Dynamic Adjustments of Cognitive Control Across Adolescence

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Thesis Abstract

Cognitive control refers to our ability to stay on task even in the face of distractions. During task performance, control is dynamically adjusted trial-by-trial, based on changes in task demands (e.g., the occurrence of response conflict). In my thesis, I investigated how the ability to dynamically regulate control levels in response to conflict changes across adolescence when control-related brain areas such as the anterior cingulate cortex are still undergoing maturation. I also examined whether the frequency of lapses in attention during a task (mind-wandering; MW) is related to age and dynamic adjustments of control. Before addressing my central research questions, I first investigated whether dynamic control adjustments are motivated by the aversive nature of response conflict using an affective priming paradigm, but found no robust evidence for this hypothesis (Chapter 2), therefore this avenue was not pursued further. Across two subsequent studies (Chapters 3 & 4) I found no significant age-related differences in the size of the congruency sequence effect (CSE) - an effect hypothesized to reflect dynamic control adjustments - between adolescents and young adults in reaction time on a Simon and a flanker task. However, adolescents did show less flexible and less temporally consistent recruitment of control processes in response to conflict at the neural level as indicated by non-adult-like dynamics in the theta frequency range (4-7 Hz) during the flanker task (Chapter 4). MW frequency was inconsistently related to age (Chapters 3 & 4), however, it did appear to correlate negatively with CSE magnitude. Using a modified flanker task, I examined this association in Chapter 5 but the relationship did not replicate. In sum, this thesis provides some evidence for the protracted maturation of control, however, it also suggests that certain aspects of control, such as the ability to dynamically regulate control levels mature early on.

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Chapter 1 - General introduction

1.1 Introduction

The focus of my thesis concerns the development of cognitive control, specifically the dynamic aspects of control engagement, across adolescence. In this chapter, I will introduce the concepts central to my research questions. In the first part of the chapter, I will define cognitive control and describe what aspects of the construct I have been focusing on in my empirical work. In the second part, I will summarize the most relevant models of cognitive development and the empirical findings that provide the basis of my thesis.

1.2 The structure and dynamics of cognitive control

Cognitive control is a complex, multi-componential construct (e.g., Badre, 2011; Gratton, Cooper, Fabiani, Carter, & Karayanidis, 2018; Miyake & Friedman, 2012; Satpute, Badre, & Ochsner, 2011). It refers to a collection of cognitive processes involved in generating and maintaining task-relevant goals and suppressing task-irrelevant goals (Gratton et al., 2018). In other words, these processes are responsible for ensuring the goal-directedness of behaviour even in the face of distractions, by setting and modifying the attentional weights assigned to different aspects of the environment (Gratton et al., 2018). This conceptualization of cognitive control is based on the biased competition framework of selective attention (Desimone & Duncan, 1995) which posits that internal goals can bias response pathways relevant to a given goal by selecting and strengthening them over other response pathways activated by goal-irrelevant stimuli (or over alternative, goal-irrelevant pathways activated by the goal-relevant stimulus).

The exact structure of this construct (i.e., the number of components that belong under the umbrella of this term) is a matter of some debate (Karr et al., 2018), but one prominent framework introduced by Miyake and colleagues (2000; Miyake & Friedman, 2012) partitions it into three distinct, but correlated subcomponents based on latent variable analysis of performance on a variety of cognitive control tasks. These components are: suppressing task-irrelevant goals and response tendencies (inhibition); replacing the current contents of working memory with new information (updating), and changing flexibly between task-sets and goals (shifting). In the empirical studies presented in this thesis, I have investigated performance on tasks of inhibition to study the dynamics of cognitive control, i.e., how it is implemented and how its level waxes and wanes across a task. It is therefore important to note that in later iterations of the Miyake et al. model no specific inhibition factor was found; it was completely explained by a common executive factor that affected performance on all tasks of control, and that likely reflects the general top-down biasing mechanism described in the biased competition framework (Friedman & Miyake, 2017). Furthermore, some recent studies have questioned the validity of inhibition as a unitary construct, e.g., because proposed behavioural indicators of inhibition often do not correlate across tasks, (Rey-Mermet, Gade, & Oberauer, 2018; Rey-Mermet, Gade, Souza, von Bastian, & Oberauer, 2019). Importantly, however, these findings do not necessarily mean that inhibition as a mechanism does not exist, but simply imply that its manifestations might be highly task-specific (Egner, 2008).

One class of tasks that is theorized to measure response inhibition is conflict tasks, such as the Stroop (Stroop, 1935), flanker (Eriksen & Eriksen, 1974) or Simon tasks (Simon, 1969). In each of these paradigms participants have to respond to a target stimulus (or stimulus dimension) while ignoring task-irrelevant distractor stimuli (or stimulus dimension). In the most classic example, the Stroop task, participants have to respond to the colour the names of different colours are printed in while ignoring the meaning of the word. Trials where the colour and the meaning – i.e., the task-relevant and task-irrelevant dimensions, respectively – coincide and they both prime the same response are called congruent trials (e.g., GREEN printed in green). Trials where the two dimensions mismatch are called incongruent trials (e.g., GREEN printed in red). In the flanker task, participants typically have to identify a central target stimulus flanked on each side by task-irrelevant stimuli (e.g., →→→ and ←→←, where the former is a congruent trial, and the latter is incongruent, and the task is to identify the direction of the central arrow). Finally, in the Simon task participants have to respond to the identity of a stimulus, while ignoring its location on the screen (e.g., a rightward pointing arrow on either the right or left side of the screen, where the former is a congruent trial, and the latter is incongruent, and the task is to identify the direction of the arrow). Regardless of the task, individuals are typically slower and commit more errors on incongruent trials compared to congruent trials. This performance decrement is called the congruency effect which is commonly thought to result from interference caused by the task-irrelevant stimulus or stimulus feature.

Different models have been put forward to explain how exactly this interference occurs in tasks that engender different types of conflict. For the Stroop and the Simon tasks, the most prominent models are connectionist (parallel distributed processing, PDP) models with dual-pathway architecture. According to one such model of the Stroop task (Cohen, Dunbar, & McClelland, 1990), there is a colour-naming pathway that links input units sensitive to the colour information in Stroop stimuli to their corresponding response unit (e.g., the unit representing "green" is associated with the unit representing the response "say green"), and a word-reading pathway which links word input units to the same, shared response units (e.g., the unit "GREEN" to "say green"). When the activated pathways do not converge on the same response unit, e.g., on incongruent trials, it takes longer for the correct response unit to reach its activation threshold leading to a delay in responding in this condition. A task demand unit representing the goals of the task (e.g., “name the colour”) biases one pathway (the colour naming pathway in this case) over another to ensure goal directedness.

Performance on the Simon task is explained in similar terms by Kornblum, Hasbroucq, & Osman (1992) who propose that the spatial location of the stimulus leads to the direct, automatic activation of the associated response (e.g., “respond left” in case of a stimulus on the left side) through a dedicated pathway and stimulus identity also leads to response activation through a controlled process via a different pathway. If the two responses are the same (congruent trials), the response activated by the location can be executed quickly, however if they are not (incongruent trials), the pre-activated response needs to be suppressed, and a new motor program has to be retrieved, explaining the RT difference between these conditions.

A different type of model has been found to capture extant empirical data in the flanker task the most parsimoniously (White, Ratcliff, & Starns, 2011). In this model, both the target and the flankers contribute some evidence to the decision-making process on each trial, however the influence of flankers gradually decreases as attention narrows in on the central target over the course of the trial. The congruency effect arises because at first, evidence is accumulating faster in favour of the incorrect response on incongruent trials compared to congruent trials due to attention being allocated to the flankers too. A PDP explanation of flanker performance has also been proposed (see Cohen, Servan-Schreiber, & McClelland, 1992) which is more reminiscent of the previous two models, and contains target- and flanker-related pathways, with spatial attention units - the equivalent of task demand units - modulating the weight of different pathways. Liu, Holmes, & Cohen (2008) showed that this connectionist model can be reduced to an evidence accumulation model of the flanker similar to the one postulated by White et al. (2011).

In sum, models of conflict task performance typically conceptualize conflict in these tasks as the simultaneous activation of multiple, incompatible response tendencies. This leads to an increased probability of errors and slower execution of the correct response on conflicting (incongruent) trials. Conflict, however, may also impact performance on subsequent trials. In the next section, this possibility will be explored in depth.

1.3 Sequential modulation of the congruency effect: The congruency sequence effect

The magnitude of the congruency effect has been found to be modulated by the congruency of the previous trial. Gratton, Coles, & Donchin (1992) demonstrated that the congruency effect on trial N is smaller if trial N-1 was incongruent, compared to when it was congruent (Fig. 1.1), in other words, the difference in performance between incongruent trials that were preceded by an incongruent trial (iI trials) and congruent trials that were preceded by an incongruent trial (iC trials) is smaller than the difference between incongruent trials that were preceded by a congruent trial (cI trials) and congruent trials that were preceded by a congruent trial (cC trials). This effect has since then come to be known as the congruency sequence effect (CSE). The authors originally proposed that this pattern appears because participants can adjust the weights assigned to the target- and distractor-related pathways based on their expectancy regarding the congruency of the upcoming trial which, in turn, is based on the congruency of the current trial, i.e., people tend to expect the congruency condition to repeat, so they give more weight to the distractor-related pathway following a congruent trial in preparation for another congruent trial, than after an incongruent trial. In later studies, however, this subjective expectancy-based explanation has been largely abandoned (Jiménez & Méndez, 2013, 2014) in favour of a different cognitive control account, the conflict monitoring theory (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Botvinick, Cohen,

& Carter, 2004). According to this account, the CSE reflects conflict adaptation: conflict (interference) on incongruent trials is detected by a dedicated conflict monitoring unit in the cognitive system, and cognitive control is up-regulated in response, leading to a decrease in the congruency effect on the following trial. After congruent trials, control is transiently down-regulated. In other words, according to the conflict monitoring theory, the CSE reflects dynamic adjustments of top-down control levels.

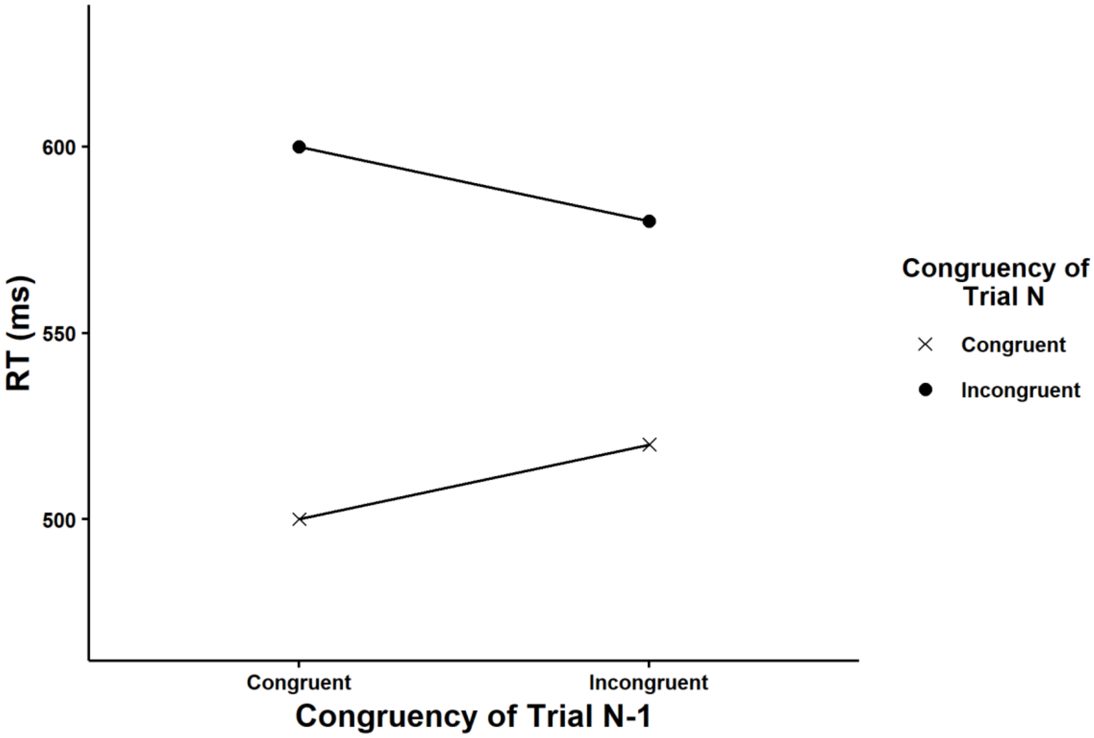


Figure 1.1 – Illustration of the congruency sequence effect (CSE) in RT. The congruency effect – the difference between the two lines - is smaller following incongruent compared to following a congruent trial. This figure is not based on real data; it is merely a visual representation of the ideal CSE pattern.

In computational terms, Botvinick et al. (2001) extended the Stroop and flanker models of Cohen et al. (1990, 1992) by adding a conflict monitoring unit that monitors the response layer of the model for the co-activation of responses, i.e., the occurrence of conflict. When such conflict is detected (e.g., on incongruent trials), the conflict monitor signals to the task demand unit or the spatial attention unit which then exerts control by biasing the task-relevant pathway over the task-irrelevant pathway (e.g., the colour-naming pathway over the word-reading pathway in the Stroop task) in advance of the next trial.

Although conflict adaptation is indubitably the most prominent account of the CSE (Duthoo, Abrahamse, Braem, Boehler, & Notebaert, 2014a; Egner, 2007), there are alternative explanations as well that do not invoke any control-related mechanisms, and are based on learning and memory related processes. The first of these is the feature integration account (Hommel, Proctor, & Vu, 2004; Mayr, Awh, & Laurey, 2003). This posits that in most early studies of the CSE, simple trial-by-trial repetition effects can explain the sequential modulation pattern. Exact stimulus repetitions (i.e., where two successive trials are identical) speed responding, and in a typical 2-alternative version of conflict tasks (e.g., a Stroop task with only two colours, red or green), such exact repetitions can only occur on cC trials, or iI trials. These two trial types are exactly those two conditions where speeding occurs (Fig. 1.1) generating the CSE pattern. In other words, cC trials are faster than iC trials, and iI trials are faster than cI trials, and this may simply be because all complete trial repetitions are either cC or iI trials. There is also evidence that partial repetitions – i.e., repeating only one of the two features used on trial N-1 on trial N, e.g., RED in green followed by GREEN in green – which can only occur on cI or iC trials can actively *slow* performance (Hommel et al., 2004). According to Hommel et al. (2004) this is because on trial N-1, trial features including stimulus dimensions and the associated responses are bound together into a temporary event file-like representation, and if any of these features is activated on trial N, the rest of the representation is activated along with it. This now irrelevant representation first needs to be unbound and overwritten before a response can be given, leading to prolonged RTs in conditions with partial repetitions. In conclusion, the lower level mechanisms of repetition priming and/or feature integration can fully account for the CSE pattern.

One way complete and partial repetitions can be avoided either by design or by excluding them later during analysis, is to increase the number of stimulus features from 2 to 4 or any higher number. However, 4-alternative task variants create another confound which can account for the CSE pattern without invoking conflict-related control mechanisms. In such tasks, researchers typically aim to keep the proportion of congruent and incongruent trials equal, 50% each. However, this usually means that any given task-irrelevant feature will appear three times as often with its corresponding congruent task-relevant feature as it will with any of the other task-relevant features (Mordkoff, 2012). For instance, in a Stroop task with four colours, RED, GREEN, BLUE, and YELLOW, the word RED would have to appear three times as often in the colour red than in any of the other colours, in order to keep the congruency proportion balanced. This, however, creates a contingency between the colour red and the word RED, so the task-relevant feature and its corresponding task-irrelevant feature, making the task-irrelevant feature slightly predictive of the correct response, calling into question its “task-irrelevant” nature. This is a problem for the control accounts of the CSE because in a 4-alternative conflict task, contingency and congruency are perfectly confounded (congruent trials are high contingency trials, and incongruent trials are low contingency trials), and Schmidt, Crump, Cheesman, & Besner (2007) found that not only was there a performance difference between highly contingent and low contingency trials in a simple colour identification task with no conflict, reminiscent of the congruency effect, but this contingency effect was also modulated by previous trial contingency, in a fashion that precisely matches the CSE in conflict tasks. As such, trial-by-trial changes in contingency can also account for the CSE in 4-alternative conflict tasks with 50% congruent trials.

Some early studies that allowed feature repetitions to occur but controlled for them *post-hoc*, either by excluding them from analysis or by including repetition status as a variable failed to detect the CSE (e.g., Chen & Melara, 2009; Mayr et al., 2003;

Nieuwenhuis et al., 2006), while others found it even in the repetition-free subset of trials (e.g., Bugg, 2008; Kerns et al., 2004; Ullsperger, Bylsma, & Botvinick, 2005). Two studies controlling for contingency learning as well did not find a reliable CSE (Mordkoff, 2012; Schmidt & De Houwer, 2011). More recent studies, however, have attempted to control for feature repetitions and contingency learning *a priori*, by not allowing either to occur in the trial sequence because it is possible that top-down control changes may only occur as a last resort, in the absence of lower level memory biases that could otherwise guide performance (Bugg, 2014). These studies have mostly succeeded in detecting the CSE (e.g., Aschenbrenner & Balota, 2017; Duthoo, Abrahamse, Braem, Boehler, & Notebaert, 2014b; Schmidt & Weissman, 2014; Weissman, Colter, Drake, & Morgan, 2015, and partly, Weissman, Jiang, & Egner, 2014) providing support for the conflict adaptation account.

Importantly, these latter findings do not invalidate the feature integration and contingency learning accounts either, merely suggest that the CSE can appear in the absence of such mechanisms too. Interestingly, these low-level learning processes and higher level control processes do not appear to be independent, they have been found to interact to generate the CSE (Weissman, Hawks, & Egner, 2016) supporting an episodic retrieval based hybrid account of the effect according to which a memory is formed on each trial in conflict tasks that includes not only concrete stimulus features and responses (as described above), but more abstract information as well, such as the congruency of the trial and the associated control settings (Grant & Weissman, 2019; Spapé & Hommel, 2008). Congruency repetitions, but not congruency alternations, will then lead to facilitated retrieval of control settings, and increased performance. In a similar vein, a recent proposal by Abrahamse, Braem, Notebaert, & Verguts (2016) suggests that the dichotomy between learning and memory based accounts and top-down control based accounts of adaptive control effects, including the CSE is a false one, as both classes of processes are instances of associative learning: perceptual, motor, and goal representations (e.g., “inhibit pathway”, “switch task set”) that are active at the same time are bound together in an associative network, and the implementation of control is just the activation of goal representations by different perceptual representations that are connected to it within the network.

Finally, it is important to note that there is at least one further mechanism unrelated to top-down control that could account for the CSE, called temporal learning, which is more difficult to adequately control for both *a priori* and after the fact than feature repetitions and contingency learning, it could therefore explain previous findings that were taken as evidence for control adjustments. The temporal learning idea suggests that participants might be developing expectancies about when to respond on trial N based on their response speed on trial N-1 (Schmidt, 2013; Schmidt & Weissman, 2016). Put simply, it posits that they will expect to respond slowly after slower responses, and quickly after faster responses. In other words, participants might be modulating their response thresholds based on the response time information of the previous trial. Because responses on incongruent trials are generally slower than on congruent trials, the learning of the temporal structure of the task may be sufficient to generate the CSE (Schmidt & Weissman, 2016). Recent findings, however, suggest that evidence for the contribution of temporal learning to conflict task performance is inconsistent at best (Cohen-Shikora, Suh, & Bugg, 2018 who evaluated the account as an alternative to global, as opposed to trial-by-trial, top-down control adjustments).

In sum, research in the past two decades has demonstrated that in order to isolate the contributions of top-down control adjustments to the CSE, certain confounds, such as feature repetitions and target-distractor contingencies need to be controlled for in the design of the experimental tasks used to investigate the effect. Unfortunately, even after doing so it is impossible to guarantee that no other mechanisms, such as temporal learning, contaminate the pattern, however the weight of current empirical evidence favours a control-related interpretation in such a design.

1.4 The mechanisms of control adjustment

What changes in response to conflict to generate the CSE? There are two major alternative accounts that answer this question, the attentional shift hypothesis (e.g., Botvinick et al., 2001, 2004; Gratton et al., 1992) and the response modulation hypothesis (e.g., Grant & Weissman, 2019; Weissman, Egner, Hawks, & Link, 2015). Both are situated *within* the top-down control interpretation of the effect, that is, they both propose that control-related mechanisms are involved in the effect, but they differ in what these mechanisms exactly are.

The attentional shift hypothesis posits that the detection of conflict biases perceptual processing away from the distractor and/or to the target, resulting in smaller interference on the following trial. This idea was part of the original, expectancy-based account of the effect by Gratton et al. (1992), but it is also the mechanism proposed by the conflict monitoring theory (Botvinick et al., 2001, 2004). It is supported by neuroscientific evidence, such as the findings of Egner & Hirsch (2005) who showed that cortical responses to task-relevant information were amplified following conflict compared to following no conflict.

It is, however, also possible that control modulates the *responses* activated by different stimulus features instead of, or in addition to, the perceptual processing of such features. This response modulation account is based on dual-pathway models of conflict task performance as well (as introduced above, e.g., Cohen et al., 1990; Kornblum et al., 1990) which contain separate response activation pathways for the distractor and the target, and it posits that control processes inhibit the distractor-related response pathway to a greater extent following incongruent compared to congruent trials, when activation along that pathway would have led to an incorrect response (Ridderinkhof, 2002; Grant & Weissman, 2019; Weissman, Egner, et al., 2015). Some recent findings by Weissman et al. (2014, Weissman, Egner, et al., 2015) provide support for this account of the CSE. In two studies they found that the CSE was larger in a flanker-type task where distractors preceded the target (a prime-probe task) than in tasks without similar stimulus-onset asynchrony (SOA), presumably because this manipulation leaves more time available for the active suppression of the distractor-related response on the current trial (see also Gyurkovics et al., in principle acceptance). The extent of this active suppression should also be bigger after incongruent compared to congruent trials, generating the CSE pattern. Weissman, Egner, et al. (2015) also observed a negative congruency effect (incongruent RT < congruent RT) after incongruent trials with 1000 ms SOA between distractor and target (i.e., presumably resulting in strong inhibition of the distractor response), which is not compatible with the attentional shift account of the CSE as even when attention to the target is maximal, the congruency effect should only be 0 or close to 0, but not reversed in sign.

