI trials), it is expected that were such classifications performed, that most participants would exhibit a class one congruency-sequencing effect (see Figure 5). However, the results from all of the experiments throughout this thesis reliably revealed that class two (post-congruent adaptation) was most frequent, followed next by class one (post-congruent and post-incongruent adaptation) with class three (post-incongruent adaptation) rarely observed. This strongly implicates congruent and not incongruent trials as the driving factor underpinning the congruency-sequencing effect. As such, this questions the way that 'conflict adaptation' should be considered. Although this classification analysis

has not previously been performed, it does align with reports in the literature (Compton et al., 2012, Lamers and Roelofs, 2011) that challenge the views that conflict adaptation derives from conflict (an incongruent trial). Lamers and Roelofs (2011) performed a manual Stroop task which further included neutral trials. They postulated that if 'conflict' was the driver of the congruency-sequencing effect then the Stroop effect will be smaller post-incongruent compared to post-congruent and post-neutral trials. They reported that, compared to post-neutral trials, the Stroop effect was indeed 5ms smaller post-incongruent trials, but remarkably, the Stroop effect was also 16ms larger on *post-congruent* trials. As such, there is adaptation following both congruent and incongruent trials but to a greater extent on trials proceeding congruent trials, which was an unexpected result. (They reported a comparable pattern of results after removing feature-repetitions, so are not specific to the FRW task.) These results were replicated by Compton et al. (2012) who further reported that congruent trials elicited the lowest alpha power recorded from an array of frontal regions, including the DLPFC. This demonstrates greatest involvement of said regions in trials following congruent compared to neutral or incongruent trials. They suggest this could represent detection of complimentary information on congruent trials, which then signals a reduction in attentional resources allocated to the task-relevant stimulus which would benefit a subsequent congruent trial (cC), debilitate an incongruent trial (cI) and hence produce a large Stroop effect following a congruent trial.

The reason a similar approach to Lamers and Roelofs (2011) and Compton et al. (2012) was not adopted by this thesis is because extent to which the inclusion of neutral trials may affect the sequential modulation of the Stroop effect (the congruency-sequencing effect) is unknown. Therefore, to tackle the same question and investigate *how* the congruency-sequencing effect is produced, be that through post-congruent, post-incongruent adaptation, or a combination of the two, the classification system was devised and performed on each experimental chapter.

In experiment two of Chapter Three, younger and older participants performed both the FRF and FRW tasks. In the FRF task, only 59% of younger and 64% of older adults produced a congruency-sequencing effect. However, in the FRW task, this increased to 100% of younger and 92% of older adults. Interestingly, in both instances most younger adults produced a class two (post-congruent adaptation) and most older adults produced a class one (post-congruent and post-incongruent adaptation). Perhaps, with ageing, the preferential post-congruent only adaptation is supplemented with the addition of post-incongruent adaptation as a compensatory mechanism (greater reliance on additional sources of information) to negate any age-related declines in DLPFC functioning. This would supplement the conclusion from Section 6.1. that, based on the mean congruency-sequencing effects, older adults may display heightened conflict adaptation by suggesting where these differences are derived from.

6.3. Chapter Four

A key finding from the previous chapter was the presence of a reliable congruency-sequencing effect in the absence of feature-repetitions. This demonstrates that whilst feature-repetitions do indeed contribute to, and magnify, the congruency-sequencing effect, there is a top-down component as well, as put forward by the Repetition Expectancy and Conflict-Monitoring model.

Whilst the notion of a FRF task was slowly becoming more frequent (i.e., Aschenbrenner and Balota, 2017), many researchers continued to investigate conflict adaptation with an FRW task and favoured Kerns et al. (2004)'s post-hoc removal approach to addressing feature-repetitions, opposed to using an FRF task design. In light of the findings highlighted above (that post-hoc removal of feature-repetitions is not equivocal to utilising a FRF task design) it was considered prudent to establish causal evidence for the involvement of the DLPFC from an FRF task, research which, to best knowledge, had not been undertaken. Therefore, Chapter Four used tDCS, a form of non-invasive brain stimulation, to

modulate the cortical excitability of the left DLPFC which was expected to amplify the magnitude of the congruency-sequencing effect as compared to tDCS applied to a control region (the motor cortex).

Remarkedly, the results revealed no differences in the magnitude of the congruency-sequencing effect between stimulation of the DLPFC or M1. Without an external measure to validate that the stimulation modulated the cortical excitability, it is difficult to draw conclusions from the null results. Possible explanations were that the DLPFC may not be involved in conflict adaptation, that tDCS modulated the DLPFC but not sufficiently to elicit a change in excitability, or that the stimulation simply had no effect on the DLPFC. On balance, it was concluded that the stimulation had no effect on the DLPFC as supported by no differences in the mean magnitude of the congruency-sequencing effect reported here was identical to that reported in Chapter Three where there was no stimulation applied. Further, the distribution of classifications between the two stimulation sites and between Chapter Three (where no stimulation was applied) were all very closely matched, which further supports that there was no influence of stimulation.