In more recent studies, Weissman and colleagues (Weissman, Colter, Grant, & Bissett, 2017; Grant & Weissman, 2019) offered another formulation of the response modulation hypothesis which they call the response cueing account, and which no longer considers the occurrence of conflict to be necessary for control to be engaged. This proposes that identifying stimuli that cue multiple different responses (e.g., a distractor/prime and a target) triggers proactive, preparatory control processes that inhibit the distractor-related response and/or activate the opposite response in the next trial. As opposed to the active suppression idea described above, this variant of the account does not require a dual pathway architecture, and suggests that it is sufficient that multiple responses are cued on a trial for the CSE to appear, neither of those responses has to be incorrect for control to be triggered. Across multiple experiments, the authors found that the CSE appeared in a prime-probe arrow flanker task even if participants had to respond to the prime arrows too, turning the distractors into targets. Prime arrows, therefore, could not engender “incorrect” response activation because the prime-related responses had to be executed as well before the appearance of the target. The authors propose that in this situation participants use the prime-related response to predict what the target-related response will be, based on previous trial congruency, i.e., if the previous trial was congruent (the prime and the target both required the same response), participants prepare the same response for the target as for the prime, whereas if it was incongruent, participants inhibit the prime-response and/or activate the opposite response, generating the CSE pattern. While this idea is still consistent with the active suppression of a response playing a part in the CSE, it reinterprets what triggers the effect (activation of multiple responses, instead of conflict between an incorrect and a correct response) and how it affects performance (via the prediction of the target response based on the prime and previous trial history, instead of minimizing task-irrelevant interference and/or amplifying task-relevant processing).

As we have seen, the response modulation account predicts that the magnitude of the CSE might differ across tasks, depending on their temporal structure (e.g., prime-probe vs standard flanker), but it still proposes a domain-general mechanism behind the CSE. Some findings, however, suggest that the mechanisms behind the CSE might be task-specific or at least be implemented in a task-specific way (Braem, Abrahamse, Duthoo, & Notebaert, 2014). Different conflict tasks engender different types of conflict – conflict between two stimulus features in the Stroop task; conflict between spatially segregated stimuli in the flanker, and conflict between an automatically activated response and stimulus identity in the Simon -, and it is possible that detection of a given conflict type only leads to adaptation to that conflict type, possibly through a dedicated conflict-control loop, which exists independently of other loops that are responsible for adaptation to other types of conflict (Egner, 2008). Empirical evidence for this hypothesis comes from studies that combined different types of conflict either factorially where every trial could either be congruent or incongruent with respect to both types of conflict (e.g., Akçay & Hazeltine, 2011; Wendt, Kluwe, & Peters, 2006), or in a task-switching manner where trials were alternating randomly between two different conflict types (e.g., Funes, Lupiáñez, & Humphreys, 2010; Verbruggen, Liefooghe, Notebaert, & Vandierendonck, 2005). Most such studies (albeit not all, see Braem et al., 2014 for a review) found the CSE within, but not between conflict types, suggesting a lack of transfer of control mechanisms from one conflict type to the other. Furthermore, Aschenbrenner & Balota (2017) found that while the magnitude of the CSE decreases with age in the Simon and the flanker tasks, it increases in the Stroop task, once again underlining that mechanisms behind the same pattern in different tasks might not be identical. This conclusion is also in line with recent findings that the CSE does not covary across different tasks, i.e., the magnitude of the CSE in one task does not correlate with the magnitude of the effect in another (Whitehead, Brewer, & Blais, 2018). This observation, however, could also be explained by the psychometric properties of the variables, such as the low reliability of the CSE when it is used as an individual difference measure. Incidentally, the largely domain- or task-specific nature of the CSE is also in line with the idea that the effect is a manifestation of associative learning (e.g., Abrahamse et al., 2016) as control then should only affect representations that are bound together in a given associative network (e.g., that belong to the same task set).

Finally, it is also possible that even within the same task the CSE does not reflect one mechanism (e.g., a top-down modulation of response activation), but a combination of mechanisms. Using reach tracking variants of standard conflict tasks, i.e., tasks in which participants have to reach out with their hands to a target location, and this motion is recorded and analysed, Erb and colleagues (Erb & Marcovitch, 2018; Erb, Moher, Sobel, & Song, 2016; Erb, Moher, Song, & Sobel, 2018) have been able to identify two processes that are both modulated by congruency and previous trial congruency, and might be responsible for the CSE pattern in conjunction: the first process is a threshold adjustment process which is a temporary inhibition of motor output in response to conflict (participants are generally slower to initiate a movement after conflict), and the second is a controlled selection process triggered by conflict which allocates resources to the target-related pathway as opposed to the distractor-related pathway (and is manifested in movements that are less drawn to the incorrect response location). This conceptualization of the CSE is still located within the top-down control framework, and depending on the exact nature of the controlled selection progress, can be compatible with either top-down sub-hypothesis detailed in this section (perceptual modulation vs response modulation). However, these findings further highlight how complex the determinants of the CSE are.

In sum, the exact mechanism or mechanisms of control adjustment are not clearly defined, and they may vary from task to task (or they might be implemented in different ways depending on the task). As such, it is advisable to use multiple tasks to measure the CSE in studies of dynamic control regulation to increase the generalizability of findings, as was done, for instance, in the study presented in Chapter 3 of this thesis.

1.5 Neural substrates and correlates of the CSE

A well-established finding in cognitive neuroscience is that the core brain region of the neural circuitry behind cognitive control is the prefrontal cortex (PFC; Diamond, 2013; Gratton et al., 2018; Miller & Cohen, 2001). This area has rich connections with other cortical and subcortical areas, which enables it to effectively bias processing and behaviour in favour of internal goals (Miller & Cohen, 2001). In line with the region's central role in control, areas within the PFC are consistently found to be activated during response inhibition performance as well (e.g., Hazeltine, Poldrack, & Gabrieli, 2000; Ridderinkhof, van den Wildenberg, Segalowitz, & Carter, 2004; Rubia, Smith, Brammer,

& Taylor, 2003). One strength of the conflict monitoring theory is that it provides a clear account of the CSE on the neural level, situating it within this traditional control-related neural circuitry. It suggests that the dorsal anterior cingulate cortex (dACC) is responsible for monitoring the processing stream for conflict as supported by a wealth of neuroimaging data (e.g., Barch et al., 2001; Botvinick, Nystrom, Fissell, Carter, & Cohen, 1999; Van Veen, Cohen, Botvinick, Stenger, & Carter, 2001). Once conflict is detected, the ACC sends a signal to the dorsolateral prefrontal cortex (DLPFC) which then upregulates control (Botvinick et al., 2001, 2004). In recent years, it has been proposed that these two areas are situated within two, dissociable networks in the brain that support different control functions – the ACC is part of the cingulo-opercular (CO) network supporting task-set maintenance, and the DLPFC is part of the frontoparietal (FP) network involved in moment-to-moment adaptive control (Gratton, Sun, & Petersen, 2018).

Studies using electroencephalography (EEG) to investigate neural responses to different stimuli (event-related potentials, ERPs) have also identified ERP components that are theorized to reflect conflict monitoring processes (Larson, Clayson, & Clawson, 2014). The most prominent of these, the N2 is a frontocentral negativity in flanker tasks whose amplitude is larger on incongruent compared to congruent trials (van Veen & Carter, 2002a, 2002b; Yeung, Botvinick, & Cohen, 2004; Larson et al., 2014). It has also been found to show the CSE pattern, i.e., its magnitude is modulated not only by current trial congruency but also by previous trial congruency (e.g., Clawson, Clayson, & Larson, 2013; Clawson, Clayson, Keith, Catron, & Larson, 2017; Clayson & Larson, 2011a; 2011b; 2013; Larson, Clawson, Clayson, & South, 2012). While these studies have all contained feature repetition confounds, Feldman & Freitas (2018) have also found sequential N2 modulation (i.e., N2 CSE) in a newly developed complex Stroop-like task without feature repetitions or distractor-target contingencies. To the best of our knowledge, however, the CSE has not been investigated in the N2 component using a confound-minimized variant of a classic conflict task thus far. A de-confounded prime-probe flanker-like task, however, has been used by Larson, Clayson, Kirwan, & Weissman (2016) who found a CSE in a parietal component (the conflict slow potential; SP) and the frontomedial N450. The N2 and the N450 are both hypothesized to originate from the ACC (Hanslmayr et al., 2008; Ladouceur, Dahl, & Carter, 2007; Liotti, Woldorff, Perez, & Mayberg, 2000; Yeung et al., 2004; van Veen & Carter, 2002a) lending further support to the neural architecture proposed by the conflict monitoring theory.

The oscillatory dynamics of conflict detection and adaptation have also been investigated via electrophysiological methods. Neural oscillations are rhythmic fluctuations of electrical activity in the brain, that can occur in a wide range of frequencies (Clayton, Yeung, & Cohen Kadosh, 2015; Cohen, 2014a). Oscillations in the 4-8 Hz frequency band, the so-called theta band, have been the focus of intense research in the cognitive control literature (Gratton et al., 2018), especially concerning conflict resolution (Cohen, 2014a). Power in the theta band over midfrontal regions – most likely including the ACC - has been shown to increase in response to conflict (e.g., Cohen & Donner, 2013; Hanslmayr et al., 2008; Nigbur, Cohen, Ridderinkhof, & Stürmer, 2012; Nigbur, Ivanova, & Stürmer, 2011), and this theta conflict effect has also been found to be modulated by previous trial congruency (Bombeke, Langford, Notebaert, & Boehler, 2017; Gulbinaite, van Rijn, & Cohen, 2014; Jiang, Zhang, & van Gaal, 2015; Pastötter, Dreisbach, & Bäuml, 2013). Furthermore, theta oscillations appear to play a role in the long-range communication between midfrontal and other, task-relevant cortical regions (Cavanagh, Cohen, & Allen, 2009; Nigbur et al., 2012), and thus, may be involved in transmitting the conflict signal to sensory, motor, or attentional systems. Based on these findings, Cohen (2014a) proposed a midfrontal neural microcircuit in which the different layers of the cortex serve specific functions, e.g., conflict detection or the broadcasting of the conflict signal, and generate a theta rhythm. In this proposal, the CSE reflects synaptic augmentation of deeper layer (layer 5) pyramidal cells responsible for conflict detection, meaning that these neurons are more excitable immediately following periods of excitation (e.g., due to conflict on an incongruent trial) than after a longer period with no stimulation (e.g. due to the previous trial being congruent).

In sum, midfrontal regions of the brain (the ACC in particular) are thought to be involved in conflict detection, and potentially the broadcasting of the conflict signal through theta oscillations to frontal brain regions that form part of a frontoparietal control network. These ideas informed the design of the study reported in Chapter 4, where I used EEG to examine how this neural circuitry changes across adolescence during conflict task performance. In the next section, I will outline some fundamental findings and unanswered questions regarding cognitive control development, with a special emphasis on adolescence, as one of the key aims of my thesis was to explore age-related changes in the CSE both at the neural and behavioural levels, across the adolescent period.

1.6 The development of cognitive control

There is evidence that both the structure and the dynamics of cognitive control change across the first decade of life. In terms of structure, it is hypothesized that executive functions (processes that largely overlap with cognitive control processes, Gratton et al., 2018) transition from a unitary function to a multicomponent (e.g., tripartite) construct during maturation, suggesting a differentiation of higher-order cognition as a function of age (Bardikoff & Sabbagh, 2017; Brydges, Fox, Reid, & Anderson, 2014; Lee, Bull, & Ho, 2013; Miller, Giesbrecht, Müller, McInerney, & Kerns, 2012). There is some, albeit limited evidence from latent variable analysis studies supporting the differentiation hypothesis, with inhibition and updating differentiating first, and shifting emerging the latest, in early adolescence (see Karr et al., 2018 for a recent review underlining the potential methodological confounds that could also explain this pattern). Performance on tasks measuring either factor consistently shows improvement across the preschool years (Best & Miller, 2010). With respect to the dynamics of control, experimental findings suggest that a qualitative shift occurs after the age of 6, whereby new control strategies emerge (e.g., verbalization and the dominance of preparatory, proactive control) which are then coordinated more flexibly to meet the demands of a given task (Chatham, Frank, & Munakata, 2009; Chevalier, 2015; Chevalier, Huber, Wiebe, & Andrews Espy, 2013; Chevalier, Martis, Curran, & Munakata, 2015, Lucenet & Blaye, 2014).

Changes in cognitive control across the second decade of life have also been extensively researched (Best & Miller, 2010; Blakemore & Choudhury, 2006). Most accounts of cognitive control development in this period come from models of adolescent risk-taking (Shulman et al., 2016). Adolescence is a transitional period following childhood that by most definitions starts at the onset of puberty, around age 10, and lasts until the beginning of adulthood. Defining this endpoint is challenging, as it does not refer simply to the attainment of adult status in the legal sense of the word (e.g., at 18 or 21 years of age) because individuals even at the age of 21 are often not regarded as fully mature adults outside the legal system (Shulman et al., 2016). Adolescence as a developmental stage might extend as far as 24 years of age, based on the protracted maturation of the brain (described in more detail below) and the delayed timing of important role transitions, such as the completion of education or the start of married life (Sawyer, Azzopardi, Wickremarathne, & Patton, 2018).

Risk-taking and impulsive behaviour peak during adolescence (Steinberg, 2004, 2007), and according to prominent models of developmental changes in adolescence, this is partly because cognitive control abilities are still undergoing maturation (Shulman et al., 2016). This class of theories is known as dual systems models because they propose that increased risk-taking in adolescents is a result of the interplay between two neural systems involved in decision-making (Casey, Getz, & Galvan, 2008; Duckworth & Steinberg, 2015; Luna & Wright, 2016; Somerville, Jones, & Casey, 2010; Steinberg, 2008, 2010). The first one is a socio-emotional system that controls sensitivity to rewards, and biases decision-making in favour of the pursuit of incentives. The second one is a cognitive control system that encompasses many of the processes ascribed to cognitive control in the present chapter, and is also the foundation of self-regulation and impulse control. The first system is hypothesized to be reliant on dopaminergic pathways, and subcortical limbic structures, while the second is supported by the frontal (frontoparietal) neural circuitry introduced above (Casey et al., 2008; Steinberg, 2008). The models posit that these two systems follow different developmental trajectories, and heightened risk-taking in adolescence is a consequence of a more mature/hyper-reactive socio-emotional system amplifying the effect of incentives on behaviour, and a still maturing cognitive control system that is unable to adequately restrain the former. The models mostly differ in terms of the supposed trajectory of the socio-emotional system: Steinberg (2008) and Luna & Wright (2016) propose a peak in mid-adolescence, followed by a decrease from adolescence to adulthood, whereas Casey et al. (2008) posit a simple maturational trajectory where the socio-emotional system instead reaches a plateau (adult-like levels) in mid-adolescence. Most importantly for the discussion of cognitive development, all models propose that the cognitive control system continues to mature in adolescence, either more or less linearly into the twenties (Casey et al., 2008; Steinberg, 2008), or with a deceleration of changes occurring after mid-adolescence (Luna & Wright, 2016).

The notion that cognitive control is still maturing after the end of childhood is supported by neurobiological findings (Blakemore & Choudhury, 2006; Ordaz, Foran, Velanova, & Luna, 2013), namely the observation that PFC activity, structure, and connectivity mature at a slower pace than most other cortical or subcortical regions, and are still actively undergoing changes across adolescence (e.g., Adleman et al., 2002; Casey, Galvan, & Hare, 2005; Gogtay et al., 2004; Yurgelun-Todd, 2007). How exactly PFC engagement during task performance changes as a result (i.e., increases, e.g., Rubia et al., 2006, or decreases, e.g., Durston et al., 2002, Ordaz et al., 2013) appears to be dependent on the exact subregion of the PFC being investigated, the paradigm that is being used, and the type of control that is required (Crone & Dahl, 2012; Crone & Steinbeis, 2017; Luna, Padmanabhan, & O'Hearn, 2010). Notably, the dACC, another key region of the cognitive control network(s), also undergoes protracted maturation, showing a linear increase in activation during error processing from 9 to 26 years (Ordaz et al., 2013).

In general, the activation of the cognitive control circuitry is thought to become more focal and functionally specialized as a function of age (relevant activity increases, irrelevant activity decreases; Casey et al., 2005; Casey, Tottenham, Liston, & Durston, 2005; Durston et al., 2006; Kelly et al., 2009). Network integration also increases in this period, meaning that the functional collaboration between specialized networks subserving different components of control within the circuitry become stronger (Grayson & Fair, 2017; Kelly et al., 2009; Luna et al., 2010; Luna, Marek, Larsen, Tervo-Clemmens, & Chahal, 2015; Satterthwaite et al., 2013). This is supported by maturational changes in the adolescent brain, such as the continued pruning of redundant synapses (Petanjek et al., 2011) and the increase in white matter pathway integrity due to myelination (Simmonds, Hallquist, Asato, & Luna, 2014), both of which improve the signal-to-noise ratio of neuronal communication.

Behavioural performance in studies of cognitive control provides some support for the continued maturation of this construct (Huizinga, Dolan, & van der Molen, 2006; Shulman et al., 2016), and suggests that what is still changing is not the *ability* to generate a correct response, but the *rate* of correct responses (Luna et al., 2010). When focusing on conflict resolution in particular, however, findings are mixed. In accordance with the idea of attentional control becoming more fine-tuned in adolescence, some studies report a decrease in the congruency effect at least during the early years of this period. Using a flanker task, Waszak, Li, & Hommel (2010) found that the magnitude of the effect only reaches adult levels after the age of 15 (see also Li, Hämmerer, Müller, Hommel, & Lindenberger, 2009). The effect similarly levels off in the flanker after mid-adolescence (age 15) in Huizinga et al. (2006), but these authors also reported a continued improvement into early adulthood in conflict resolution in the Stroop task, similarly to the findings of Marsh et al. (2006). Leon-Carrion, García-Orza, & Pérez-Santamaría (2004) and Prencipe et al., (2011) also found that the Stroop effect decreases with age in adolescence, although their studies did not include adults or late adolescents (age ranges were 6-17 and 8-15 for the two studies, respectively). Some studies, however, found no age differences in the size of the congruency effect. These studies used the Stroop task, and investigated 7-22 year-olds (full range of adolescence; Adleman et al., 2002), 14-25 year-olds (mid-adolescence to young adulthood; Andrews-Hanna et al., 2011), or 18-19 year-old late adolescents compared to 23-25 year-old young adults (Veroude, Jolles, Croiset, & Krabbendam, 2013). Finally, also using the Stroop task in 10-30 year-olds Duell et al. (2018) found a slight increase in the size of the effect in RT, but a decrease in accuracy. Rubia et al. (2006) also reported a weak positive correlation between age and the congruency effect in a Simon task, using a similarly broad age range (10-43). In sum, while the neural mechanisms behind control are still going through considerable changes, this is not always reflected in behavioural differences across different stages of adolescence, as even early adolescents (10-13) can perform at adult-like levels.

Differences in findings regarding the developmental trajectory of conflict processing might be attributable to methodological differences between studies, e.g., in sample sizes, the exact age groups that were used, or the conflict type the given task engenders. It is worth reiterating at this point that indicators of conflict resolution from different conflict tasks tend to correlate poorly (e.g., Hedge, Powell, & Sumner, 2018; Huizinga et al., 2006; Rey-Mermet et al., 2018, 2019), and while this phenomenon may have simple psychometric explanations (e.g., low reliability, Hedge et al., 2018), it is also in line with the idea that there are multiple independent conflict-control loops in the cognitive system (Egner, 2008) which may, in turn, have slightly different developmental trajectories.

Next, we turn to the question of whether the detection of conflict leads to top-down control mobilization, as indicated by the CSE, in children and adolescents. If yes, is the magnitude of top-down control mobilization similar in these groups to adults? Based on the conflict monitoring theory, there are at least three processes necessary for the CSE to appear – conflict detection, signalling the need for control, and control deployment -, and participants with less mature cognitive systems might differ in each one of them from adults. As reviewed above, *conflict experience* changes across maturation, but its exact trajectory during adolescence is unclear. However, since conflict magnitude and CSE magnitude are not closely and consistently related (e.g., Weissman et al., 2014; Gyurkovics et al., in principle acceptance), this trajectory would not be the most informative in formulating a prediction regarding the development of the CSE in any case. Once conflict has been detected, the necessity to upregulate control needs to be *signalled* to the control unit. This signalling process may still be undergoing changes in adolescence, given that neural models suggest that communication between components of the control circuitry is still maturing in its efficiency in this period (Hwang, Velanova, & Luna, 2010; Luna et al., 2015; Marek, Hwang, Foran, Hallquist, & Luna, 2015). Finally, the ability to *deploy control* in response to the incoming conflict signal might also be deficient in adolescence, due to the protracted maturation of the prefrontal cortex. Thus, the CSE pattern is likely to undergo changes across development if (or when) it indicates control-related processes. In the next section I will summarize the findings of developmental studies of the CSE thus far. This overview will not be limited to adolescence, because studies focusing on that developmental period are extremely rare.

In a comprehensive study, Ambrosi, Lemaire, & Blaye (2016) tested 5-6-year-olds using a Stroop, a flanker, and a Simon task, and found that the CSE is already present in 5-6-year-olds in all three tasks. Iani, Stella, & Rubich (2014) also detected the pattern in 6-8-year-olds using the Simon task. 12 year-old early adolescents showed conflict modulation as well in the flanker (Nieuwenhuis et al., 2006, Exp. 5; Stins, Polderman, Boomsma, & de Geus, 2007) and the Simon (Stins et al., 2007). All of these studies, however, contained feature integration confounds that were not controlled for, or were only controlled for *post-hoc*, not *a priori* (Nieuwenhuis et al., 2006), consequently it might be premature to conclude that top-down control modulation is already present by 5 years of age based on these findings. Furthermore, these studies did not contrast performance of younger participants with that of an adult comparison group, thereby precluding conclusions about how the magnitude of the effect changes with age. Studies that did investigate the developmental trajectory of the CSE have quite consistently found that its size does not appear to change substantially with age (at least after pre-adolescence). Larson et al. (2012) used a Stroop task to investigate conflict monitoring in 8-11-year-olds and 19-30-year-olds, and found no age differences in the effect at either the behavioural or the neural level (in EEG event-related potentials). In the only confound-minimized developmental study of the effect to date that I am aware of, Cragg (2016) found that the CSE does not interact with age in a flanker task in a sample of 7-, 10-, and 20-year-olds. Surrey, Kretschmer-Trendowicz, Altgassen, & Fischer (2019), however, found no significant CSE in reaction times in a number Stroop task in 9- and 12-year-olds, while young adults (19-33) did show the classic pattern with the same paradigm. In line with the idea that the ability to modulate control is still not fully developed by 12, Waxer & Morton (2011) found that 9-11 year-olds show smaller or no modulations in RT and conflict-related ERP components (the N2 and the N4) than 14-15 year-old mid-adolescents did in a card sorting task with a conflict component and an additional task-switching manipulation. However, this latter group did not differ from 18-25 year-old adults in terms of the size of the effect. Conversely, Smulders, Soetens, & van der Molen (2018) found that the CSE *decreases* with age in the Simon (and other tasks of inhibition) in a sample of 7-9-year-olds, 10-12-year-olds, and 18-25-year-olds; however, this pattern did not survive controlling for baseline speed differences between groups. Furthermore, all three of these studies contained confounds complicating the interpretation of findings (although such confounds were minimal in the Surrey et al. study due to a large stimulus set). Finally, using a reach-tracking variant of the flanker task, Erb & Marcovitch (2018) found that both the threshold adjustment process and the controlled selection process discussed in the previous section mature with age, however the former reaches adult-like (18-24-year-olds) levels by pre-adolescence (10-12) and the latter still changes between pre-adolescence and adulthood.

Based on this review of the literature the following conclusions can be drawn: 1) confound-minimized studies of age-related changes in the CSE are badly needed to understand how top-down control mobilization develops. It is especially important to control for learning and memory confounds such as feature repetitions and contingencies *a priori*, by avoiding them in the trial sequence of tasks because if they are present, more costly top-down control mechanisms may not be engaged (Bugg, 2014). 2) All adult comparison groups were at least partly or completely comprised of late adolescents (18 – early 20s) meaning that it was unclear what exactly adult-like performance looked like in these studies. 3) The sole study with a confound-minimized design (Cragg, 2016) used a single task only. It might be advisable to use multiple tasks to investigate if findings can be generalized from one domain to another (Egner, 2008; Smulders et al., 2018). For instance, as mentioned above Aschenbrenner & Balota (2017) recently found divergent trajectories of the CSE as a function of age across three tasks in an aging study, with the effect getting smaller in the Simon and the flanker tasks, but increasing in magnitude in the Stroop. 4) Most developmental studies thus far focused on children and pre-adolescents, while the investigation of adolescence-related changes has been somewhat neglected. 5) While the previous four observations limit the interpretability of developmental findings, it is still worth noting that previous studies rarely found robust differences between adults and younger participants in terms of the size of the CSE. This is surprising given that if we accept the conflict monitoring account of the effect, the CSE reflects the interaction between a conflict monitoring unit in the ACC and a prefrontal control unit, and such between-network communication is hypothesized to still be maturing across adolescence (see network integration, Luna et al., 2015). This makes the investigation of the neural mechanisms behind the CSE across development a particularly interesting endeavour (Larson et al., 2012).

The studies reported in the present thesis were designed to address these issues and questions. Chapter 3 presents an investigation of the CSE in two tasks (the Simon and the flanker tasks) with confound-minimized designs, across the full range of adolescence, from early adolescence (12-13-year-olds) to young adulthood (25-27-year-olds). Confound-minimized designs were used as an attempt to isolate control-related processes as well as possible. Multiple tasks were used to test whether developmental trajectories, if they were to appear, are task-specific or not. Finally, an adult group over even the most liberal upper bound of adolescence (24; Sawyer et al., 2018) was tested to ensure that we capture adult performance as a reference.

The study presented in Chapter 4 investigated neural correlates of the CSE by recording EEG while early adolescents and young adults performed a confound-minimized flanker task. To the best of my knowledge, this is the first study using a classic conflict task without any additional manipulations and devoid of learning and memory confounds in conjunction with EEG. It is also most likely the first to do so developmentally. We investigated not only the N2, but midfrontal theta dynamics as well to gain insights into potentially ACC-mediated conflict detection processes in adolescence. We also examined functional connectivity between midfrontal and lateral prefrontal regions in the two age groups, as a potential indicator of conflict signalling.

The studies reported in Chapters 2 and 5 were designed to answer somewhat different questions. The study reported in Chapter 2 investigated the core assumption of a recent account of the CSE which proposes that it is the aversive nature of the conflict signal that motivates control regulation after conflicting trials (Dreisbach & Fischer, 2015). This was pilot work undertaken in healthy undergraduates (late adolescents and adults), and its aim was to establish a paradigm that could investigate the affective aspects of control regulation in future developmental work. Due to the inconclusive findings of this study, this avenue of inquiries was not pursued further.

Finally, the study reported in the penultimate chapter investigated a potential correlate of the CSE in healthy adults. It examined the relationship between the CSE and lapses in attention (mind-wandering). The rationale for this study was largely empirical: a tentative association between being focused on the task at hand and the magnitude of conflict-related sequential modulation emerged in Chapters 3 & 4. The construct of mind-wandering and how it might be related to cognitive control will be introduced in the appropriate chapters in more detail.

In sum, the purpose of my thesis studies was to learn more about if and how the dynamic aspects of cognitive control and response inhibition in particular change as a function of age in the adolescent period. Additional aspects of the attentional system, such as the propensity to mind-wander, and how it relates to dynamic adjustments of control were also explored

Chapter 2 - Is Response Conflict an Aversive Signal?

Abstract

The conflict monitoring theory argues that once response conflict is detected in a conflict task such as the Stroop, flanker, or Simon tasks, cognitive control is upregulated as a consequence. What motivates this mechanism, i.e., why does conflict lead to the mobilization of control? A recent account proposed by Dreisbach & Fischer (2015) suggests that conflict is an aversive signal and control is recruited in order to counteract the negative affective state elicited by such a signal. Direct evidence for this idea comes from affective priming studies (Fritz & Dreisbach, 2013, 2015) in which neutral target stimuli were judged more negatively after viewing incongruent Stroop prime stimuli (e.g., the word RED in green) as compared to after congruent prime stimuli (e.g., the word RED in red), possibly due to the carry-over of valence information from the prime to the target. This effect was also found to reverse after longer prime durations suggesting that negative affect was actively counter-regulated over time. In the present study, I attempted to conceptually replicate this finding in a sample of 34 healthy undergraduates (mean age = 19.38, SD = 3.88). Participants had to evaluate Chinese characters that were presented immediately after incongruent or congruent Stroop prime stimuli. Prime stimuli were presented for 200, 400, or 800 ms. No effect of prime congruence or prime duration were found on target evaluation, even though the sample size and number of observations by condition matched those of the original studies. It is possible that changes in design compared to the original studies (e.g., within-subject prime duration manipulation instead of between-subject) reduced the effect in our sample making it harder to detect.

2.1 Introduction

In Chapter 1, cognitive control was introduced as a construct that refers to a collection of cognitive processes involved in setting and maintaining task-relevant goals and suppressing task-irrelevant goals (Gratton et al., 2018). The dynamic aspects of cognitive control were then described in more detail, primarily through the introduction of research on the congruency sequence effect (CSE), the finding that the effect of cognitive conflict on performance is smaller following conflicting, incongruent trials than after non-conflicting, congruent trials (Gratton et al., 1992). In the present chapter I will outline a pilot study that was conducted to investigate what might motivate this effect. Briefly, it has recently been hypothesized that cognitive conflict is aversive, and adjustments of control are aimed at down-regulating the negative affective state elicited by such conflict (Dreisbach & Fischer, 2015). The present study attempted to replicate a key finding of this account (to be described below) in healthy adults, with the goal of establishing a paradigm that could be used in future, developmental studies looking at the behavioural consequences of the aversive conflict signal (e.g., control regulation) across adolescence. Foreshadowing the results, we were unable to reliably replicate the key effect, thus the focus on affective aspects of the CSE was dropped from future studies.

2.1.1 What motivates control regulations?

The most prominent account of the CSE, the conflict monitoring theory (Botvinick et al., 2001, 2004) suggests that the effect reflects conflict-induced behavioural adaptation: once cognitive conflict is detected in the processing stream by a dedicated conflict monitoring unit, cognitive control is strengthened, leading to smaller interference on the following trial. As detailed in the previous chapter, there is a wide variety of hypotheses regarding *how* this control adjustment occurs (e.g., modulation of stimulus processing, modulation of stimulus-evoked response activations), but there have been fewer attempts at clarifying *why* it occurs. Why does cognitive conflict lead to the recruitment and/or sustained engagement of presumably costly control processes especially given that the nature of the upcoming trial is unpredictable? Recently, Dreisbach & Fischer (2015) proposed that the reason for this phenomenon is that cognitive conflict is an aversive experience, and thus, generates an aversive signal, a transient negative state which motivates the strengthening of cognitive control. Control is recruited to down-regulate this signal and to avoid further negative affect. As such, conflict adaptation is a special case of affect regulation.

The central claim of this account is that cognitive conflict is aversive. Findings in the literature provide both indirect and direct support for this notion. Indirect evidence, for instance, includes results that have shown that the anterior cingulate cortex (ACC) is sensitive not only to control signals such as conflict (Botvinick et al., 2001, 2004) but to negative affective events as well, suggesting that the ACC may be a hub where aversive signals relevant for performance are integrated into action control (Botvinick, 2007; Cavanagh & Shackman, 2015; Saunders, Lin, Milyavskaya, & Inzlicht, 2017; Shackman et al., 2011). More direct evidence, however, comes from studies using affective priming paradigms that have originally been developed to gauge the affective valence of attitude objects. In the classic version of such paradigms (e.g., Fazio, Sanbonmatsu, Powell, & Kardes, 1986), negative/positive affective primes are presented before negative/positive affective targets that participants have to categorize according to their valence. Primes that match the valence of the target speed target valence judgments, whereas mismatching primes slow them, purportedly because primes automatically activate an attitude which then facilitates the processing of stimuli of similar valence, and impairs the processing of dissimilar stimuli. Based on the assumption that congruent and incongruent stimuli have affective valence, Dreisbach & Fischer (2012) used Stroop stimuli (colour words, printed in different colours) as primes in an affective priming task. Primes were viewed passively; participants did not have to respond to them. In accordance with their account, participants were faster to categorize negative targets as negative following incongruent primes (e.g., the word RED printed in green) than after congruent primes (e.g., the word RED printed in red). Furthermore, they showed that neutral stimuli are judged more negatively following incongruent primes compared to congruent primes possibly because the valence of the prime transfers to the target (Fritz & Dreisbach, 2013). These results suggest that conflict stimuli are aversive, and this affective information influences judgments on subsequent events.

In a recent study, Fritz & Dreisbach (2015) investigated the time course of the presumed aversive conflict signal in an affective priming paradigm. Findings showed that when primes were presented briefly, for 200 ms or 400 ms, neutral stimuli were judged more negatively following incongruent stimuli than after congruent stimuli, replicating previous findings. However, when presentation duration was increased to 800 ms, the effect was reversed: neutral stimuli were judged more positively following incongruent primes than following congruent primes. The authors suggest that this was because conflict persisted longer in the latter condition, and this protracted negative signal initiated processes that counter-regulated the affective state initially automatically elicited by the prime. Participants may also have implicitly resolved the conflict in the long prime duration condition, and resolved conflict is hypothesized to foster positive affect, not negative (see Schouppe et al., 2015 for a similar conclusion). The reversal in conflict-induced priming with longer prime duration was subsequently replicated in an EEG study by a different research group (Pan, Shi, Zhang, Lu, & Xue, 2016).

Both of the studies cited above (Fritz & Dreisbach, 2015; Pan et al., 2016) used a between-subject design to manipulate prime duration. In the present study, we attempted to replicate the effect of prime duration using a within-subject design. The reason for this was primarily methodological. We were interested in creating a paradigm that is sufficiently powerful to detect prime-related changes in subsequent target evaluation, and is more economical than a between-subject design in terms of number of subjects required (and consequently, length of data collection period). The end goal of creating such a paradigm was to then use it in a series of studies investigating the time course and the magnitude of the aversive conflict signal across adolescence.

A further deviation from the design of Fritz & Dreisbach (2015) was the nature of the neutral target stimuli which were not words in our paradigm. Instead, in accordance with Fritz & Dreisbach (2013), Chinese characters were used, as we argue that neutrality can be better approximated with unfamiliar non-figurative stimuli than with purportedly neutral words that participants could have complex associations with. Further changes include applying a more differentiated, four-point response scale instead of a simple binary (positive/negative) categorization. We expected to find that Chinese characters would be judged more negatively following incongruent primes compared to congruent primes in the short prime duration conditions (200 ms and 400 ms), but more positively in the long duration condition (800 ms). As an additional question of interest, we also investigated whether trait anxiety modulates the perceived aversiveness of cognitive conflict. High trait anxiety is known to impair cognitive control, and one mechanism for this might be through modulating the cognitive conflict signal and its relative aversiveness (Inzlicht, Bartholow, & Hirsh, 2015). Hypotheses regarding this question were exploratory in nature.

2.2 Method

We report how we determined our sample size, all data exclusions (if any), all manipulations, and all measures in the study. Data files and the analysis script for this study are available on the Open Science Framework at the following URL: https://osf.io/yaj36/.

2.2.1 Participants

Thirty-four (30 females) undergraduate students (mean age = 19.38, *SD* = 3.88) from the University of Sheffield took part in the study. Two additional participants were excluded because they reported that they are or have been taking medication for anxiety. In order to match the data exclusion criteria of Fritz & Dreisbach (2015), we also planned to remove anyone with mean performance accuracy (see below for explanation) below 75%, and with a proportion of negative/positive judgments higher than 75%, however, no participants in the sample met these criteria. Participants were all native speakers of English, right-handed, and received course credit for taking part. We aimed to collect a sample that was at least as large as the largest sample (30) reported by previous studies using a similar design (Fritz & Dreisbach, 2013, N = 24; Fritz & Dreisbach, 2015, N_{max} = 30 in a single group; Pan et al., 2016, N = 20). The study was approved by the Ethics Committee of the University of Sheffield.

2.2.2 Procedure

Following a short colour vision test (Ishihara tables), participants completed a computer task designed using E-Prime 2.0 software (Psychology Software Tools, Pittsburgh, PA), in which they had to evaluate Chinese characters that were preceded by word primes. On each trial, participants first saw a fixation cross for 250 ms on a grey background. This was followed by the presentation of the prime, for either 200 ms, 400 ms, or 800 ms with equal probability. The colour words RED, GREEN, BLUE, and YELLOW were used as primes, printed in red, green, blue, or yellow. A prime was congruent if the meaning of the colour word and the colour it was shown in matched (e.g., RED in red), and was incongruent if they did not (e.g., RED in green). 50% of the primes were congruent. No response was required to prime stimuli. The prime was then immediately followed by the target, until response. 360 Chinese characters served as targets. These characters were drawn randomly from a complete list of simplified Chinese characters, published online by Denis Roegel in 2008 (retrieved from https://members.loria.fr/Roegel/publications.html in October, 2016). After response, a blank screen was displayed for 1000 ms, then the next trial started.

Participants were instructed to press one of four buttons on a six-button response box to evaluate the targets. The rightmost button was labelled '++' and was described in the instructions as indicating a judgment of "positive", whereas the leftmost button was labelled '--' meaning "negative". Out of the two buttons in between, the right one was labelled '+' meaning "slightly positive", and the left one was labelled '-' meaning "slightly negative." Participants were instructed to try and use both sides of the scale – negative and positive - equally frequently (i.e., to counter potential negativity or positivity biases). The valence – response side mapping was held constant across participants (i.e., positive buttons were always on the right, negatives always on the left) because it has been shown that individuals tend to associate positive/negative valence with their dominant/non-dominant side (Casasanto, 2009, also see Fritz & Dreisbach, 2013, 2015), and all participants were right-handed (i.e., right was their dominant side) in our sample.

The two remaining buttons of the response box were used on catch trials. Like in previous studies (Fritz & Dreisbach, 2013, 2015), catch trials were included to ensure that participants were paying attention to and processing the primes. In our task, on these trials the prime was not followed by a target, but by the question: "Was the colour of the previous word X?". On 50% of catch trials, X was the correct answer, whereas on the remaining 50% it was not. Participants indicated "yes" or "no" using the two buttons of the response box. 50% of catch trials followed congruent primes, and 50% followed incongruent primes. 72 catch trials were intermixed randomly into the experimental task, leading to a total of 432 trials (360 experimental trials + 72 catch trials). Every 72 trials, participants could take a short, self-paced break, resulting in 6 blocks of trials. Before the main task, participants completed a short practice session with 20 regular trials (these 20 targets did not reoccur during the main task), and 4 catch trials. During practice only, feedback was provided after each catch trial.

Following the computer task, participants filled in two questionnaires to measure trait anxiety; the trait-version of the State-Trait Anxiety Inventory (STAI; Spielberger, 1989) and the Depression, Anxiety, Stress Scale (DASS; Lovibond & Lovibond, 1995). The trait-version of the STAI consists of 20 statements about different thoughts and emotional states, and participants have to indicate on a 4-point scale how much the items describe them generally. The DASS contains 21 statements about thoughts and emotional states, and participants have to indicate on a 4-point scale how much each statement has applied to them during the previous week. The scale has three subscales: Depression, Anxiety, and Stress.

Participants also completed brief questionnaires on risk-taking (de Haan et al., 2011) and approach and avoidance behaviour (Reuter, Cooper, Smillie, Markett, & Montag, 2015), however, these were not analysed further because no hypotheses or exploratory research questions were formulated regarding these two constructs and control. The measures were only collected to gain insight into the reliability of the questionnaires for future use in our lab. Data for these questionnaires can be found on the project's OSF website.

The whole session lasted approximately 45 minutes.

2.2.3 Statistical analyses

Data was analysed using general and generalized linear mixed-effects models (LMEs) as fitted by the "lme4" package in R (Bates, Maechler, Bolker, & Walker, 2015). These models are an extension of simple linear regressions, but they allow the intercepts and slopes of the fixed effects (predictors) of interest to vary across different variables, known as random effects. They are particularly useful for hierarchical data with nonindependent observations, such as in the present study, where observations from each trial (level 1 of the hierarchy) are nested within participants (level 2 of the hierarchy). In this case, for example, the intercept and slope of the effect of prime congruency on target evaluation (a fixed effect) can be set to vary from participant to participant (the random effect), and the model tests whether the fixed predictor has an effect on the outcome above and beyond the variability due to the random effect. General linear mixed-effects models are an extension of general linear models (e.g., multiple linear regression), while generalized linear mixed-effects models are an extension of generalized linear models (e.g., binary logistic regression). In practical terms one important difference between the two classes of models is that mixed-effects models use all observations available (i.e., trial level data) and control for their dependence by specifying which observations belong together (e.g., by coming from the same participant), while non-mixed-effects models use aggregated data (e.g., mean reaction time of a participant) to circumvent the non-independence of the trial-level observations.

For the exploratory analysis of catch trial accuracy, a generalized linear mixed-effects approach was used, with predictors Prime Congruency (coded as 0 and 1 for congruent and incongruent, respectively), Prime Duration (with the shortest duration – 200 ms - serving as the reference category), Catch Trial Type (coded as 0 and 1 for match and mismatch, respectively), and their interactions. Catch Trial Type coded whether the correct answer to the catch trial question was “yes” – the colour mentioned in the question matches the colour of the preceding prime – or “no” – the colour mentioned and the colour of the prime do not match. Following the analyses reported by Fritz & Dreisbach (2015), we also analysed RT to the target character (decision time), using a linear mixed-effects model with Prime Congruency and Prime Duration as categorical predictors, Target Evaluation as a continuous predictor, and their interactions. For the hypothesis-driven analysis of target evaluation, a general linear mixed-effects model with predictors Prime

Congruency, Prime Duration, and their interaction was used. For all three models, the random effects structure was determined by examining the Akaike Information Criterion (AIC) values of models with random structures of varying complexity, ranging from no random slopes, only random intercepts per participants to models containing random slopes for the interaction of predictors by participant. The model with the lowest AIC value was selected. For the target RT and target evaluation analyses, after determining the random structure by participants, the random effects of individual target characters were also entered into the model (i.e., the effects of the fixed predictors were allowed to vary from target to target as well), and their structure was determined similarly. The Type II ANOVA table of the final model generated by the Anova() function from the "car" package (Fox & Weisberg, 2019) is reported.

For the target evaluation and target RT analyses, trials where decision time was extremely fast (< 150 ms) or extremely slow (> 3000 ms) were removed. This resulted in the removal of 4.42% of trials. Fritz & Dreisbach (2015) reported no such filtering, however, we considered it best to remove responses a) that are less likely to be the outcome of conscious deliberation, and b) where the decision was made so far away from the prime that its effect might have considerably dissipated by then. Importantly, this filtering does not have a substantial impact on the results as primary findings do not change whether the analyses are run with or without this step.

2.3 Results

2.3.1 Catch trial performance

Participants were instructed to try and use both sides (positive and negative) of the response scale equally often when responding. To investigate whether this successfully counteracted any negativity or positivity biases in responding, we examined the mean frequency of positive responses across participants (responses “slightly positive” and “positive” were grouped together as positive responses, with the other two responses being negative). The mean frequency was 50.18% (*SD* = 10.11), which was not significantly different from 50%, *t*(33) = 0.103, *p* = .919, suggesting that there was no detectable positivity or negativity bias in the sample.

Next, we examined performance on catch trials to see if participants were actually processing the colour dimension of the prime stimuli. Catch trial accuracy was high in the sample (*M* = 95.67%, *SD* = 4.94). Mean accuracy as a function of catch trial type is shown in Fig. 2.1.

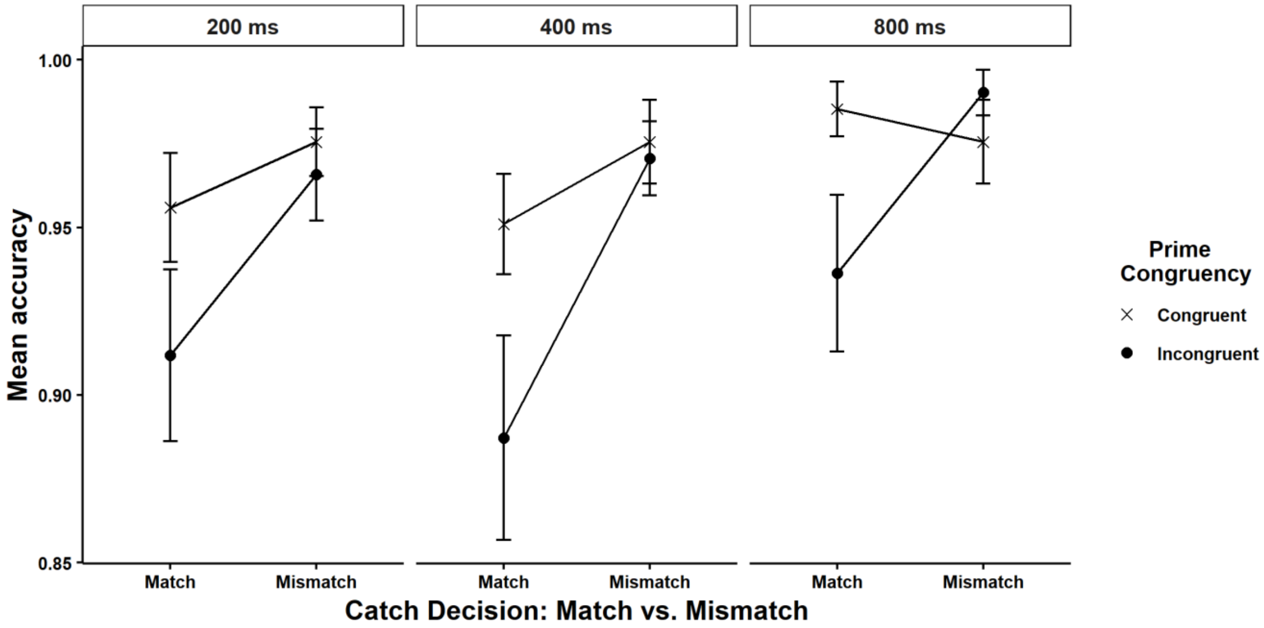


Figure 2.1 - Mean accuracy on catch trials as a function of Prime Duration (panels), Catch Trial Type, and Prime Congruency. Error bars represent ± 1 SEM.