Simulation modelling was performed to maximise the current density over the DLPFC before stimulation took place. Future studies could look to use HD-tDCS, as per Gbadyen et al. (2016, 2019) however, they also reported only modest influences of stimulation. This agrees with others who have failed to report a change in response time (Anguis et al., 2019, Baumert et al., 2020), a moderation of the congruency effect (Zmigrod et al., 2016 – Simon task; Baumert et al., 2020 – Stroop task); nor moderation of the congruency-sequencing effect (Baumert et al., 2020, Frings et al., 2018). Therefore, the evidence suggests there is a minimal capacity for tDCS to modulate the DLPFC and its functioning and without an external validation to objectively measure changes in the cortical excitability, there appears to be minimal moderation of behavioural outcomes. For this reason, Chapter Five sought to

return to behavioural outcomes to try and differentiate between proactive and reactive control strategies.

6.4. Chapter Five

Chapter Five sought to use a behavioural paradigm with training and test phases to measure differences in the magnitude of the congruency-sequencing effect to try and dissociate proactive and reactive control processes. The experiment included two tasks: the repetition and alternation task which, in the training phases, differed in the likelihood of the congruency of the previous trial repeating or alternating. The full predictions from the experiment were listed in Chapter Five, but as an overview, a proactive account expected: 1) The congruency-sequencing effect in the repetition training phase will be larger than the alternation training phase. This is because Duthoo and Notebaert suggested that participants always expect the congruency to repeat from trial to trial. 2) Therefore, a transfer of the magnitude of the congruency-sequencing from the training phase to the test phase (smaller congruency-sequencing effect from the repetition training to test phase; larger congruency-sequencing effect from the alternation training to test phase). 3) The test phases will not be the same (a reactive account would expect identical magnitudes of the congruency-sequencing effects in the test phases of both tasks).

Unexpectedly, there was a significant congruency-sequencing effect in the alternation training phase. This is not consistent with the proactive account outlined above and is not supported by the reactive account either. Therefore, the way in which proactive control was assumed to operate (as a short-term, repetition expectancy account) was challenged. As such, Chapter Five concluded that proactive control is a global, long-term strategy and as such, participants were able to predict the congruency-level alternations to produce a congruency-sequencing effect in the alternation training phase. This conclusion was supported by the transfer in the magnitude of the congruency-sequencing effect from

the training to the test phase where congruency-level alternations were less frequent. Finally, there were minimal differences in the distribution of classifications between the alternation training and test phases, which supports a proactive strategy. The repetition task showed the same pattern of results, a transfer in the magnitude of the congruency-sequencing effect from the response times, coupled with no main effect of phase on the distribution of classifications. Therefore, a proactive control strategy was concluded to be utilised in the repetition task, also. This contrasted the results of Duthoo and Notebaert (2012), however, it is discussed that perhaps their analytical design did not adequately allow for the observation of a proactive control strategy.

The conclusion of a proactive control strategy in a Stroop task is consistent with work from Braver's research group who have used the AX-CPT and reported that younger adults preferentially engaged in a proactive control strategy (Paxton et al., 2008).

6.5. Overall Limitations

The limitations specific to each chapter have been highlighted throughout the relevant discussion sections, however, all experimental chapters used similar tasks and designs, the limitations of which are yet to be discussed. The most pertinent of which is the choice of the vocal Stroop task.

One of the main aims and successes of this thesis was to design a task that removed the bottom-up influence of feature-repetitions. It soon became apparent that this was only possible by selecting a task with a large stimulus-response pool so that a trial sequence could be generated using an alternation from both the task-relevant and task-irrelevant stimulus from trial *n*-1 to trial *n*. This lent itself to the selection of a Stroop task.

Throughout this thesis, a vocal Stroop task was used and was accompanied with some limitations, primarily, identifying the response onset. As fully outlined in the General Methods, an automated script was programmed to identify when the rectified and smoothed microphone trace crossed a noise threshold. Whilst this often correctly identified the response onset, each trial was manually verified and corrected where appropriate. Across this entire thesis, data was collected from over 290 participants totalling more than 1 million trials. This was an enormously time consuming and would not have been associated with a manual task. However, there were two key reasons a vocal task was selected over a manual task: 1), According to Kornblum et al. (1990)'s dimensional overlap (see General Introduction), the vocal Stroop task provides a high degree of conflict that is not offered by other tasks. This weighed heavily on the decision to use a vocal because a high conflict task can elicit a larger congruency effect (Augustinova et al., 2019). Therefore, if isolating only a top-down component (which was predicted to be smaller than in an FRW task), a vocal Stroop task may provide an optimal environment to observe any trial by trial modulation of the congruency effect. 2) After explaining the instructions, the task is intuitive to the participant: to speak the colour seen. For contrast, some tasks require participants to make timed responses using the index, middle and ring finger of both hands (Duthoo et al., 2014). The vocal task does not require complex mapping of keys that needs to be maintained in working memory whilst performing the task and may remove any potential confounds associated at a response, opposed to processing level.