The generalized mixed-effects model exploring the effects of catch trial type on accuracy that was selected only contained random intercepts per participant (AIC value: 800.04, all competing models were higher). It revealed a main effect of Prime Congruency, $OR = .453$, 95% CI [.164, 1.036], $\chi^2(1) = 10.05$, $p = .002$, whereby participants were more accurate after congruent compared to incongruent primes. Participants were also more accurate on mismatch trials compared to match trials, $OR = 1.883$, 95% CI [.558, 10.262], $\chi^2(1) = 18.64$, $p < .001$, an effect that interacted with Prime Congruency, $OR = 1.543$, 95% CI [.226, 8.451], $\chi^2(1) = 4.57$, $p = .033$. As depicted in Fig. 2.1, the prime congruency effect was smaller for mismatch than for match trials. The most likely reason for this is that on incongruent mismatch catch trials participants often saw a third colour as the probe colour that was not present at all in the prime, making the decision relatively easy, compared to incongruent match trials. An example of incongruent mismatch would be seeing the word "RED" in green, and then being asked if the colour of the prime word was yellow. An example of incongruent match would be seeing "RED" in green, then being asked if the colour of the prime was green. Finally, time had a main effect as well, $\chi^2(2) = 6.74$, $p = .034$. This was due to participants being significantly more accurate in the 800 ms condition than in the 400 ms condition ($p = .038$).

Fritz & Dreisbach (2013, 2015) reported no analyses of RT on catch trials as in their design, no response was made on these trials (participants had to withhold responding after certain primes). In our design, RT was also available as catch trials required a response, consequently we explored the effects of Prime Congruency, Catch Trial Type, and Prime Duration on RT on correct catch trials, using a general linear mixed-effects model (Figure 2.2). RTs below 150 ms an above 3000 ms were removed, just like for target RT analyses (Section 2.3.2). Main effects of congruency and catch trial type were found, $\chi^2(1) = 30.10$, $p < .001$ and $\chi^2(1) = 87.79$, $p < .001$ respectively, as participants were slower to make decisions following incongruent compared to congruent primes, and on mismatch compared to match trials. A weak three-way interaction was also found, $\chi^2(2) = 6.41$ $p = .041$. This was due to a significant interaction between Prime Congruency and Catch Trial Type whereby the effect of congruency was greater for match than mismatch trials, that was only present in the 200 ms condition ($p = .015$), but not the other two.

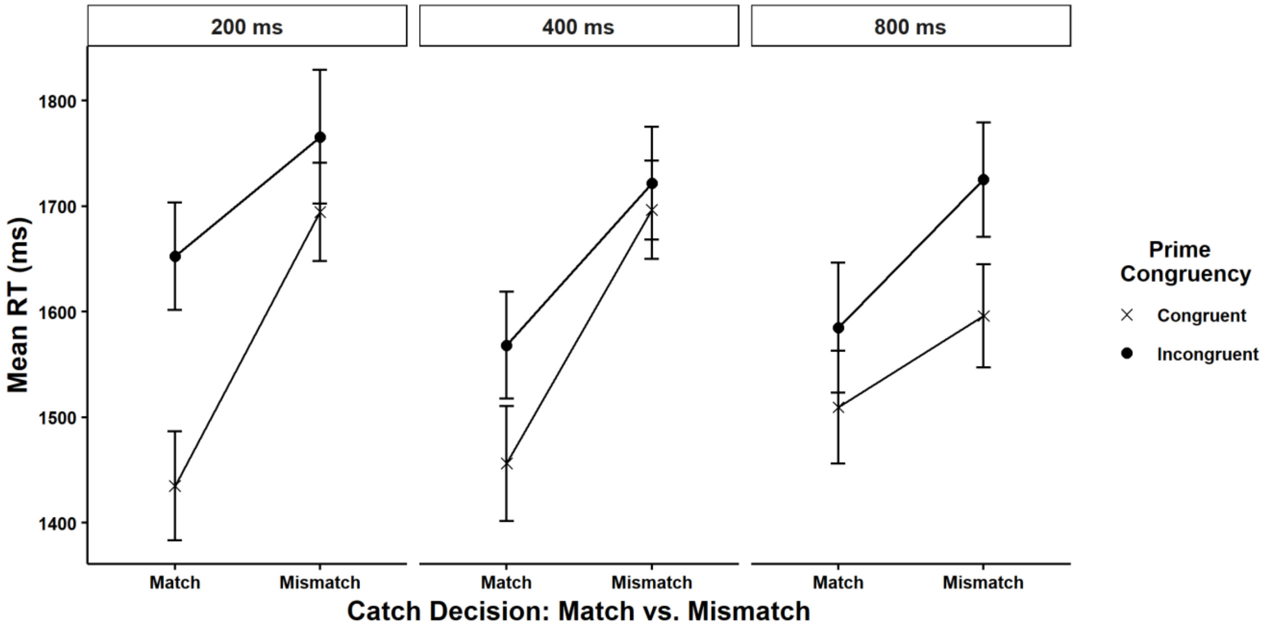


Figure 2.2 - Mean reaction time on catch trials as a function of Prime Duration (panels), Catch Trial Type, and Prime Congruency. Error bars represent ± 1 SEM.

In conclusion, the congruency of primes had a detectable impact on catch trial performance suggesting that participants processed the colour information as well as word meaning on primes.

2.3.2 Reaction time to neutral targets

In accordance with previous studies, RT to target characters was also analysed, to see if decision time differed as a function of prime features and/or the eventual decision that was made (positive/negative). The model that was selected contained random slopes for Target Evaluation per participant (AIC value: 174828.50, all competing models were higher). This revealed an effect of Prime Congruency, $\chi^2(1) = 11.64$, $p < .001$. Replicating Fritz & Dreisbach (2015) Exp. 2, participants were slower to respond following an incongruent prime (mean RT = 1071.42, *SD* = 271.99) compared to following a congruent prime (mean RT = 1041.59, *SD* = 232.67). The main effect of Prime Duration was also significant, $\chi^2(2) = 17.23$, $p < .001$. Participants were slower after 200 ms primes (mean RT = 1078.01, *SD* = 260.61) than in the 400 ms condition ($p < .001$; mean RT = 1044.41, *SD* = 257.14) or the 800 ms condition ($p = .002$; mean RT = 1047.11, *SD* = 248.72). The latter two conditions did not differ from each other. No other main effects or interaction effects approached significance (all χ^2 values < 3.5, *p*s > .13).

2.3.3 Target evaluation

Next, target evaluation data was analysed to investigate our two main hypotheses regarding Prime Congruency and the interaction between Prime Congruency and Prime Duration. Figure 2.3 illustrates target evaluation across the three Prime Duration conditions as a function of Prime Congruency.

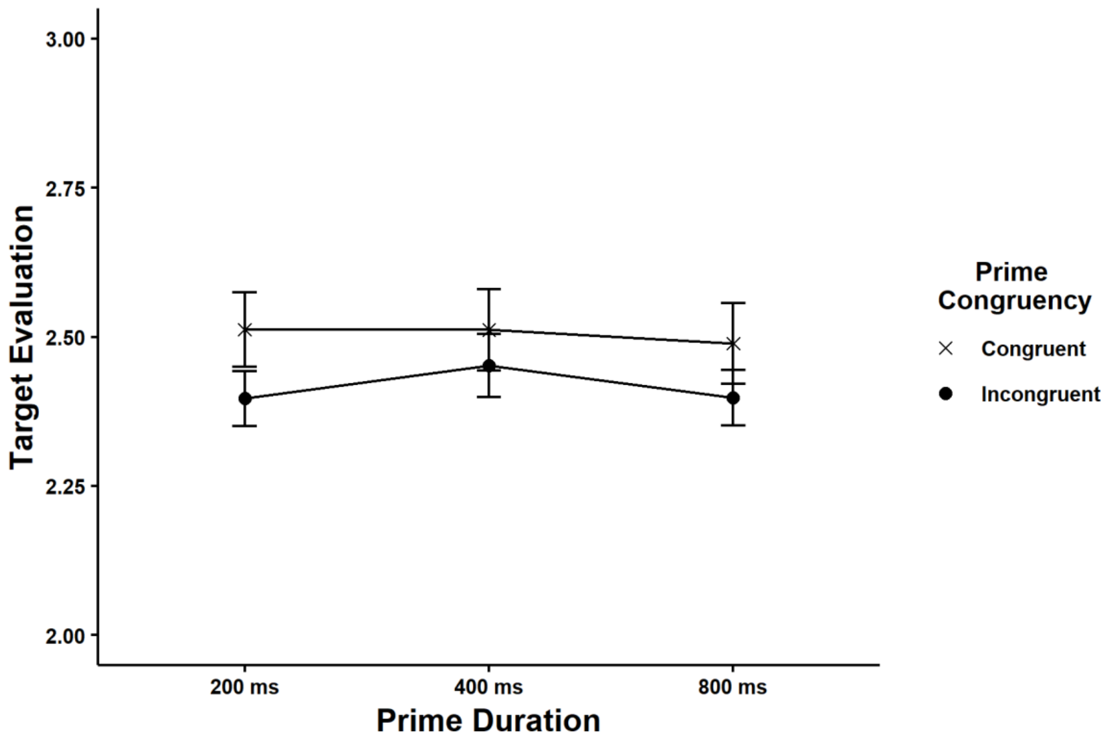


Figure 2.3 - Mean target evaluation as a function of prime congruency and prime duration. Lower scores on Target Evaluation mean a more negative evaluation, with the neutral midpoint being between 2 and 3. Error bars represent ± 1 SEM.

The final model that was selected contained random slopes for Prime Congruency per participant and random intercepts for individual target characters (AIC value: 34274.24, all competing models were higher). It revealed no significant effects (Prime Congruency: $\chi^2(1) = 2.23$, $p = .136$; Prime Duration: $\chi^2(2) = 2.59$, $p = .273$; Prime Congruency × Prime Duration: $\chi^2(2) = 1.59$, $p = .451$).

To explore whether dispositional anxiety had an effect on performance, the above model was rerun twice with anxiety scores added as a predictor: once using STAI trait anxiety scores and once using the Anxiety subscale of the DASS. Neither of them interacted significantly with any of the other terms (all interactions involving anxiety: χ^2 values < 2.5, *p*s > .30). The two measures of anxiety were correlated with each other in our sample, Kendall's $\tau = .65$, $p < .001$.

Finally, we conducted two control analyses to examine whether the null findings regarding Prime Congruency are a consequence of our analytic strategy to use a four-point scale as a continuous outcome variable. To this end, we dichotomized target judgments by labelling "slightly negative" and "negative" responses as negative, and "slightly positive" and "positive" responses as positive, just like we did for the investigation of potential valence biases. This made our data more similar to that of the original studies by Fritz & Dreisbach (2013, 2015). First, a 3 (Prime Duration) × 2 (Prime Congruency) ANOVA was run with proportion of positive evaluations as the outcome, which was the analytic approach used by previous studies. This identified no significant effects (all Fs < 2.1, ps > .135). Finally, a generalized linear mixed-effects model was run that was identical to our previous target evaluation model, but used the binary evaluation variable as the outcome. This also revealed no significant effects (χ^2 values < 4.5, ps > .10).

2.4 Discussion

The present study investigated the time course of the affective signal elicited by cognitive conflict, using a within-subject design. As a secondary aim, we also explored the role of trait anxiety in how cognitive conflict is evaluated. We failed to replicate the results of Dreisbach and colleagues (Dreisbach & Fischer, 2012; Fritz & Dreisbach, 2013, 2015) who have found that congruent and incongruent trials can effectively be used as prime stimuli in affective priming studies, impacting the processing of affective stimuli or the evaluation of neutral stimuli presented subsequently. Specifically, in our sample no evidence was found that neutral stimuli are judged more negatively following incongruent trials compared to congruent trials, albeit the effect was present numerically, i.e., Chinese characters following incongruent Stroop primes were judged more unfavourably than those following congruent Stroop primes. This, however, failed to reach the level of statistical significance.

Prime congruency did have some effect on behavioural performance, suggesting that conflict was detected by participants. Participants were slower and less accurate on catch trials – included precisely to ensure engagement with the primes – following incongruent compared to congruent primes hinting that participants typically processed both prime dimensions (colour and meaning), and their decision making was impacted by conflict between those dimensions. However, focus on the task-relevant aspect was generally maintained, as indicated by accuracy rates that were far from floor. Prime congruency also had a small effect on the evaluation time of subsequent targets. As such, it is unlikely that our failure to obtain a reliable effect was due to participants not experiencing conflict on incongruent primes or not processing primes at all.

There are a number of reasons that could explain the null findings concerning our hypotheses. First, it is possible that the study was underpowered. Even though the current sample size matched – and slightly exceeded – those obtained by Fritz & Dreisbach, the number of observations per participant may still be too low to detect a small effect. Although trial number in the present study was substantially larger than in previous studies, the number of within-subject conditions was also increased (i.e., due to the additional prime duration manipulation). It is possible that in a more complex design such as ours, trial number should have been increased further. Nevertheless, low trial count is unlikely to explain the lack of a prime *congruency* effect given that trial numbers by congruency condition were higher than in previous studies (180 vs. 48, Fritz & Dreisbach, 2015; 96, Fritz & Dreisbach, 2013), and a more powerful analytic approach was used (linear mixed-effects models vs. ANOVAs).

Second, in the current study participants had to execute a more complex cognitive process in order to evaluate the target than in previous studies. While in previous studies (Dreisbach & Fischer, 2012; Fritz & Dreisbach, 2013) participants categorized the target as either positive or negative (a binary choice), in the present setup they had to rate them on a four-point scale. It is possible that the more complex task of choosing from four different alternatives is more resistant to previous stimulus influences (i.e., the effect of prime congruence) than the simpler task of selecting one of two judgments. Future studies are necessary to empirically test this possibility. To examine whether our analytic strategy to treat a four-point scale as a continuous variable contributed to the weakened effects in our sample, we also conducted control analyses where target responses were dichotomized into positive and negative categories matching the setup of the original studies. These analyses also revealed no significant effects.

Third, it is possible that target complexity may have had an effect as well, in addition to or instead of task complexity, as discussed in the previous paragraph. Targets in the present study were more complex and novel than in the original Fritz & Dreisbach (2015) study that investigated the time course of the aversive signal (Chinese characters vs. neutral words). Importantly, however, Chinese characters had already been used in an earlier study (Fritz & Dreisbach, 2013) in which the conflict priming effect was detected successfully. Thus, it seems unlikely that a change in target complexity could fully explain the findings (or lack thereof).

Finally, it is possible that a change in the nature of catch trials could have affected the results in some way. In previous studies, participants had to withhold responding to targets and perform a different response if the prime was of a particular colour (purple), essentially creating the analogue of a Go-No Go paradigm or a prospective memory task. There was no such additional load in the present study, as catch trials occurred independently of prime features (i.e., unpredictably). It could be argued, however, that this introduced a different type of extra load, namely that participants had to hold the colour of the prime in working memory on all trials, as they had no means of predicting if the subsequent event – following the prime – will be a target or a catch question. As there was no delay between the two events (the second event followed the prime immediately), this working memory load is unlikely to be substantial; however, it is still possible that it weakened the effects of prime congruency in some way.

Not only was there no significant effect of prime congruency in the data, there was also no hint of a reversal in the longest prime duration condition (800 ms; see Fritz & Dreisbach, 2015; Pan et al., 2016). Chinese characters were always evaluated more favourably – albeit only numerically as emphasized above – after congruent trials compared to incongruent trials, regardless of prime duration. It is possible that participants did not engage in affective counter-regulation because on the majority of trials (66%) prime duration was too short for that to be effective or necessary, and since primes were not blocked according to duration (i.e., they were randomly intermixed) the participant had no way to predict at the onset whether a given trial would be long (minority) or relatively short (majority of trials). Future studies are required to investigate whether a prime duration effect can be detected within-subject with different designs, such as ones where the proportion of long primes is higher or ones where prime duration is cued before prime onset.

Trait anxiety was also found to have no significant effect on target evaluation or as a moderator of conflict priming. Even though individuals with higher levels of anxiety tend to show an increased neural response to conflict and errors (Cavanagh & Shackman, 2015), this is typically not translated into stronger control regulation as cognitive control is often found to be deficient in anxious individuals (Berggren & Derakshan, 2013; Bishop, 2009; Eysenck & Derakshan, 2011). One proposed reason for this is that the aversive conflict signal essentially gets drowned out by task-irrelevant threat signals in these individuals (Inzlicht et al., 2015). This could have been reflected in the evaluation of neutral stimuli in our study as well; for instance, either as a main effect of anxiety on target evaluation (negativity bias) or as a congruency × anxiety interaction with a decreased difference between congruent and incongruent primes as a function of anxiety. More powerful studies might be able to uncover evidence for such effects, however, in our sample anxiety and conflict priming appeared to be largely unrelated.

While we were unable to reliably establish conflict priming in the present study, there is an abundance of different findings in the literature that suggests conflict is indeed aversive (for a recent review, see Saunders et al., 2017). For example, Braem et al. (2017) found that ACC response was diminished to negative (positive) images following incongruent (congruent) Stroop trials, in line with the idea that the successive presentation of similar stimuli reduces the neural response to the second stimulus (repetition suppression, e.g., Grill-Spector, Henson, & Martin, 2006). Furthermore, studies have indicated that response conflict elicits changes in arousal similar to those associated with emotional stimuli, such as changes in pupil dilation (Van Steenbergen & Band, 2013). It has also been shown that unexpected, performance non-contingent rewards between trials eliminate the CSE, probably because they counteract the negative affective state elicited by conflict and thus, disrupt the motivation for conflict adaptation (Van Steenbergen, Band, & Hommel, 2009). Recently, in an EEG study Fröber, Stürmer, Frömer, & Dreisbach (2017) directly tested the causal role of aversive signals in control regulation: after each trial in a Simon task, participants rated how pleasant they found that given trial. Suppression of automatic response activation on the following trial was greater following unpleasantly vs pleasantly rated trials, irrespective of conflict. In sum, there is strong evidence from various paradigms and designs to support the idea that conflict is aversive, and some evidence to suggest that this aversiveness has a causal role in subsequent action control.

In conclusion, the present study yielded inconclusive results. Neither the simple conflict priming effect – a difference between congruent and incongruent prime conditions -, nor its interaction with prime duration was detected. Unfortunately, it is hard to determine which feature of the current design might be behind the failure to replicate the original findings because a number of dimensions of the original paradigm were altered simultaneously, leading to uncertainty with respect to why the findings do not parallel those of the original studies. Regardless of the exact reason for this conceptual replication failure, it was decided that future studies in my PhD will focus on the mechanisms of control adjustments instead of the potential affective aspects of their origin. The first such study will be introduced in Chapter 3.

A Note Regarding Chapter 3

The second study of my PhD has been accepted for publication and is currently (September 2019) in press at the *Journal of Experimental Psychology: General*. The following chapter contains the manuscript of this upcoming publication in the form it was accepted in, with two alterations: 1) the numbering of sections, tables, and figures has been made consistent with the rest of the thesis, and 2) a new figure (Fig. 3.1) has been added.

Three supplemental tables and two supplemental figures have been created for this publication, these have been placed at the end of Chapter 3, after the conclusion of the text.

Reference

Gyurkovics, M., Stafford, T., & Levita, L. (in press). Cognitive control across adolescence: Dynamic adjustments and mind-wandering. *Journal of Experimental Psychology: General*.

Chapter 3 - Cognitive Control Across Adolescence: Dynamic Adjustments and Mind-Wandering

Abstract

Models of cognitive development suggest that cognitive control, a complex construct that ensures goal-directedness even in the face of distractions, is still maturing across adolescence. In the present study, we investigated how the ability to dynamically adjust cognitive control develops in this period of life, as indexed by the magnitude of the congruency sequence effect (CSE) in conflict tasks, and how this ability might relate to lapses of attention (mind-wandering, MW). To these ends, participants from four age groups (12-13, 14-15, 18-20 and 25-27 year-olds) completed confound-minimized variants of the flanker and Simon tasks, along with a Go/No Go task with thought probes to assess their frequency of mind-wandering. The CSE was present in both tasks, but was not affected by age in either of them. In addition, the size of the CSE in the flanker, but not in the Simon task was negatively associated with the frequency of MW with awareness. Trait MW and the probability of reporting MW during the task was found to increase with age in accordance with cognitive resource views of MW. Our findings suggest that at the behavioural level there are no substantial developmental changes through the adolescent period in control adjustment ability as measured by the CSE. Response inhibition performance in the Go/No Go task, however, improved significantly with age. The implications of the present results for the conflict monitoring account of the CSE and extant theories of MW are discussed.

3.1 Introduction

Cognitive control refers to a collection of processes involved in setting and adjusting attentional biases in order to carry out goal-relevant actions (Gratton, Cooper, Fabiani, Carter, & Karayanidis, 2018). According to multiple models of development, these processes are still maturing and improving across adolescence (e.g., Casey, Getz, & Galvan, 2008; Luna, Marek, Larsen, Tervo-Clemmens, & Chahal, 2015; Luna & Wright, 2015; Steinberg, 2008; Steinberg et al., 2018); a period of life defined here as beginning around the age of 10 and lasting until one's mid-twenties (Casey, 2015; Shulman et al., 2016). Neurobiological findings support the notion of protracted development as many control-related brain areas are still maturing and their activation patterns are still changing across this developmental period (for reviews, see Casey, Galvan, & Hare, 2005; Casey & Jones, 2010; Luna et al., 2015), such as those of the prefrontal cortex (PFC; Gogtay et al., 2004; Spear, 2000) or the anterior cingulate cortex (ACC; Eshel, Nelson, Blair, Pine, & Ernst, 2007).

At the behavioural level, aspects of cognitive control are often gauged with the help of response inhibition tasks. Response inhibition is a component process of cognitive control that involves overcoming prepotent but momentarily goal-irrelevant responses in favour of goal-relevant ones (Gratton et al., 2018). Some studies have shown protracted maturation of response inhibition across adolescence as indicated by the rate of successful performance on tasks that require participants to withhold a dominant response that temporarily becomes incorrect (e.g., stop-signal tasks, Vink et al., 2014, or Go/No Go tasks, Braet et al., 2009; Carriere, Cheyne, Solman, & Smilek, 2010; Luna, Padmanabhan, & O'Hearn, 2010; Rubia et al., 2006; Somerville, Hare, & Casey, 2011; Stawarczyk, Majerus, Catale, & D'Argembeau, 2014). Studies using conflict tasks, on the other hand, have yielded somewhat inconsistent results. In these tasks, participants have to identify a task-relevant stimulus dimension while ignoring a task-irrelevant dimension. On congruent trials, the two dimensions prime the same response, whereas on incongruent trials, the irrelevant dimension primes an incorrect response. Performance is typically slower and less accurate on incongruent compared to congruent trials, a difference known as the interference or congruency effect. Some studies investigating adolescence found that the magnitude of the interference effect decreases with age (e.g., Huizinga, Dolan, & van der Molen, 2006; Marsh et al., 2006; at least up to a certain point, e.g., 14-15 years of age, Waszak, Li, & Hommel, 2010), others found that it increases in reaction times (e.g. Duell et al., 2018; Rubia et al., 2006), but decreases in accuracy (e.g., Duell et al., 2018), while some found no change in the effect across adolescence at all (e.g., Adleman et al., 2002; Andrews-Hanna, Mackiewicz Seghete, Claus, Ruzic, & Banich, 2011; Veroude, Jolles, Croiset, & Krabbendam, 2013). This heterogeneity across studies might be in part due to methodological differences, e.g., the type of conflict task that was used, or the particular age ranges that were investigated.

Irrespective of the exact developmental pattern in behavioural interference resolution, it is clear that interference has an effect on performance in all age groups. One aspect of cognitive control that has received relatively little attention in the developmental literature thus far is how inhibitory control is adjusted dynamically in response to the occurrence of interference. It has been shown that the magnitude of the interference effect is modulated by the congruency of the previous trial, such that the congruency effect is smaller following incongruent compared to congruent trials (Duthoo, Abrahamse, Braem, Boehler, & Notebaert, 2014a; Gratton, Coles, & Donchin, 1992); a sequential modulation known as the congruency sequence effect (CSE). According to the most prominent account of the CSE, the conflict-monitoring theory (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Botvinick, Cohen, & Carter, 2004), this effect reflects a dynamic, top-down adjustment of control levels after conflict is detected by a dedicated conflict monitoring unit. At the neural level, the effect is considered to be a consequence of communication between the ACC which is responsible for the detection of conflict, and the dorsolateral PFC which is thought to modulate control levels (Botvinick et al., 2001; 2004). Because maturation of the cognitive system across adolescence is characterized by the refinement of communication between different neural systems supporting cognitive control (Luna et al., 2015), the CSE might be particularly sensitive to developmental changes in this period.

Therefore, the present study was designed to investigate how the ability to dynamically adjust control in such a manner changes across adolescence at the behavioural level, if at all. However, certain regularities in the task sequence of typical conflict tasks can make it difficult to interpret the CSE purely as an indicator of dynamic control adjustments (Duthoo et al., 2014a; Egner, 2007; Schmidt, 2013). We will briefly outline these learning- and memory-related confounds, to illustrate their effect on the interpretation of the CSE, and to highlight the importance of controlling for them.

In standard two-alternative variants of conflict tasks, exact stimulus repetitions on congruent trials preceded by congruent trials (cC trials) and incongruent trials preceded by incongruent trials (iI trials) will speed responding via response priming compared to congruent trials preceded by incongruent trials (iC trials) and incongruent trials preceded by congruent trials (cI trials), generating a CSE-like pattern (Mayr, Awh, & Laurey, 2003). Furthermore, Hommel, Proctor, & Vu (2004) suggested that even partial stimulus repetitions on cI and iC trials can complicate interpretations, as the repeated stimulus feature can activate the event file associated with the previous trial (i.e., a representation that contains both stimulus and response characteristics). As this outdated event file then needs to be overwritten, performance is slowed on these trials, once again resulting in a CSE-like pattern.

Increasing the number of stimulus features and responses used in the task from two to four can solve the feature repetition problem because complete and partial stimulus repetitions can be removed from analyses or avoided altogether. However, this solution introduces a new confound (Mordkoff, 2012; Schmidt & De Houwer, 2011). In a 4-alternative task, a 50% congruent trial sequence is typically generated by inflating the number of congruent trials compared to what would be expected if stimulus features were combined randomly. For example, to maintain 50% congruence in a four-arrow flanker task, a right-ward central arrow would have to be paired with right-ward distractors three times as often as with left-, up-, or down-ward arrows. This, would mean that a right-ward distractor is paired more often with a right-ward response than with any other response; in other words, a contingency would exist between the distractor and the congruent response. This would result in the supposedly task-irrelevant dimension becoming informative. Importantly, Schmidt, Crump, Cheesman, & Besner (2007) found that not only do individuals respond faster to high-contingency trials compared to low-contingency trials in a non-conflict task, the size of this contingency effect is also modulated by previous trial contingency. Since contingency is perfectly confounded with congruency in 4-alternative 50% congruent trial sequences, this sequential contingency modulation can account for the CSE-pattern as well. Therefore, it is important to control for the effects of stimulus repetitions and contingency learning if one wants to interpret the CSE in terms of control adjustments. Notably, recent studies have found the CSE pattern even after removing feature repetitions and target-distracter contingencies from the trial sequence, lending credence to the view that the CSE can occur in the absence of learning and memory confounds, presumably as a function of control adjustments (e.g., Aschenbrenner & Balota, 2017; Duthoo, Abrahamse, Braem, Boehler, & Notebaert, 2014b; Schmidt & Weissman, 2014; Weissman, Colter, Drake, & Morgan, 2015).

Developmental studies of the CSE in children found that 5-7- and 6-8-year-olds already show sequential modulation (Ambrosi, Lemaire, & Blaye, 2016; Iani, Stella, & Rubichi, 2014) and Larson, Clawson, Clayson, & South (2012) found no difference in the size of the CSE between 9 year-old children and 22-year-olds. Smulders, Soetens, & van der Molen (2018) also found no significant age differences between children, preadolescents, and a group of late adolescents and young adults (18-25 year-olds) after controlling for baseline speed differences between groups. These studies, however, have all contained either feature repetition or both feature repetition and contingency learning confounds. Notably, using a confound-minimized flanker task, Cragg (2016) also found no age difference in the CSE between 7-, 10-, and 20-year-olds, groups that might correspond to children, preadolescents, and late adolescents, respectively. Similarly, Waxer & Morton (2011) who used a complex modified conflict task with an additional task-switching manipulation, found no difference in the size of the CSE between mid-adolescents (14-15-year-olds) and an older group consisting of both late adolescents and young adults (18-25). One empirical finding, however, that supports the idea that some control-related processes show protracted maturation comes from a study by Erb & Marcovitch (2018) who decomposed the CSE into a response threshold adjustment process and the controlled, top-down selection of the target response using reach tracking, and found that the latter process showed significant gains between preadolescents (10-12 year-olds) and a group of both late adolescents and young adults (18-24 year-olds). Their task, however, also contained confounds, further underlining the necessity to study potential age-related changes in the CSE using confound-minimized paradigms where control-related processes are isolated, and appropriate adult comparison groups that do not overlap with late adolescence.

Consequently, the present study was designed to investigate changes in dynamic control adjustments across adolescence using confound-minimized variants of two commonly used conflict tasks, the flanker (Eriksen & Eriksen, 1974) and the Simon task (Simon, 1969), in four age groups: early adolescence (12-13-year-olds), mid-adolescence (14-15), late adolescence (18-20), and young adulthood (25-27). These two tasks were chosen because a recent study (Aschenbrenner & Balota, 2017) concluded that the CSE in these two paradigms likely reflects a cognitive control adjustment mechanism, whereas the CSE found in the colour-word Stroop task (Stroop, 1935) might reflect a priming-related mechanism.

Based on previous findings (Ambrosi et al., 2016; Cragg, 2016; Iani et al., 2014) we expected to find the CSE in every age group. Furthermore, based on models of cognitive control development (Shulman et al., 2016) the CSE was predicted to increase in magnitude across the age groups, reflecting greater deployment of top-down control in response to changing task demands as a function of age, in line with previous studies that interpreted larger CSEs in the Simon and flanker tasks as reflecting better control modulation (e.g., Aschenbrenner & Balota, 2017). An alternative interpretation of CSE magnitude could be that a larger modulation actually means that there is less cognitive control deployed to tackle conflict in the first place, leading to incongruence impacting performance to a greater extent, therefore smaller CSEs might be an indicator of optimal performance. This would lead to the alternative hypothesis that the CSE should decrease across age as control matures. Importantly, both interpretations suggest that a) the CSE indexes some control related phenomenon, and b) its magnitude should change across age. Challenging the latter prediction are previous empirical findings that suggest control adjustment abilities reach maturity in late childhood (Cragg, 2016; Larson et al., 2012; Waxer & Morton, 2011). If that is the case, we might see no substantial age differences in the CSE at all.

3.1.1 Mind-wandering, cognitive control, and age

In addition to the control of attention across age groups, we also investigated lapses in attention in our sample, as captured by mind-wandering (MW). We aimed to explore the relationships between development and MW, and cognitive control and MW. MW is a multidimensional construct that includes a wide variety of subjective experiences (Seli, Kane et al., 2018), and in the present study, was defined as task unrelated thoughts occurring during goal-directed activities (e.g., Gyurkovics, Balota, & Jackson, 2018; Jackson & Balota, 2012). Flexible cognitive control may be imperative in re-focusing attention to the task once the mind has wandered, as such, more flexible modulation of control may be associated with less time spent in MW during the task. Based on this notion, Drescher, Van den Bussche, & Desender (2018) investigated the relationship between the CSE in a flanker task, and MW frequency as captured by performance on the Sustained Attention to Response Task (SART; Robertson, Manly, Andrade, Baddeley, & Yiend, 1997), a Go/No Go task often used in MW research because of its unengaging nature (e.g., Christoff, Gordon, Smallwood, Smith, & Schooler, 2009; Gyurkovics et al., 2018; Jackson & Balota, 2012). The authors expected a negative relationship in accordance with a "bigger means better control deployment" interpretation of the CSE. No reliable relationship was found, but numerically the coefficients were in accordance with predictions. We examined whether the association between the CSE and MW frequency was present in a larger sample using two different conflict tasks and generalized linear mixed-effects models to maximize the power of analyses.

Finally, we investigated age-related differences in MW across adolescence both at the state and the trait level. We formulated two competing hypotheses. Theories that consider MW to be a consequence of failures of executive control (e.g., McVay & Kane, 2010, 2012) would predict that MW decreases in frequency as a function of age as executive abilities mature. This is also in line with our previous hypothesis that better control regulation would be associated with less MW. However, there is another prominent view of MW which considers this type of cognition to be resource dependent (Smallwood & Schooler, 2006), and receives support from aging studies that find that older adults tend to report fewer instances of MW during a task (e.g., Giambra, 1989, 2000; Jackson & Balota, 2012; for a recent review see Maillet & Schacter, 2016), in everyday life (Maillet et al., 2018), or at the trait level (Seli, Maillet, Smilek, Oakman, & Shacter, 2017) than young adults, possibly because cognitive resources decline with age, thus older adults have fewer resources left over to maintain a task unrelated train of thought when already engaged in a task. This view would predict that the frequency of MW should increase as a function of maturation (and an associated increase in resources, e.g., Conklin, Luciana, Hooper, & Yarger, 2007; De Luca et al., 2003; Luna, Garver, Urban, Lazar, & Sweeney, 2004) in our study.

To our knowledge, thus far only one study has compared adolescent MW rates with adult MW rates to explore developmental changes in MW frequency (Stawarczyk et al., 2014). Based on their responses to probe questions embedded in the SART, mid-adolescents (14-16-year-olds) did not differ from a group of late adolescents and adults (19-26-year-olds) in how frequently they experienced MW, defined as task-unrelated thoughts while attention was decoupled from the environment, but they did report being distracted by external events more frequently during the task than did young adults. Consequently, in the current study, we explored whether age-related changes in MW frequency might become apparent if MW reports are differentiated based on the associated level of metacognition (i.e., were they aware that their mind had wandered before the probe question; Jackson & Balota, 2012; Smallwood, McSpadden, & Schooler, 2007). Furthermore, in this study we also investigated possible changes in MW across different stages of adolescence early, mid- and late; and contrasted these groups with young adults in their late twenties, above even the most liberal upper limit of adolescence (age 24; Shulman et al., 2018).

Although the main focus of our study was self-reported MW, proposed behavioural indices of MW such as Go and No Go accuracy, and reaction time variability to Go trials (Cheyne, Solman, Carriere, & Smilek, 2009) were also investigated, both across adolescence and with respect to cognitive control. Furthermore, age-related differences in SART performance were also examined because of the wealth of previous findings showing that Go/No Go task performance improves with age (Braet et al., 2009; Carriere et al., 2010; Rubia et al., 2006; Stawarczyk et al., 2014).

3.2 Method

We report how we determined our sample size, all data exclusions (if any), all manipulations, and all measures in the study. Data files and the analysis script for this study are available on the Open Science Framework at the following URL: https://osf.io/7vbtr/ .

3.2.1 Participants

Participants with normal or corrected-to-normal vision were recruited from 4 different age groups: 1) early adolescents (n = 30, 10 females, mean age = 12.43, *SD* = .57, age range: 12-13, mean pubertal development score (Carskadon & Acebo, 1993): 2.17, *SD* = .57), 2) mid-adolescents (n = 25, 16 females, mean age = 14.36, *SD* = .49, age range: 14-15, mean pubertal development score: 3.07, *SD* = .51), 3) late adolescents (n = 28, 19 females, mean age = 18.57, *SD* = .57, age range: 18-20), and 4) young adults (n = 25, 16 females, mean age = 25.76, *SD* = .78, age range: 25-27). We aimed to collect 30 participants in each age group, as previous studies, and a pilot study conducted by the authors (data available on request), were able to detect the CSE with a sample of this size, and this number was attainable given other, practical constraints as well (time and funding available). Deviations from the target number are primarily due to the removal of some participants due to neurological or psychiatric problems undisclosed during recruitment. Participants were recruited through social media, via a volunteers' database maintained by the University of Sheffield, and from amongst the undergraduate and postgraduate students of the same University. Every volunteer received £10 as compensation for their time taking part. The study was approved by the Ethics Committee of the Department of Psychology, University of Sheffield.

3.2.2 Materials

3.2.2.1 Conflict tasks

Participants completed two conflict tasks: the flanker task and the Simon task (Figures 3.1A & 3.1B, respectively). In the flanker task, participants had to identify the direction the central target arrow was pointing in (left, right, up, or down) out of a string of 5 arrows displayed in the centre of the screen. On congruent trials, the arrows all pointed in the same direction, while on incongruent trials the target arrow in the middle pointed in a different direction from the other four, flanking arrows. In the Simon task, participants only saw a single arrow on each trial, and had to identify which direction it was pointing in, regardless of the location it was presented in. Arrows could be presented either above, below, to the left of, or to the right of fixation. On congruent trials the location and the direction of the arrow matched (e.g., an upward pointing arrow above fixation), whereas on incongruent trials they were the opposite (e.g., a downward pointing arrow above fixation).

Both tasks started with 24 practice trials which were extended with an additional 12 trials if the participant did not give at least 19 correct responses on the first 24 trials. Feedback was given after every trial during the practice session. Experimental sessions consisted of 3 blocks of 97 trials separated by short self-paced breaks, resulting in a total of 291 trials for both tasks. In each block, there were 24 trials in each condition (cC, iC, iI, cI). The first trial in each block had no previous congruency, and was not included in CSE analyses. The congruency of the first trial was determined randomly for each block.

The following measures were taken to control for both feature integration and contingency confounds: the four stimulus values (left, right, up, down) were divided into two pairs. In the flanker task, this was done randomly (any direction could be paired with any other), while in the Simon task, right was always paired with left, and up was always paired with down. Only values from one pair were used on odd trials, and values from the other pair on even trials to create the target (e.g., if right (R) was paired with up (U), and left (L) with down (D) in the flanker, incongruent trials could be RRURR or UURUU on odd/even trials, and LLDLL or DDLDD on even/odd trials, but never RRDRR, LLULL, etc.). In other words, the trial sequence was alternating between two two-value variants of the same task. This guaranteed that no features were repeated, and ensured that the irrelevant stimulus feature was not disproportionately predictive of the correct answer. This method has been used in previous studies to control for these two confounds (Aschenbrenner & Balota, 2017; Jiménez & Méndez, 2013; Kim & Cho, 2014; Schmidt & Weissman, 2014; Weissman, Jiang, & Egner, 2014).

Following the design used by Aschenbrenner & Balota (2017), the following sequence of events occurred on each trial, in both tasks: a fixation cross was displayed for 500 ms, followed by a blank screen for 200 ms. After this, the target stimulus was presented for 3000 ms, or until a response was made. Participants had to indicate the direction of the target arrows by pressing the 2, 4, 6, or 8 keys on the numeric keypad to respond down, left, right, or up, respectively. Participants were asked to use the index finger of their dominant hand. Following the target stimulus, a blank screen was presented for 1000 ms if the response to the target was correct. On incorrect trials an error message was displayed for 1000 ms instead of the blank screen, saying either ‘ERROR’ if the participant pressed an incorrect key, or ‘TOO SLOW’ if the participant failed to respond within the response deadline. Finally, the message “Press 5 to continue” appeared on screen, until the participant pressed the 5 key on the number pad, and started the next trial. This was done to ensure that the participant’s index finger was equal distances away from all four response buttons.

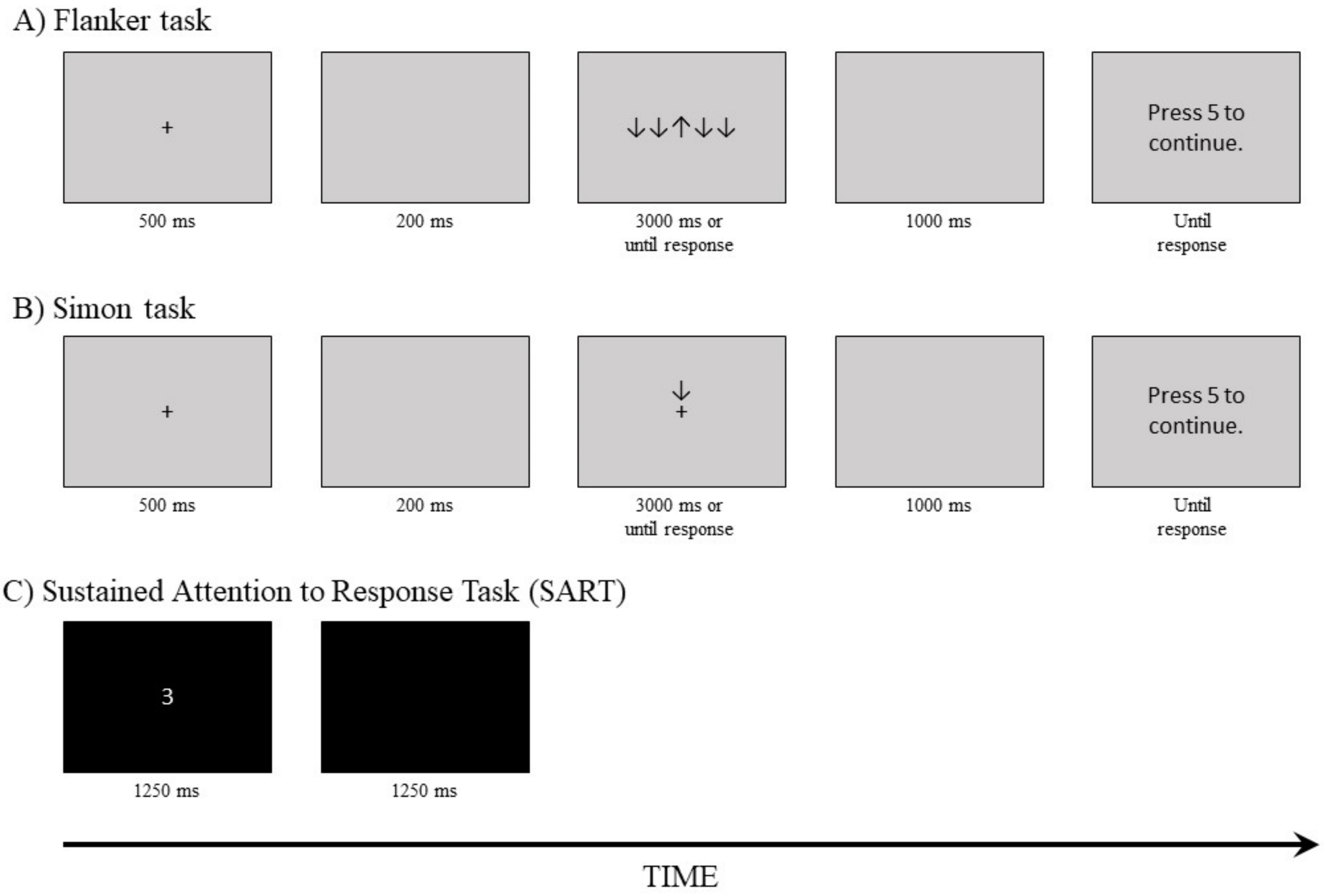


Figure 3.1 – Task designs in the study. A) Design of the flanker task. Participants had to identify the direction of the central arrow. An incongruent trial is pictured. B) Design of the Simon task. Participants had to identify the direction of the central arrow. Participants had to identify the direction of the arrow. An incongruent trial is pictured. C) Design of the Sustained Attention to Response Task (SART). Participants had to press SPACE every time a digit appeared (Go trials) except if the digit was 3 (No Go trial, pictured).

3.2.2.2 Sustained Attention to Response Task (SART) with thought probes

In the SART (developed by Robertson et al., 1997), the task of the participants was to press the SPACE bar every time a digit between 1 and 9 appeared on screen, except if that number was 3. In other words, digits 1, 2, and 4 to 9 were identified as Go stimuli, and the number 3 was identified as the No Go stimulus (Fig. 3.1C). With the exception of number identity, Go and No Go trials were identical. There were two blocks of 131 trials, resulting in a total of 262 trials. The two blocks were separated by a short self-paced break. Out of the 262 trials, 224 (85.5%) were Go trials, and 28 (10.69%) were No Go trials. On the remaining 10 trials (3.82%) instead of a digit, participants saw the following probe question until they responded: “Please choose the one option below that best describes your experience with the task just now” (see Gyurkovics et al., 2018; Jackson & Balota, 2012). The options were: “I was thinking about the task”, “My mind was blank”, “My mind drifted to things other than the task, but I wasn’t aware of it until you asked me”, and “While doing the task I was aware that thoughts about other things popped into my head”; corresponding to on-task thoughts, space outs, zone outs, and tune outs respectively (Smallwood et al., 2007). Trials were intermixed pseudo-randomly, so that targets (No Go trials) were never preceded or immediately followed by another target or a probe. Proportions of different trial types were identical across the two blocks. On digit trials (Go or No Go trials), a digit in white was presented on black background in the centre of the screen for 1250 ms. The stimulus was then followed by an intertrial interval of 1250 ms, during which a blank black screen was presented. No performance feedback was provided during the experimental blocks. The two experimental blocks were preceded by three practice blocks. In the first, participants completed 9 trials (1 target), and received feedback on their performance after each one. In the second one, participants similarly completed 9 trials with feedback, however, this time a probe question was also added. In the final practice block, 9 trials and a probe appeared, with no feedback. As such, this practice block was identical to the experimental blocks. All tasks were programmed using the Psychtoolbox extension in MATLAB R2014b.

3.2.3 Procedure

After obtaining informed consent from participants and their parents in the case of participants who were under 18, they first completed the Positive and Negative Affect Schedule (PANAS; Watson, Clark, & Tellegen, 1988) for the first time (PANAS1) to measure their baseline emotional state prior to the start of the session. Then the experimenter administered the Wechsler Abbreviated Scale of Intelligence (WASI; Psychological Corporation, 1999). This took approximately 15-20 minutes. After this, the participant was seated at a computer, and the two conflict tasks (the flanker and the Simon tasks) were completed. Their order was counterbalanced across participants. The two tasks together took approximately 30-40 minutes to complete. As the next step, the PANAS was completed for the second time (PANAS2), followed by the State-Trait Anxiety Inventory (STAI; Spielberger, 1989), and the Mind-Wandering Questionnaire (MWQ; Carriere, Seli, & Smilek, 2013) that measures the everyday frequency of deliberate and spontaneous MW. Early and mid-adolescents also completed a self-rated measure of pubertal development (Carskadon & Acebo, 1993). Finally, the SART was run, which lasted approximately 10-15 minutes. Altogether one experimental session lasted about 75-90 minutes. Descriptive data for the individual difference measures can be found in Supplementary Table 3.1. With the exception of the MWQ individual difference measures were collected as part of standard practice in our lab to enable better characterization of each age group but no hypotheses were formulated regarding these variables and their association with cognitive control.

3.2.4 Statistical Analysis

Before statistical analyses, RTs shorter than 150 ms were removed. This resulted in the removal of only 0.05% of trials in the flanker, 0.08% of trials in the Simon, and

1.60% of trials that had RTs in the SART. Then outliers, identified as trials with RTs beyond 3 SDs of the participant's mean were also removed. This resulted in the removal of 1.55%, 1.69%, and 1.44% of trials in the flanker, Simon, and SART, respectively. For RT analyses in the conflict tasks, error trials and trials immediately following error trials were also removed. For accuracy analyses, these trials were retained.

Age effects in behavioural performance on the tasks were investigated with linear mixed-effects modelling using the "lme4" package in R (Bates, Maechler, Bolker, & Walker, 2015). For the flanker and the Simon tasks, predictors Current Trial Congruency (coded as 0 and 1 for congruent and incongruent, respectively), Previous Trial Congruency (coded as 0 and 1 for congruent and incongruent, respectively), Age Group (with young adults serving as reference category), and all their interactions were specified as fixed effects, with RT as an outcome variable, and a random effect of participants. The random effects structure was determined by examining the Akaike Information Criterion (AIC) values of models containing no random slopes, only random intercepts per participant; random slopes for Current Congruency, and random slopes for the Current Congruency × Previous Congruency interaction. The model with the lowest AIC value was selected. The Type II ANOVA table of the final model generated by the Anova() function from the "car" package (Fox & Weisberg, 2019) is reported. Follow-up pairwise analyses for interactions containing group were conducted using the "emmeans" R package (Lenth, 2018). For accuracy analyses similar generalized linear mixed-effects models were run. For the sake of brevity, accuracy analyses are only reported if they in any way contradict or complement RT findings. Descriptive accuracy data is presented in Supplementary Table 3.2. Furthermore, the code for supplementary models containing different control variables that may affect findings (e.g., baseline mood, IQ, or sex) is available on the project's OSF page at https://osf.io/7vbtr/.

Accuracy and RT data from the SART was analysed using a strategy identical to the one outlined above, with the exception that the variables included in these models were Trial Type (Go or No Go, coded as 0 and 1 respectively) and Age Group. Reaction time variability changes as a function of age were investigated with a between-subject ANOVA. The outcome variable was the Go stimulus coefficient of variation (CV; Go RT SD / mean Go RT).

To investigate the relationship between self-reported MW and cognitive control (i.e., the size of the CSE), generalized linear mixed-effects models were used. In these analyses, binary dummy variables indicating whether a given thought report category was chosen in response to a probe question or not were the outcome variables. The magnitude of the CSE for each participant was calculated using the formula (cI – cC) – (iC – iI) where each letter combination corresponds to the mean RT of that condition. Random intercepts per participants were specified to account for multiple observations (i.e., probe questions) by individual. This strategy is similar to the one used by Van den Driessche et al. (2017). This same strategy was used to analyse group differences in MW frequency. Generalized linear mixed-effects models were also used to examine the relationship between SART accuracy – a proposed behavioural indicator of MW - and cognitive control. The results of the Anova() function are reported, along with exponentiated coefficients (odds ratios, ORs) where appropriate. Pearson correlations were used to investigate whether cognitive control and behavioural variability (Go trial CV) are related. Finally, Kendall rank correlation was used to investigate the relationships between SART accuracy and self-reported MW, and behavioural variability and self-reported MW.

The α level was set at .05 in all analyses.

3.3 Results

3.3.1 Conflict tasks

3.3.1.1. Reaction time analyses

Raw RTs were analysed first (for means and *SD*s, see Supplementary Table 3.3). Table 3.1 contains the relevant terms of the various models run. In the flanker task, a model with random slopes for the Previous Congruency × Current Congruency interaction was selected over a model with only random intercepts, and a model with random slopes for the effect of Current Congruency only. A main effect of Congruency was found, indicating slower responses on incongruent compared to congruent trials. This was modulated by Previous Congruency, in other words, a reliable CSE was found. However, the CSE by Age Group interaction did not approach significance. Figure 3.2 shows the CSE by age groups.

Table 3.1 - Terms of interest from the four general linear mixed-effects models investigating the conflict task performance across age groups

Model (AIC value)	**Flanker – raw RT (373188.6)**			**Flanker – z-scored RT (82204.5)**			**Simon – raw RT (377831.5)**			**Simon – z-scored RT (78557.6)**		
Effect	**χ^2**	***df***	***p***	**χ^2**	***df***	***p***	**χ^2**	***df***	***p***	**χ^2**	***df***	***p***
Age Group	33.52	3	< .001	0.40	3	.940	38.93	3	< .001	0.15	3	.985
Congruency (C)	314.52	1	< .001	572.26	1	< .001	588.52	1	< .001	1130.92	1	< .001
Previous Congruency (PC)	2.57	1	.109	8.98	1	.003	14.36	1	< .001	10.56	1	.001
C × Age Group	6.33	3	.096	20.28	3	< .001	2.24	3	.524	14.50	3	.002
PC × Age Group	0.22	3	.975	1.04	3	.792	6.94	3	.074	6.00	3	.112
PC × C (CSE)	13.20	1	< .001	17.25	1	< .001	62.92	1	< .001	105.39	1	< .001
PC × C × Age Group	1.55	3	.671	4.57	3	.206	7.54	3	.057	4.79	3	.188

Note: CSE = congruency sequence effect, AIC = Akaike Information Criterion. For raw RT analyses, models with random slopes for the PC × C interaction were selected over models with a slope only for C, or no random slopes at all. The AIC values of the competing models in the flanker were: 373209.4 for C slope model, and 373525.9 for no slope model. In the Simon: 377837.7 for C slope model, and 378317.3 for no slope model. For zRT analyses, the C slope models were favoured. The AIC value of competing models in the flanker: 82214.5 for PC × C slope model (failed to converge), and 82394.6 for no slope model. In the Simon: 78562.6 for PC × C slope model (failed to converge), and 78777.8 for no slope model.

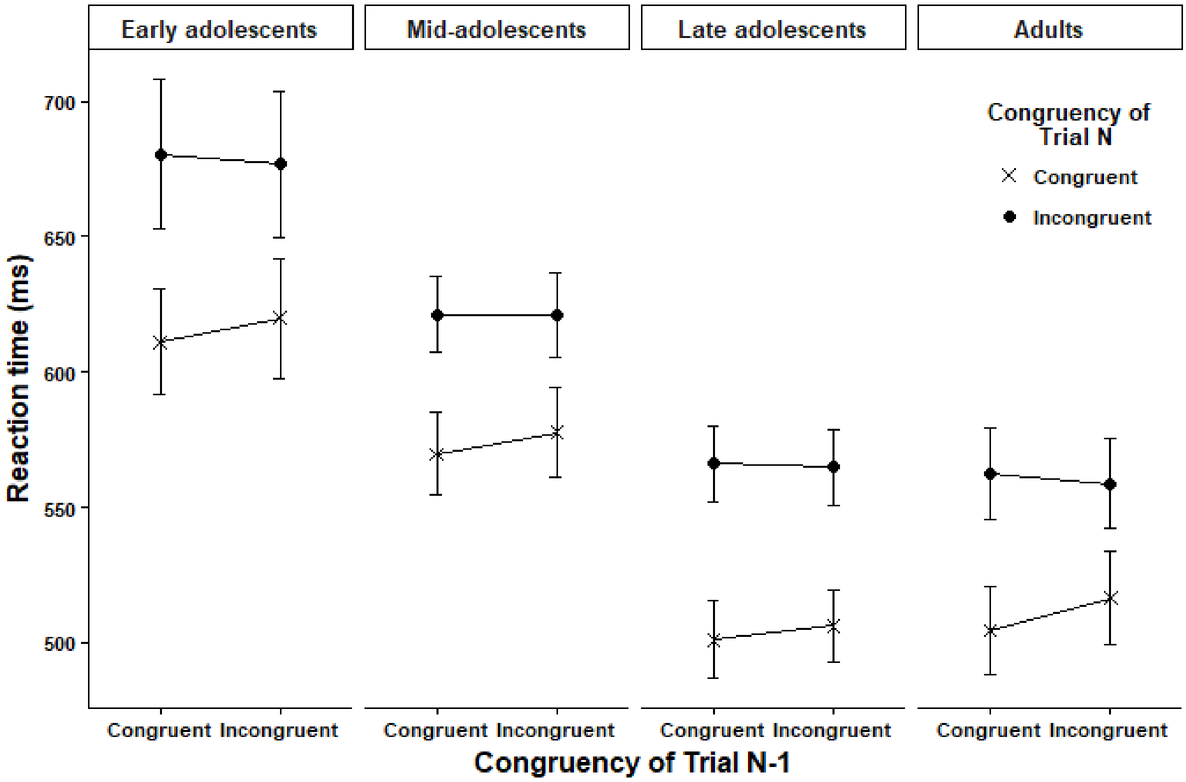


Figure 3.2 - The effect of congruency as a function of previous trial congruency, or the congruency sequence effect in raw RT in the flanker task. Error bars represent +/- 1 SE.

In the Simon task, similarly to the flanker, the model with random slopes for the Previous Congruency × Current Congruency interaction was preferred, as opposed to the model with only random intercepts, or the model with random slopes for the effect of Current Congruency only. A significant Congruency effect and a CSE were found in this task too. The CSE was not significantly modified by Age. Figure 3.3 depicts the CSE by age groups in the Simon task.

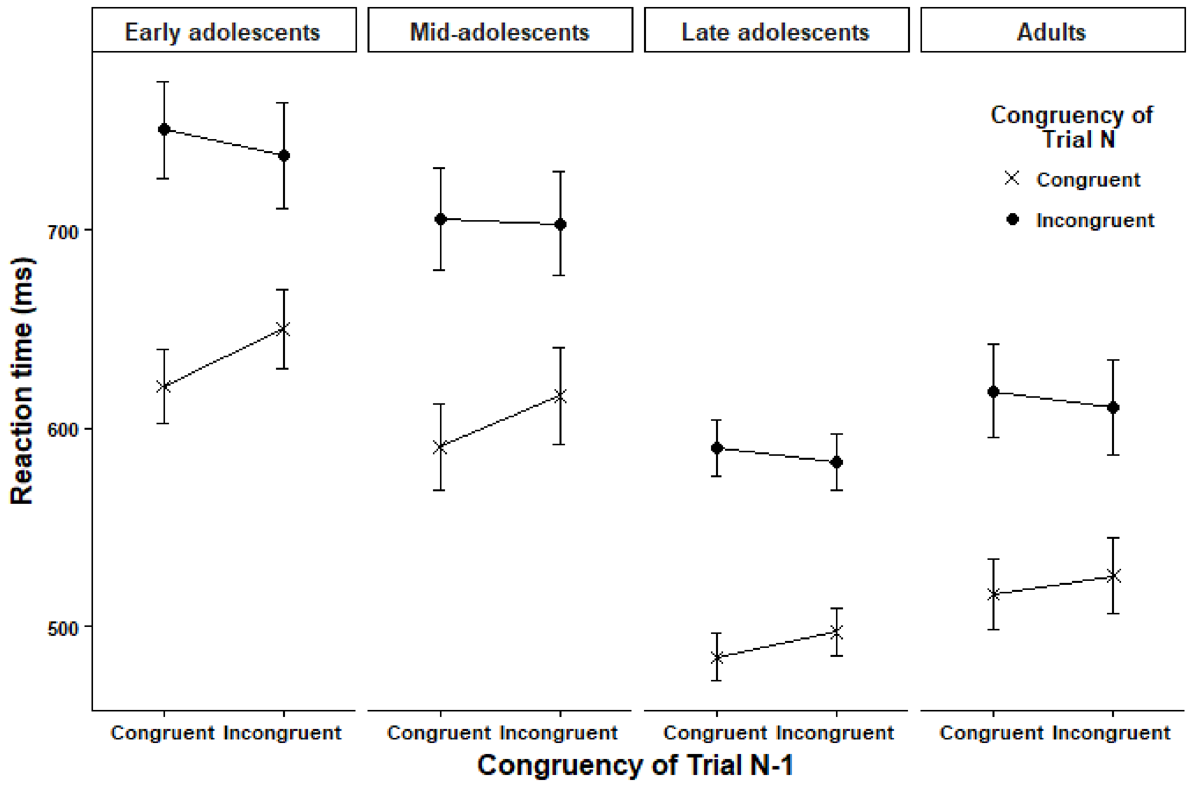


Figure 3.3 - The effect of congruency as a function of previous trial congruency, or the congruency sequence effect in raw RT in the Simon task. Error bars represent +/- 1 SE.

The same pattern of results emerged for the terms of interest after controlling for baseline speed differences across groups by standardizing reaction times on each participant's mean and *SD* (Supplementary Figures 3.1-3.2, for descriptive data, see Supplementary Table 3.3). As can be seen in Table 3.1, the Age Group × Current Congruency interaction was significant in these analyses in both tasks. Early adolescents showed smaller congruency effects than late adolescents and adults in both tasks (all *p*s < .05). Mid-adolescents also differed from the two older groups in the flanker task.

3.3.1.2 Exploratory analyses

We conducted additional cross-task analyses, examining the two conflict tasks together. These analyses were run to explore whether the CSE interacts with Task, and whether the CSE by Age Group interaction interacts with Task. A significant Previous Congruency × Current Congruency × Task interaction was found, both in raw and standardized RT, $\chi^2(1) = 12.19$, $p < .001$, and $\chi^2(1) = 17.33$, $p < .001$, respectively, reflecting the fact that the CSE was bigger in the Simon compared to the flanker task. The Previous Congruency × Current Congruency × Task × Age Group interaction did not reach significance.

3.3.2 Sustained Attention to Response Task (SART)

3.3.2.1 Behavioural performance

Indices of behavioural performance on the SART are summarized in Table 3.2. For RT analyses, the model with random slopes for Trial Type per participant was preferred over a model that only contained random intercepts (AIC values: 299341.3 and 299364.4, respectively). The main effects of Trial Type and Age Group were significant, $\chi^2(1) = 183.90$, $p < .001$, and $\chi^2(3) = 45.75$, $p < .001$, respectively. Participants were faster on incorrect No Go trials than on correct Go trials, and early adolescents were generally slower than any other group (all *p*s < .01). When standardized RTs were examined to control for the baseline speed difference across groups, only the random intercepts model converged. Trial Type still had a main effect, $\chi^2(1) = 208.63$, $p < .001$, but neither of the other effects approached significance.

Table 3.2 - SART task performance indices – means (SDs) – for early, mid-, and late adolescents and young adults

		Early adolescents	**Mid-adolescents**	**Late adolescents**	**Young adults**
Accuracy					
	N	30	24	28	24
	Go accuracy	.98 (.02)	.99 (.02)	.99 (.01)	.99 (.01)
	No-Go accuracy	.70 (.19)	.72 (.18)	.78 (.15)	.82 (.15)
Go Reaction Time					
	N	30	24	28	24
	Go RT	552.34 (81.90)	473.24 (64.95)	442.67 (87.24)	425.85 (51.96)
	Go zRt	.02 (.01)	.02 (.02)	.01 (.01)	.01 (.01)
No-Go Reaction Time					
	N	29	24	27	24
	No-Go RT	438.20 (82.10)	380.83 (71.50)	363.81 (51.73)	349.51 (58.34)
	No-Go zRT	-.62 (.37)	-.65 (.39)	-.59 (.35)	- .69 (.48)
Intraindividual variability					
	N	30	24	28	24
	Go RT CV	.31 (.06)	.30 (.06)	.26 (.06)	.25 (.04)

Note: Accuracy reflects the proportion of correct responses. CV = coefficient of variation (Go RT SD / Go RT mean), SART = Sustained Attention to Response Task.

When accuracy was analysed, main effects of Trial Type and Age Group were found, *OR* = .012, 95% CI [.006, .024], $\chi^2(1) = 552.09$, $p < .001$, and $\chi^2(3) = 17.97$, $p < .001$, respectively. As would be expected, participants were more error-prone on No Go trials than on Go trials, and early adolescents were more error-prone than late adolescents or adults (all *p*s < .05). The Trial Type × Age Group interaction was significant in this analysis, $\chi^2(3) = 10.07$, $p = .018$, with a bigger difference between the two conditions in early adolescents compared to young adults ($p = .011$).

To examine RT variability, the coefficient of variation (CV) was calculated for each participant (correct Go trial RT *SD* / correct Go trial RT mean). This was significantly different across groups, $F(3, 102) = 8.60$, $p < .001$. The CV in early and mid-adolescents was significantly different from late adolescents and adults (all *p*s < .05), suggesting that intra-individual variability in RT on correct Go trials was higher in the two under-18 compared to the over-18 age groups.

3.3.2.2 Mind-wandering and age

First, we investigated age differences in self-reported MW frequency during the SART (Table 3.3). The frequency of each thought content category across groups is illustrated in Figure 3.4. A significant difference was found in the probability of reporting tune outs (MW with awareness) across age groups. Post-hoc tests suggested this was due to early adolescents reporting fewer tune outs than late adolescents, *OR* = .375, 95% CI [0.158, 0.888], $z = -2.92$, Tukey adjusted $p = .018$. No reliable age effects were found in the other thought content categories. To explore the data further, MW with and without awareness were collapsed into a new category, “overall MW”. There was an age effect in this category too (Table 3.3, bottom row), which closely mirrored the pattern of the age effect in tune outs: early adolescents reported MW less frequently than late adolescents, *OR* = .406, 95% CI [0.181, 0.910], $z = -2.87$, Tukey adjusted $p = .022$.

Table 3.3 - Terms from the generalized linear mixed-effects models investigating the frequency of different thought content reports across age and as a function of CSE magnitude in the two tasks.

	Age		Flanker CSE (RT)		Flanker CSE (zRT)		Simon CSE (RT)		Simon CSE (zRT)	
	$\chi^2(3)$	**p**	**$\chi^2(1)$**	**p**	**$\chi^2(1)$**	**p**	**$\chi^2(1)$**	**p**	**$\chi^2(1)$**	**p**
On-task Reports	6.92	0.074	7.53	0.006*	3.39	0.066	0.39	0.535	< .01	0.964
Space Outs	6.59	0.086	0.07	0.786	0.45	0.504	0.78	0.377	0.45	0.503
Zone Outs	0.58	0.902	0.26	0.607	0.2	0.658	0.04	0.843	0.05	0.821
Tune Outs	10.29	0.016*	7.34	0.007*	5.71	0.017*	0.09	0.769	0.61	0.436
Overall MW	10.21	0.017*	8.32	0.004*	4.52	0.034*	0.02	0.892	0.33	0.567

Note: * $p < .05$. In the RT models, the predictor variable was the magnitude of the congruency sequence effect (CSE) in raw, unstandardized RT, whereas in the zRT models the CSE was based on standardized RT. MW = Mind-Wandering.

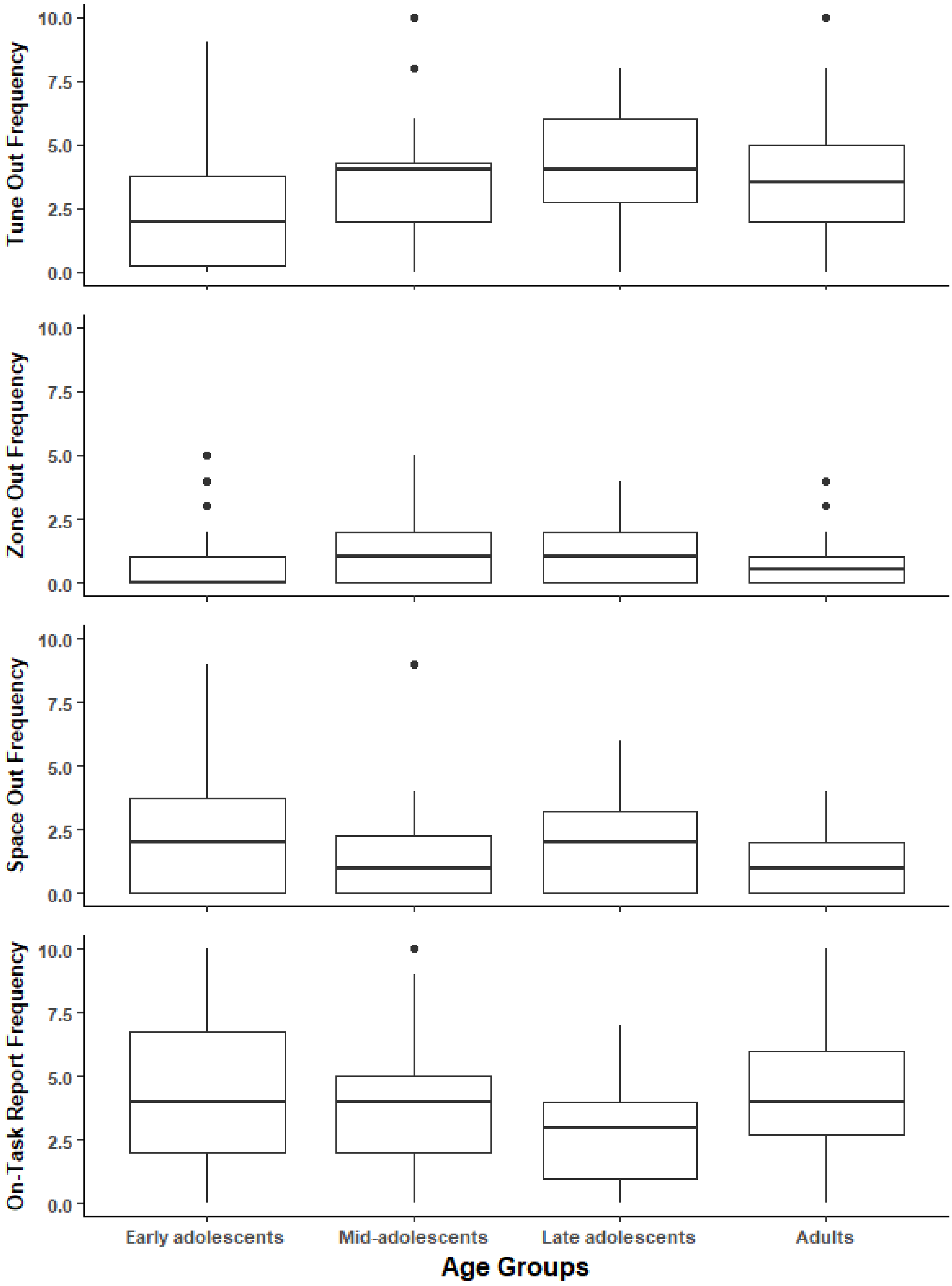


Figure 3.4 - Box-plots of the frequencies of different categories of thought reports across age groups during the Sustained Attention to Response Task (SART).

Next, we analysed self-reported trait MW, as measured by the two subscales, Deliberate and Spontaneous, of the Mind-Wandering Questionnaire. In a 2 (MW Type: Deliberate, Spontaneous) × 4 (Age Group) ANOVA, a main effect of Group was found, *F*(3,102) = 5.09, *p* = .003. This was due to early adolescents reporting less MW ($\text{Mean}_{\text{Deliberate}}$: 3.91 ± 1.11; $\text{Mean}_{\text{Spontaneous}}$: 3.35 ± 1.37) than late adolescents (Mean_{D}: 4.94 ± 1.22; Mean_{Sp}: 4.63 ± 1.22) and young adults (Mean_{D}: 4.79 ± 1.43; Mean_{Sp}: 4.36 ± 1.39, all *p*s < .05). Mid-adolescents did not significantly differ from any other group (Mean_{D}: 4.72 ± 1.30; Mean_{Sp}: 4.06 ± 1.54). Participants in every age group reported less spontaneous MW than deliberate, *F*(1,102) = 21.71, *p* < .001. The MW Type × Age Group interaction did not approach significance (*F* < 1).

Neither of the potential, performance based behavioural indices of MW (Go accuracy, No Go accuracy, Go RT CV in the SART) were significantly related to self-reports of MW, either state or trait level. The two levels of self-reports, however, were correlated in our sample: both deliberate and spontaneous trait-MW predicted the probability of on task reports, *OR* = .687, 95% CI [.562, .831], $\chi^2(1) = 14.93$, *p* < .001, and *OR* = .708, 95% CI [.593, .839], $\chi^2(1) = 15.88$, *p* < .001, respectively; and tune out reports during the task, *OR* = 1.426, 95% CI [1.186, 1.733], $\chi^2(1) = 14.12$, *p* < .001, and *OR* = 1.299, 95% CI [1.093, 1.560], $\chi^2(1) = 8.77$, *p* = .003, respectively.

3.3.2.3 Mind-wandering and cognitive control

We next examined whether the magnitude of the CSE was related to the self-reported frequency of MW during the SART (Table 3.3). The frequency of MW with awareness (tune outs) was negatively related to the magnitude of the CSE in the flanker in both raw and standardized RT, *OR* = .986, 95% CI [.975, .996], and *OR* = .236, 95% CI [.069, .775], respectively. Similar associations were found using overall MW as the outcome in both raw and standardized RT: *OR* = .986, 95% CI [.976, .995], and *OR* = .296, 95% CI [.093, .915], respectively. A positive relationship of similar magnitude was also found between raw RT CSE in the flanker and on-task thought report frequency, *OR* = 1.015, 95% CI [1.004, 1.026]. These relationships did not interact with age. No significant relationships were found in the Simon task or with other thought report categories. The magnitude of the CSE was also not a significant predictor of any of the potential behavioural indices of MW (Go accuracy, No Go accuracy, Go RT CV; all *p*s > .05), and was not related to trait MW (all *p*s > .05).

3.4 Discussion

In the present study, we investigated different aspects of the cognitive control system across early, mid- and late adolescence, and young adulthood. Confound-minimized versions of two classic conflict tasks, the Simon task and the flanker task, were used to examine whether adolescents show evidence of dynamic modulations of cognitive control as indicated by the presence of the congruency sequence effect (CSE), and whether the magnitude of this modulation changes across adolescence. Furthermore, we also investigated self-reported mind-wandering (MW) in a Go/No Go task in these age groups, and the relationship between MW and cognitive control.

3.4.1 Cognitive control across adolescence

The main focus of this study was to investigate age-related changes in dynamic adjustments of cognitive control as indexed by the CSE. The typical CSE pattern in RT was observed in both tasks and was larger in the Simon compared to the flanker task, replicating an effect reported by Weissman et al. (2014). The authors suggested that this difference might be because distractor information is translated into a response more rapidly than target information in the Simon task compared to the flanker task, giving a “head start” for the inhibition of the distractor-related response (Weissman, Egner, Hawks, & Link, 2015). This inhibition is then further amplified after incongruent trials, generating a larger CSE. Our results support this account.

Contrary to our prediction, age did not interact with the CSE in either one of the tasks. This is consistent with previous developmental work involving children (Cragg, 2016; Larson et al., 2012; Waxer & Morton, 2011), that also found no significant age differences in the size of the CSE across different age groups. Numerically, the CSE increased slightly across age groups in the flanker task, and decreased in the Simon task. Such a divergence, coupled with the fact that there was no correlation in the CSE across tasks (r = - .10 in raw RT, r = - .05 in standardized RT) could hint at a difference between the mechanisms, or in the implementation of the same mechanism, underlying the CSE in the two tasks. This is in line with recent findings that suggest that conflict signals and/or control mechanisms are specific to a given task (Funes, Lupiáñez, & Humphreys, 2010; Whitehead, Brewer, & Blais, 2018, for a review see Braem, Abrahamse, Duthoo, & Notebaert, 2014), or even that the mechanism generating the CSE might differ from task to task (Aschenbrenner & Balota, 2015, 2017).

Similar to the CSE and consistent with some previous studies (Adleman et al., 2002; Andrews-Hanna et al., 2011; Veroude et al., 2013), the congruency effect observed in this study did not differ between age groups when examining raw RT scores. However, when baseline speed differences between groups were controlled for in the analyses, participants under 18 (early and mid-adolescents) showed smaller congruency effects compared to both over-18 groups. This was most likely an effect of the standardization procedure as adolescents showed higher intra-individual variability in accordance with previous studies showing that adolescent performance is more variable than adult performance (Montez, Calabro, & Luna, 2017). Hence, when RTs were standardized based on *SD*s, the effect appeared to be smaller compared to the high intra-individual variance in that group than in the less variable adult group.

Taken together, our findings suggest that on the behavioural level conflict resolution, as measured by the congruency effect, matures quickly and reaches adult-like levels by or before the age of 12. Similarly, patterns typically associated with conflict-induced dynamic adjustments of control levels are already present at the same age. This is in line with the conclusions of Ambrosi et al. (2016), Cragg (2016), Iani et al. (2014), and Stins, Polderman, Boomsma, & de Geus (2007) who tested children at or under the age of 12. Sequential modulations did not show substantial changes as a function of age in our sample in accordance with previous studies using confounded or more complex paradigms (Larson et al., 2012; Smulders et al., 2018; Waxer & Morton, 2011). Our results complement those of Cragg (2016) who used a confound-free flanker task in children and late adolescents, by showing a similar lack of substantial age differences in a confound-free Simon task between adolescents and adults. It is, however, important to bear in mind that we cannot draw the conclusion that there are *no* age effects in the CSE from null findings as our study and previous studies may simply have been underpowered to detect them. If so, our findings suggest that any age-related changes in CSE magnitude are likely to be extremely subtle, especially after controlling for age differences in response speed.

3.4.2 Go/No Go performance and Mind Wandering

Patterns consistent with age-related improvements in cognitive control were found in the SART, both in behavioural performance and self-reported MW with the biggest differences emerging between participants under and over 18. Early adolescents were slower and more error prone than the other groups. Furthermore, the performance of early and mid-adolescents on Go trials was more variable compared to the two older groups. This pattern of results is consistent with previous findings that adolescents show impaired performance in Go/No Go tasks both in terms of speed and accuracy (Carriere et al., 2010; Stawarczyk et al., 2014) and behavioural variability (Braet et al., 2009; Stawarcyzk et al., 2014). These findings are also in line with models of adolescent cognitive development that posit that control abilities are still maturing at this stage of life (Iselin & DeCoster, 2009; Shulman et al., 2016). According to our results, however, this improvement is more evident in certain abilities than in others, as the inhibition of prepotent but momentarily incorrect responses in the SART did show age-related changes while conflict resolution and adaptation to conflict in the flanker and the Simon tasks did not.

Turning to mind-wandering, age differences were also found in the reported frequencies of MW during the SART. Early adolescents reported significantly fewer episodes of overall MW (MW episodes with or without awareness, combined) than late adolescents, and numerically fewer episodes than adults. One explanation of this observation could be that MW, or certain aspects of MW (e.g., the maintenance of off-task thought), are resource-dependent (Smallwood & Schooler, 2006; Smallwood, 2013) and early adolescents just do not have enough cognitive resources at their disposal yet to generate and/or maintain off-task thoughts during task performance. Our finding that late adolescents reported the highest levels of MW, however, could also be explained in terms of the "control failures × current concerns" account of MW (McVay & Kane, 2010). This posits that MW is a consequence of the cognitive system's failure to defend task performance from the interference of intrusive thoughts, triggered by the current concerns of an individual. It is possible, although speculative, that late adolescents who were primarily undergraduate students had more university related current concerns that were activated by the university setting in which they were tested than any other group, leading to a disproportional increase in MW in that specific age group. Furthermore, as this age effect was driven by differences in the frequency of MW episodes with awareness, it could be due to differences in metacognitive ability across the groups (Weil et al., 2013), as opposed to differences in the actual amount or duration of MW episodes. Future studies are needed to replicate these findings and to disentangle potential mechanisms

Our results complement the findings of Stawarczyk et al. (2014) who found no difference in self-reported MW frequency between 14-16 and 19-26 year-olds. Importantly, that study did not distinguish between different types of MW and used broader age ranges, both of which factors might have contributed to the lack of age-related differences in MW. They did, however, find that their adolescent group was on-task less frequently than adults, unlike in our sample. This is seemingly at odds with the cognitive resource account of MW, however their findings suggested that this effect was a result of an increase in external distractions (not measured in our study), and not in spontaneous thoughts in adolescents. This is consistent with the idea that adolescents have less developed attention regulation abilities (e.g., Polizzotto, Hill-Jarrett, Walker, & Cho, 2018).

We also investigated trait level MW using a brief mind-wandering questionnaire developed by Carriere et al. (2013). This questionnaire measures the frequency of MW episodes engaged deliberately (intentional MW) and spontaneously (unintentional MW) in everyday life. This is an important distinction, as the two types of MW can show dissociation (Golchert et al., 2017; Seli, Carriere, & Smilek, 2015; Seli, Risko, & Smilek, 2016) and the intentionality dimension has also been shown to be different from the meta-awareness dimension (Seli, Ralph, et al., 2017). In our sample, both intentional and unintentional trait-level MW was positively correlated with MW with awareness during the SART, but not with MW without awareness. This pattern of results provides further indirect support for the idea that intentionality and meta-awareness are not identical constructs. However, it is worth noting that MW without awareness was reported very infrequently in our sample, and low variability in its incidence may have limited our ability to detect meaningful associations involving this type of MW. Finally, both deliberate and spontaneous MW were found to increase with age, paralleling our state-level results, and the findings of Seli, Maillet et al. (2017) in older adults (Exp. 1).

3.4.3 Cognitive control and MW

We also investigated the possible relationship between mind-wandering and cognitive control adjustments, as indicated by the CSE. Across all age groups, we found a reliable negative relationship between the size of the CSE in the flanker task and the frequency of overall MW during the SART which was driven by tune outs, similarly to the age effect described above. This finding suggests that participants who were better at dynamically adjusting their attention to the demands of the task reported fewer task-unrelated thoughts. This is consistent with the findings reported by Drescher et al. (2018), and might reflect that these individuals show better reactive control of their attention, e.g., they may be better able to redirect their attention to the task after it has wandered away, possibly resulting in shorter MW episodes. In support of this interpretation, Stawarczyk et al. (2014) also found that reactive control was negatively associated with MW frequency.

The negative relationship between CSE magnitude and MW frequency is seemingly inconsistent with our previous conclusion that people with more mature cognitive resources MW more. However, previous findings suggest that CSE magnitude is largely independent of cognitive resources (e.g., working memory capacity, Meier & Kane, 2013; Unsworth, Redick, Spillers, & Brewer, 2012), thus the CSE-MW relationship is probably tapping a different aspect of the cognitive system (such as reactive control efficiency) than the MW-age relationship (amount of cognitive resources available).

There are two caveats that make the interpretation of the CSE-MW relationship less straightforward. First, as mentioned in the introduction, an argument could be made that if the level of proactive, preparatory control is high, adjustments in response to conflict should be smaller, thus smaller CSEs might reflect better control allocation. Our developmental findings do not help adjudicate between this, and a “larger is better” interpretation, as young adult CSEs did not differ in size substantially from younger CSEs that are probably generated by less mature cognitive systems. However, if we assume that smaller CSEs reflect better control, the negative relationship between CSE and MW becomes harder to interpret. It is also possible that both the “larger is better” and “smaller is better” interpretations of the CSE could be viable depending on the approach a given participant takes to the task, and this approach might be fluctuating within an individual too, over the course of the task. These limitations must be taken into account in any individual difference study focusing on the CSE. Second, even though we controlled for learning and memory confounds in our design, it is still possible that the CSE reflected some non-control related process, such as temporal learning (Schmidt, 2013; Schmidt & Weissman, 2016), and that this process is related to MW frequency or duration in some way. Further complicating this is the finding that this association was only found for the flanker task, and not for the Simon. This observation provides additional support to the idea outlined above that the CSE reflects different mechanisms in these two tasks as they have different correlates. How exactly the CSE differs between the Simon and the flanker tasks and what exactly it reflects in each, however, can only be determined through further investigation. For instance, the proportion of reactive vs. proactive elements, or the additional contribution of non-control related processes in the CSE might be different in the two tasks.

The results from the current study need to be considered in light of the following limitations. First, due to practical reasons, the study did not include any measures of working memory capacity. In future studies, such measures could help explore how working memory changes across adolescence, and whether these changes are related to attentional control adjustments and reports of MW. Furthermore, although the order of the conflict tasks was counterbalanced across participants, the SART always came last, thus it is possible that the more pronounced age effects in that task are due to greater fatigue effects in younger participants compared to adult participants. This, however, does not substantially change our interpretation of the MW age effect finding in terms of the cognitive resource account of MW. Finally, future studies might benefit from including secondary measures of MW (such as eye-tracking and pupillometry) to help establish the validity of self-reports (e.g., Frank, Nara, Zavagnin, Touron, & Kane, 2015) as it is possible that participants – especially from younger age groups – were unable to report their thought contents accurately in our study.

3.4.4 Conclusion

We investigated how the sequential modulation of the congruency effect changes across adolescence in two, confound-minimized conflict tasks. The CSE did not interact with age in either of the tasks, strongly suggesting that if there are any age-related changes in the size of the effect, they are not substantial. More pronounced age effects were found in response inhibition performance in the SART (performance improved with age) and self-reports of MW (reports of MW increased with age and peaked in late adolescence). Differences were biggest between participants under 18 (early and mid-adolescents) and participants 18 or older (late adolescents and young adults). Both findings imply that certain aspects of the cognitive system are still maturing in adolescence. Finally, our results that the CSE in the flanker task, but not in the Simon task was associated with MW frequency during the SART, and that there was no relationship between the CSEs in the two tasks suggest that the CSE may not reflect the same mechanism (i.e., conflict-induced control adjustments, temporal learning) in the flanker and Simon tasks.

3.4.5 Context

The current study was conducted by Mate Gyurkovics as part of his doctoral program. The work was supervised by co-authors Drs Liat Levita and Tom Stafford. Dr Levita’s lab focuses on the investigation of cognitive and affective changes in adolescence using behavioural and electrophysiological methods. Within this program of research, Mate’s dissertation studies seek to learn more about the development of the cognitive control system, response inhibition in particular, across adolescence on both the behavioural and the neural level. As a next step, the authors are currently working on an EEG study based on the findings of the present experiment aiming to see if the neural mechanisms supporting performance in a similar conflict task are comparable across age groups. In the future, they would like to follow up on the implications these findings have for the nature of the CSE in different tasks, in order to understand what exactly the age-related changes (or lack thereof) in this particular effect tell us about the development of human cognition.

Supplementary Material

Supplementary Table 3.1 - Mean scores (SDs) on the individual differences measures by age group.

	Early	**Mid**	**Late**	**YA**
IQ	108.10 (12.11)	102.33 (10.13)	106.93 (7.91)	111.87 (11.02)
State Anxiety	1.70 (.27)	1.78 (.28)	1.73 (.35)	1.59 (.38)
Trait Anxiety	1.80 (.36)	2.00 (.45)	2.09 (.50)	1.86 (.27)
PANAS1 - Positive	2.77 (.55)	2.75 (.48)	2.97 (.69)	3.11 (.74)
PANAS1 - Negative	1.21 (.19)	1.21 (.16)	1.19 (.22)	1.10 (.10)
PANAS2 - Positive	2.70 (.76)	2.61 (.70)	2.41 (.81)	2.89 (.91)
PANAS2 - Negative	1.18 (.28)	1.16 (.25)	1.13 (.17)	1.05 (.09)

Note: Early = early adolescents, Mid = mid-adolescents, Late = late adolescents, YA = young adults; IQ = score on the Wechsler Abbreviated Scale of Intelligence; State Anxiety = score of the state subscale of the State-Trait Anxiety Inventory; Trait Anxiety = score of the trait subscale of the State-Trait Anxiety Inventory; PANAS = Positive and Negative Affect Schedule, the numbers (1 and 2) correspond to the time point it was taken (i.e., PANAS1 is the score of the given PANAS subscale – Positive, Negative – administered at time point 1). For three individuals IQ testing had already occurred as part of previous projects. In these cases, the WASI was not administered a second time, these participants only completed the rest of the tasks.

Supplementary Table 3.2 - Mean accuracy (SDs) in the flanker and Simon tasks as a function of trial type and age group.

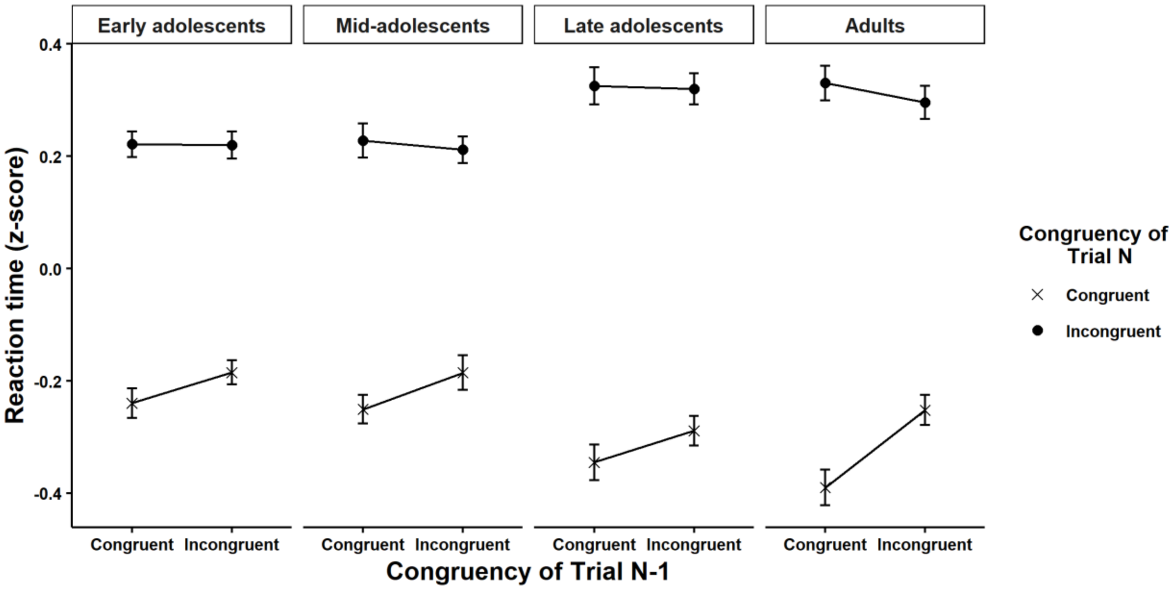
		Early	**Mid**	**Late**	**YA**
Flanker					
	cC	0.993 (.01)	0.995 (.01)	0.997 (.01)	0.999 (.004)
	cI	0.982 (.02)	0.984 (.02)	0.992 (.01)	0.997 (.01)
	iC	0.994 (.01)	0.999 (.004)	0.999 (.005)	0.999 (.003)
	iI	0.985 (.03)	0.990 (.02)	0.988 (.02)	0.992 (.01)
Simon					
	cC	0.998 (.01)	0.998 (.01)	0.999 (.004)	0.999 (.01)
	cI	0.975 (.03)	0.965 (.03)	0.972 (.03)	0.980 (.03)
	iC	0.995 (.01)	0.999 (.004)	0.999 (.01)	0.999 (.003)
	iI	0.985 (.02)	0.972 (.02)	0.982 (.02)	0.985 (.04)

Note: Early = early adolescents, Mid = mid-adolescents, Late = late adolescents, YA = young adults; cC = post-congruent congruent trials, cI = post-congruent incongruent; iC = post-incongruent congruent; iI = post-incongruent incongruent.

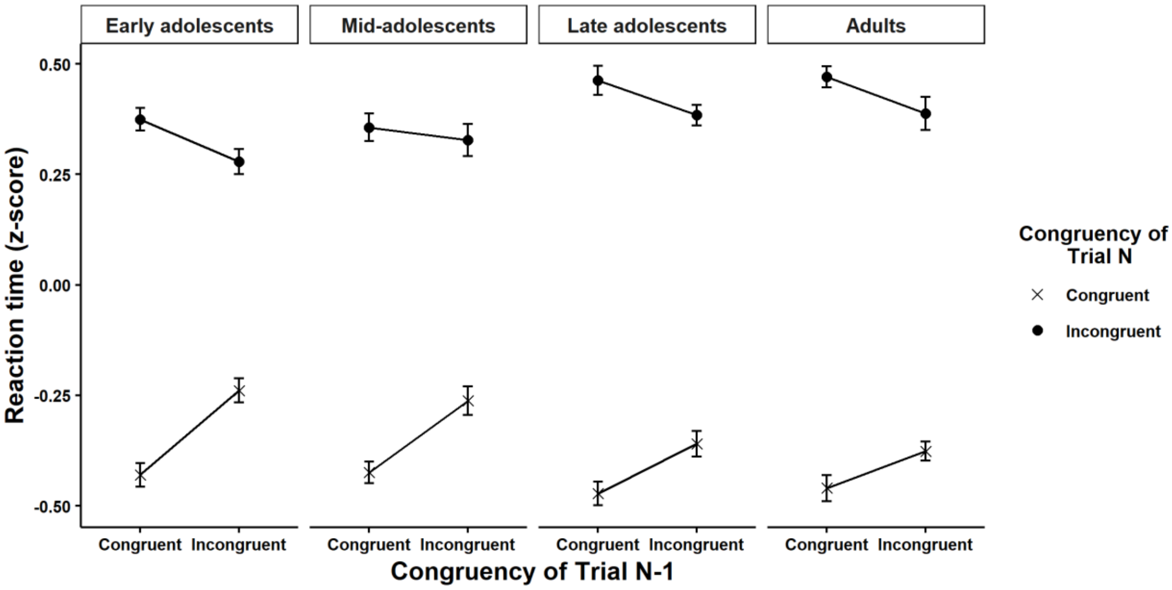
Supplementary Table 3.3 - Mean raw and standardized reaction times (SDs) for each Previous Congruency × Current Congruency condition by age group in the two conflict tasks.

		Raw RT				**Standardized RT**			
		Early	**Mid**	**Late**	**YA**	**Early**	**Mid**	**Late**	**YA**
Flanker	**cC**	611.02 (106.44)	569.67 (76.56)	501.06 (75.69)	504.58 (80.68)	-0.24 (0.15)	-0.25 (0.13)	-0.34 (0.17)	-0.39 (0.16)
	iC	619.94 (120.97)	577.58 (82.47)	506.20 (70.28)	516.54 (85.47)	-0.19 (0.12)	-0.19 (0.15)	-0.29 (0.14)	-0.25 (0.13)
	cI	680.33 (150.95)	621.14 (70.38)	566.05 (73.09)	562.28 (84.61)	0.22 (0.12)	0.23 (0.15)	0.33 (0.18)	0.33 (0.16)
	iI	676.71 (147.25)	620.95 (76.75)	564.86 (73.50)	558.63 (82.48)	0.22 (0.13)	0.21 (0.12)	0.32 (0.15)	0.30 (0.15)
	CSE	12.54	8.09	6.33	15.62	0.06	0.08	0.06	0.17
Simon	**cC**	621.13 (102.51)	590.73 (109.5)	484.25 (63.19)	516.12 (88.12)	-0.43 (0.15)	-0.42 (0.12)	-0.47 (0.14)	-0.46 (0.15)
	iC	650.37 (109.66)	616.31 (121.3)	497.19 (63.95)	525.45 (94.53)	-0.24 (0.15)	-0.26 (0.16)	-0.36 (0.15)	-0.38 (0.11)
	cI	750.67 (131.91)	705.5 (130.02)	590.1 (74.97)	618.95 (117.57)	0.37 (0.14)	0.36 (0.16)	0.46 (0.18)	0.47 (0.12)
	iI	737.89 (146.3)	703.37 (132.28)	582.9 (77.45)	610.6 (118.5)	0.28 (0.16)	0.33 (0.18)	0.38 (0.12)	0.39 (0.19)
	CSE	42.03	27.71	20.13	17.68	0.29	0.19	0.19	0.17

Note: Early = early adolescents, Mid = mid-adolescents, Late = late adolescents, YA = young adults; cC = post-congruent congruent trials, cI = post-congruent incongruent; iC = post-incongruent congruent; iI = post-incongruent incongruent; CSE = congruency sequence effect, calculated as (cI – cC) – (iC – iI) where each letter combination corresponds to the mean of that condition.



Supplementary Figure 3.1 - The effect of congruency as a function of previous trial congruency, or the congruency sequence effect (CSE) in standardized RT in the flanker task. Error bars represent +/- 1 SE.



Supplementary Figure 3.2 - The effect of congruency as a function of previous trial congruency, or the congruency sequence effect (CSE) in standardized RT in the Simon task. Error bars represent +/- 1 SE.

Chapter 4 - The Neural Correlates of Dynamic Adjustments of Cognitive Control in Early Adolescents and Young Adults

Abstract

In Chapter 3, no significant age differences were found in the magnitude of a purported marker of dynamic adjustments of cognitive control, the congruency sequence effect (CSE), across adolescence in two different conflict tasks even though control-related brain areas, e.g., ACC, DLPFC, are still undergoing maturation during this period. In the present study, we examined the neural correlates of the CSE across adolescence with the help of EEG to gain insights directly into the functioning of these brain areas. Early adolescents (ages 12-14, N = 30) and young adults (ages 25-27, N = 29) completed a confound-minimized flanker task while EEG was recorded. In analysing the neural data, we focused on the frontocentral N2 event-related potential component, and midfrontal theta oscillations because both of these measures have been linked to ACC-mediated conflict detection processes. We also investigated how conflict modulates functional connectivity between midfrontal and lateral prefrontal regions in the two age groups as a potential indicator of the broadcasting of the conflict signal from the conflict detector to the control unit, as proposed by the conflict monitoring theory. The CSE was observed in the amplitude of the N2 component and the power of theta oscillations, but was not modulated significantly by age in either. Early adolescents, however, were found to show a smaller congruency effect in theta power and the temporal consistency of theta oscillations across trials, suggesting that they were not able to recruit midfrontal control processes as flexibly and as consistently as adults in response to increased task demands. No age differences were found in functional connectivity. These findings underline the

role of midfrontal regions and theta oscillations in cognitive control, and suggest that early adolescents perform demanding tasks differently than adults at the neural level.

4.1 Introduction

Most models of cognitive development suggest that performance on tasks that require cognitive control does not reach adult-like levels until at least mid-adolescence or later (Shulman et al., 2016). However, in Chapter 3 we found that across four age groups covering the full range of adolescence from early (12-13 years of age) to late adolescence (18-19), with young adults (25-27) as a comparison group, there were no significant age differences in the congruency sequence effect (CSE). The CSE is posited to reflect the modulation of control levels in response to changing task demands, namely to the occurrence of cognitive conflict (Botvinick et al., 2001, 2004), and is taken to be the consequence of communication between the conflict monitoring component of the cognitive control circuit, i.e., the unit that detects the presence of conflict, and the response inhibition (or task demand) component, i.e., the unit that implements control. The lack of reliable age differences in our study were especially surprising given that a recent model of cognitive development across adolescence developed by Luna et al. (2015) suggests that it is exactly the communication between specialized subnetworks of the cognitive system that is still improving during the second decade of life. This notion would have predicted reduced or no modulation in younger age groups compared to adults due to less precise communication across units of control, but such an age difference was not observed.

Our findings add to a growing list of empirical findings that show no substantial difference between children and adults in terms of the magnitude of the CSE in behaviour (Cragg, 2016; Larson et al., 2012; Smulders et al., 2018; and partly, Waxer & Morton, 2011). These studies, however, employed designs that contained learning and memory related confounds (Duthoo et al., 2014a); and/or additional manipulations that could have interacted with the CSE; and/or an adult comparison group that may not have matured fully yet (between 18-24), making interpretation of findings less clear than of those presented in Chapter 3.

One possible explanation of this lack of age-related changes is that the CSE does not reflect changes in top-down control or does so only under certain circumstances or in certain tasks, a possibility that certain aspects of our behavioural study support as discussed in the previous chapter (e.g., the apparent dissociation between the CSE in the flanker and the Simon tasks). However, it is also possible that it is merely the level of investigation that is not suited for identifying developmental changes. An important question our previous study left unanswered is whether the neural mechanisms supporting performance are also similar across age groups. Given that key regions of the cognitive control networks of the brain are still maturing across adolescence (e.g., the prefrontal cortex, PFC; Gogtay et al., 2004, or the anterior cingulate cortex, ACC; Marek et al., 2015; Ordaz et al., 2013), and the functional integration between specialized brain networks underlying different component processes of control is still increasing (Luna et al., 2015; Marek et al., 2015), it is possible that even though different age groups appeared to show similar sequential modulations of congruency in RT, the neural underpinnings of behavioural performance were different across groups.

Due to its excellent temporal resolution, EEG is well-suited to investigate the neural correlates of dynamically changing, transient processes, such as conflict monitoring and conflict resolution. There are multiple ways to analyse the electrical activity of the brain, the most prominent of which is to look at the average voltage deflection across time in response to an event, e.g., the presentation of a stimulus. This is known as the event-related potential (ERP) technique which can reveal important information about the timing of different cognitive processes. A frequently investigated ERP component in conflict tasks is the frontocentral N2 (Larson et al., 2014) which is a negative deflection that peaks approximately 200-400 ms after stimulus presentation (e.g., Folstein & Van Petten, 2008; Van Veen & Carter, 2002b; Nieuwenhuis, Yeung, van den Wildenberg, & Ridderinkhof, 2003). Importantly, the magnitude of the N2 seems to track response conflict magnitude: not only is it bigger (i.e., more negative) on incongruent compared to congruent trials (van Veen & Carter, 2002a, 2002b; Yeung et al., 2004; Larson et al., 2014), it also shows sequential modulation - the CSE - as it is more negative on incongruent trials preceded by a congruent trial compared to incongruent trials preceded by another incongruent trial (e.g., Clawson et al., 2013; Clayson & Larson, 2011a; 2011b; 2013; Larson, Clayson, & Baldwin, 2012; Feldman & Freitas, 2018; Forster, Carter, Cohen, & Cho, 2011; Waxer & Morton, 2011) indicating that the process (or processes) it indexes is (are) involved in some capacity in conflict monitoring. Lending further support to this idea are source localization (Ladouceur et al., 2007; van Veen & Carter, 2002a) and intracranial studies (Wang, Ulbert, Schomer, Marinkovic, & Halgren, 2005) which suggest that the N2 is likely generated in the ACC, the conflict monitoring unit of the conflict adaptation framework (Botvinick et al., 2001, 2004).

In a review of the literature on performance (error and conflict) monitoring across the life-span, Hämmerer, Müller, & Li (2014) found that children tended to have larger N2 amplitudes than adults. This developmental finding is especially robust in Go/No Go tasks where No Go trials (trials on which a predominant response needs to be withheld) typically elicit a larger N2 than Go trials (trials where the response has to be executed, e.g., Hämmerer, Li, Müller, & Lindenberger, 2010; Johnstone, Pleffer, Barry, Clarke, & Smith, 2005; Jonkman, 2006; Lo, 2018), whereas evidence from conflict tasks is more mixed (Abundis-Gutiérrez, Checa, Castellanos, & Rueda, 2014; Clawson et al., 2017; Ladouceur, Dahl, & Carter, 2004). Hämmerer et al. (2014) suggest that this age effect means that youth respond more sensitively to conflict or experience it to a greater extent, but have trouble translating this experience into top-down control as indicated by less accurate performance and reduced error-related negativity (ERN) amplitudes after error commission, suggesting a lower focus on the correct response in this age group. The authors hypothesized that delayed maturation of the prefrontal cortex is a causal factor in this deficiency in control mobilization.

This notion provides a potential interpretation of our previous finding that there are no substantial age differences across adolescence in the size of the CSE on the behavioural level. It is possible that younger adolescents experienced greater conflict than adults but were unable to translate that into proportionally greater modulation of control – maybe due to inadequate communication between different sub-networks of cognitive control (e.g., the ACC and the dorsolateral PFC or DLPFC; Chevalier, Jackson, Roux, Moriguchi, & Auyeung, 2019; Luna et al., 2015) -, leading to a CSE that appeared adult-like. In Chapter 3, however, experience of greater conflict was not evident on the behavioural level (i.e., adolescents did not show a significantly greater congruency effect than adults in either task), further underlining the necessity to investigate the neural correlates of conflict resolution directly. To this end, in this study we recorded EEG while early adolescents (12-15 year-olds) and young adults (25-27 year-olds) completed a flanker task with learning and memory related confounds controlled for (Duthoo et al., 2014a). We expected early adolescents to show a greater conflict-related modulation of the N2 amplitude, i.e., a larger N2 congruency effect, than adults. However, we also expected the former group to show a smaller sequential modulation of the N2 component (CSE), in accordance with the idea that control mobilization is not yet fully mature at the beginning of adolescence. In addition, we investigated behavioural performance as well, expecting no substantial age-related changes in the magnitude of the CSE, in accordance with our previous study's findings.

EEG also provides information about oscillatory dynamics in the brain at different frequencies when data is transformed to the time-frequency domain (Cohen, 2014b). Out of the various frequency bands, low-frequency theta oscillations (4-7 Hz) have been most consistently linked to cognitive control-related processes (Clayton et al., 2015; Cohen, 2014a). Power in this frequency range at frontocentral electrodes has been found to increase as a function of conflict (Cohen & Donner, 2013; Hanslmayr et al., 2008; Nigbur et al., 2011, 2012), and some studies have shown that this conflict effect is also modulated by the congruency of the previous trial, resulting in a CSE pattern (Bombeke et al., 2017; Gulbinaite et al., 2014; Jiang et al., 2015; Pastötter et al., 2013; Töllner et al., 2017). These findings support the idea that changes in midfrontal theta reflect conflict monitoring processes at the neural level (e.g., Cohen, 2014a; Töllner et al., 2017). Importantly, the generation of midfrontal theta has also been linked to the ACC (e.g., Hanslmayr et al., 2008; Pastötter et al., 2013), in line with the assertions of the conflict monitoring theory (Botvinick et al., 2001, 2004). Consequently, we also explored theta-band dynamics in adolescents and young adults in response to conflict, and in interaction with trial history. We expected to find greater conflict-related modulations in theta power in early adolescents compared to adults, but smaller CSEs, in accordance with the predictions regarding the N2 component. Although just like in the case of ERP findings we must be cautious in formulating our hypothesis as there is at least one empirical study that suggests theta power increases - as opposed to decreases - as a function of age in 8-18 year-olds during response inhibition, albeit in a Go/No Go task, not a conflict task (Liu, Woltering, & Lewis, 2014).

In addition to power-related changes, the temporal consistency of theta-band oscillations across trials at a given site (electrode) can also be investigated in the time-frequency transformed signal. Inter-trial phase clustering (ITPC) is a measure that quantifies the similarity of the phases of oscillations across trials at a given time point by identifying the degree to which the phase angles of oscillations cluster around a similar value across trials at that time point, thus providing information about the consistency of the timing of oscillations from trial to trial. The lower the ITPC value is, the lower the cross-trial phase synchrony. ITPC in the theta band has been linked to intraindividual variability in behavioural performance (i.e., higher inter-trial synchronization related to lower RT variability, e.g., Cooper, Wong, McKewen, Michie, & Karayanidis, 2017; Groom et al., 2010; Papenberg, Hämmerer, Müller, Lindenberger, & Li, 2013), an index that steadily decreases with maturation (see Dykiert, Der, Starr, & Deary, 2012; Montez et al., 2017; or the findings in Chapter 3 of the present thesis). Accordingly, theta-band ITPC has also been found to increase (suggesting lower variability in the timing of oscillations) as a function of age during development (Liu et al., 2014; Müller, Gruber, Klimesch, & Lindenberger, 2009; Papenberg et al., 2013). We aimed to replicate these findings by examining the correlation between theta ITPC and RT variability, and age-related differences in theta ITPC. Because of the relationship between theta oscillations and cognitive control processes discussed above, we also investigated if response conflict and trial history, that is, current trial congruency and previous trial congruency had an effect on cross-trial phase synchrony.

Finally, time-frequency data provide information about the synchronization of the phase of theta oscillations across different brain areas as well. Phase-based measures of inter-areal functional connectivity gauge the synchronization of the timing of oscillations between two different neural populations (Cohen, 2014b). Oscillatory synchronization has been hypothesized to be an important mechanism of communication between distant neural assemblies (Buzsáki & Draguhn, 2004; Fries, 2005; Helfrich & Knight, 2016; Klimesch, Sauseng, & Hanslmayr, 2007), thus these measures can provide a direct investigation of one of the core assumptions of our hypothesis, namely that the communication between subnetworks of control is less mature at the start of adolescence than it is in young adulthood. In particular, we were interested in midfrontal to lateral-frontal communication, as captured by inter-site phase clustering (ISPC). ISPC is an analogue of ITPC, but instead of measuring the clustering of phase angles at a given electrode, it measures the clustering of the differences of the phase angles between two electrodes in a given frequency at a given time point across trials. When the phase difference is stable (i.e., clustered) across trials, showing synchronization, information transfer between neural populations is thought to be enhanced (e.g., Valera, Lachaux, Rodriguez, & Martinerie, 2001).

Synchronization between midfrontal and lateral prefrontal sites in the theta band has been shown to increase during task performance when the control demands of the task increase, e.g., during errors (Cavanagh et al., 2009) and response conflict (Cohen & Cavanagh, 2011; Gulbinaite et al., 2014; Hanslmayr et al., 2008). It is thought to reflect the signalling of conflict by the conflict monitoring unit in the midfrontal region (possibly the ACC) to the control unit in the DLPFC. In accordance with this notion, midfrontal-lateral frontal synchronization is greatest on incongruent trials that were preceded by a congruent trial, i.e., when control demands are the largest according to the conflict monitoring theory (Gulbinaite et al., 2014). We investigated whether such a pattern appears in adolescents as well as adults in our sample, and whether the strength of synchronization is weaker in adolescents compared to adults. This would be expected given the increases in the functional coupling between networks in the transition from adolescence to adulthood (Hwang et al., 2010; Marek et al., 2015) supported by grey matter thinning, synaptic pruning, and the myelination of white matter pathways in this period (Gogtay et al., 2004; Luna et al., 2015).

In sum, in the present study we investigated four aspects of the neural correlates of the CSE: 1) the amplitude of the N2 ERP component; 2) theta power at midfrontal regions; 3) the temporal consistency of midfrontal theta oscillations as captured by ITPC, and 4) the synchronization of theta oscillations between midfrontal and lateral prefrontal regions as indicated by ISPC. The first two out of these outcome measures likely reflects conflict detection processes, while the fourth is hypothesized to capture the broadcasting of the detected conflict signal to the cognitive control unit. Finally, ITPC presumably reflects intraindividual variability in the timing of the implementation of control processes. To our knowledge, this is the first study that examined the neural correlates of the CSE using a confound-minimized variant of a classic conflict task (the flanker task) making it possible to isolate – purportedly – control-related mechanisms from feature repetitions and contingency learning. The previous two studies that have looked at the ERP correlates of the confound-minimized CSE used newly-developed tasks. Larson et al. (2016) used a prime-probe word flanker task, and investigated later components, not in the N2 time range, while Feldman & Freitas (2018) used a Stroop-trajectory task with an additional Simon conflict manipulation, and importantly, did not remove complete trial repetitions from the trial sequence *a priori*, only during analysis which may weaken the engagement of control processes during task performance (Bugg, 2014). As such, our findings will provide an important contribution to the understanding of the N2 in terms of cognitive control related processes.

We are unaware of any studies investigating the CSE in theta-band dynamics that have used a completely de-confounded design, especially with a developmental focus. Consequently, the present study will also provide novel information regarding the nature of theta-band adjustments in response to changing control demands, and how these adjustments change with age, if at all.

One important caveat regarding our main hypothesis, i.e., that an adult-like CSE in adolescents may be a disproportionately smaller response to greater experienced conflict, is that in *behavioural* studies (e.g., Gyurkovics et al., in principle acceptance; Weissman, Egner, et al., 2015; Weissman et al., 2014) the magnitude of the CSE seems largely unrelated to the magnitude of conflict experienced by the individual, as indicated by the congruency effect. One explanation for this might be the low reliability of both indices (the CSE and the congruency effect) when used as individual difference measures (Hedge et al., 2018; Whitehead et al., 2018) that limits our ability to detect correlations. Another might be that the CSE is not triggered by conflict or at least its magnitude is unrelated to the magnitude of conflict. These are important questions to clarify, but are beyond the scope of the current study. The basic premise of our experiment, namely that adult-like performance in terms of the CSE in early adolescents may be supported by different neural mechanisms due to still on-going maturation of control-related areas, still stands.

A final aim of the study was to replicate the relationship between mind-wandering (MW) frequency and CSE magnitude in the flanker that was observed in the previous study. If the modest negative relationship is present in the current sample as well that will mean the association is less likely to have been spurious and thus, may be of theoretical importance for the models of both MW and the CSE. Therefore, participants in the current study also completed a Go/No Go task, the Sustained Attention to Response Task (SART, Robertson et al., 1997) with random thought probes to measure their frequency of MW during the task.

4.2 Method

We report how we determined our sample size, all data exclusions (if any), all manipulations, and all measures in the study. Data files and the analysis script for this study are available on the Open Science Framework at the following URL: https://osf.io/yaj36/

4.2.1 Participants

Fifty-nine participants completed the experiment, 30 were early adolescents (12-14 year-olds, mean age = 13.39, SD = .87, 12 females, mean self-reported puberty score

= 2.95 ± 1.19), and 29 were young adults (25-27 year-olds, mean age = 26.30, SD = .90, 19 females). Three additional participants were removed because they reported psychiatric or neurological conditions. One early adolescent participant had no Go/No Go and MW data because they accidentally aborted the second task during data collection. All participants received £12 compensation for taking part. The study was approved by the Ethics Committee of the Department of Psychology, University of Sheffield.

Group-level target sample sizes were set to match those of the previous study. This still reflects an increase in statistical power for the conflict task analyses compared to that experiment, as the number of observations in the task was more than doubled (160 vs. 72 trials by condition).

4.2.2 Materials

4.2.2.1 Conflict task

Participants completed a confound-minimized arrow flanker task, in which they had to identify the direction of the central arrow – up, down, left, or right – in an array of five arrows displayed in the centre of the screen (Fig. 4.1A). The four irrelevant distractor arrows flanking the target could point either in the same direction as the central target (congruent trials), or in a different direction (incongruent trials). The proportion of congruent trials was 50%, and the number of observations in the four within-subject conditions of interest (iI, cI, cC, and iC where i/I is incongruent and c/C is congruent, and lowercase letters indicate the congruency of the previous trial and upper case letters indicate the congruency of the current trial) was balanced. The same strategy was used as in the previous study to avoid feature repetition and contingency learning confounds: the four arrow directions were randomly split into two sets of two, and features in one set were used exclusively on odd trials whereas features in the other were used exclusively on even trials.

The task started with 24 practice trials (this was extended with an additional 12 trials if the participant did not give at least 19 correct responses). Feedback was given after every trial during the practice session. Experimental sessions consisted of 8 blocks of 81 trials separated by short self-paced breaks, resulting in a total of 648 trials. In each block, there were 20 trials in each condition (cC, iC, iI, cI). The congruency of the first trial – which was not included in further analyses - was determined randomly for each block.

The parameters of stimulus presentation were altered in the following way compared to the previous study's design: each flanker trial started with the presentation of the distractor arrows without the target arrow present. After 200 ms, the target arrow appeared and the whole array of arrows remained on screen for 200 ms. The stimulus onset asynchrony between distractors and the target was included to maximize conflict, and to bring our paradigm in line with previous EEG studies which typically employed a similar prime-probe design (e.g., Bombeke et al, 2017; Clawson et al., 2013, 2017; Clayson & Larson, 2011a; 2011b; 2013; Larson et al., 2012). Stimuli were presented in black on a grey background. Participants had to indicate the direction of the target arrows by pressing the 2, 4, 6, or 8 keys on the numeric keypad to respond down, left, right, or up, respectively, within 3000 ms of target presentation. Participants were asked to use the index finger of their dominant hand. Following the target stimulus, a fixation cross was presented for 1000 ms if the response to the target was correct, and error feedback was provided for 1000 ms in case the participant responded incorrectly ('ERROR') or too slowly ('TOO SLOW'). The next trial started after a variable ITI of 300-900 ms.