6.6. Future Directions

The primary research question proposed in the General Introduction was *'What mechanism drives conflict adaptation*?'. Figure 5 outlined the three possible mechanisms and the combined results of this thesis suggest that, under certain conditions, all mechanisms (feature-integration, proactive and reactive control) can contribute to conflict adaptation. The role of feature-repetitions is understood as follows – when stimulus features repeat from trial *n* to *n*+1, bottom-up influences can magnify the

congruency-sequencing effect. However, it is unknown whether this occurs in summation or interactively with top-down influences or if the presence of feature-repetitions negates any top-down requirement. Considerable effort was placed on trying to dissociate proactive from reactive control. Chapter Five highlighted that under specific circumstances both proactive and reactive control can be executed. However, it is currently unclear why a person may exhibit one form of control over another. The current study used a between-subjects design; therefore, it is unknown if the differences in response strategy between the two tasks is not in fact reflective of the different task demands (as currently presumed), but instead represents individual differences. Future studies may wish to identify if specific task demands elicit a change in strategy *within* participants. To do this, a replication of Chapter Five with the same participants completing the repetition and alternation task is proposed. Specific emphasis should be placed on using the classification of the congruency-sequencing effect to highlight changes within an individual between the training phases in the repetition task (which has been shown to elicit reactive control) and the alternation task (which has been shown to elicit proactive control).

6.7. Concluding Remarks

The research conducted in this thesis contributes to expanding and developing an understanding of how people adapt after experiencing response conflict. The four most important findings from this research are: 1) To champion the necessity of an FRF task and a Stroop-type task. Analysis in Chapter Three emphasised that the congruency-sequencing effect produced via post-hoc removal of feature-repetitions from a FRW task (as first performed by Kerns et al., 2004) is not of the same magnitude as that produced by a FRF task. 2) To challenge the view that adaptation arises solely as a result of 'conflict' (two alternative, competing responses such as an incongruent trial) but that a stimulus with two non-competing dimensions (such as a congruent trial) may be a stronger driver of adaptation (because most younger adults produce a class two congruency-sequencing effect) although adaptation

does occur after incongruent trials also (class one; Compton et al., 2012; Lamers and Roelofs, 2011). 3) That tDCS may have a minimal capacity to modulate the cortical excitability of the DLPFC. 4) That proactive (preparatory) control processes are preferentially utilised by younger adults when faced with a conflicting stimulus requiring a high degree of control to override prepotent responses. To return to the example provided in the General Introduction of a pedestrian stepping out in front of the traffic lights, this thesis would suggest that participants would be continuously examining pedestrians on the pavements in a preparatory, proactive strategy to avoid repeat encounters.

Chapter Seven: References

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Appendix:

Motor Control & Rehabilitation Group

School of Sport, Exercise & Rehabilitation Sciences

The University of Birmingham,

Edgbaston,

Birmingham

B15 2TT

Participant ID:	

TDCS, TACS & TMS Safety Questionnaire

If you agree to take part in this study, please answer the following questions. The information you provide is for screening purposes only and will be kept completely confidential.

Please tick the following information where it is applies to you:

Gender: • **Male** • **Female** • **Non-binary** • **Prefer not to say**

Dominant Hand: • **Right** • **Left**

Fluent English Speaker: • **Yes** • **No**

Age (please specify) ___yrs**.**

	Yes	***No***
1) Have you ever suffered from any neurological or psychiatric conditions?		
If YES please give details (nature of condition, duration, current medication, etc)		
2) Have you ever suffered from epilepsy, febrile convulsions in infancy or had recurrent fainting spells?		
3) Does anyone in your immediate or distant family suffer from epilepsy?		
If YES please state your relationship to the affected family member.		
4) Do you suffer from migraine or reoccurring headaches?		

5) Have you ever suffered from brain injury or brain trauma?		
6) Have you ever undergone a neurosurgical procedure (including eye surgery)?		
7) Have you ever lost consciousness or fainted?		
If YES (to any of the above four Questions above) please give details:		
8) Do you currently have any of the following fitted to your body?		
Cochlear implant		
Heart pacemaker		
Medication pump		
Surgical clips		
If YES please give details:		
9) Do you suffer from any chronic skin disorders?		
If YES please give details:		
10) Are you currently taking any unprescribed or prescribed medication?		
If YES please give details:		
11) Is there any chance you could be pregnant?		
12) Are you currently undergoing anti-malarial treatment?		
13) Have you drunk more than 3 units of alcohol in the last 24 hours?		
14) Have you drunk alcohol already today?		
15) Have you had more than one cup of coffee, tea, or other sources of caffeine, in the last hour?		
16) Have you used recreational drugs in the last 24 hours?		
17) Did you get significantly less sleep than usual last night?		
18) Have you ever participated in a TMS, TDCS or TACS experiment before?		
If YES please outline when and state if there were any issues:		

I confirm that the above information is accurate to the best of my knowledge.

Print Name: Signature:	Date:
This form has been verified by (researcher only): Print Name: Signature:	Date: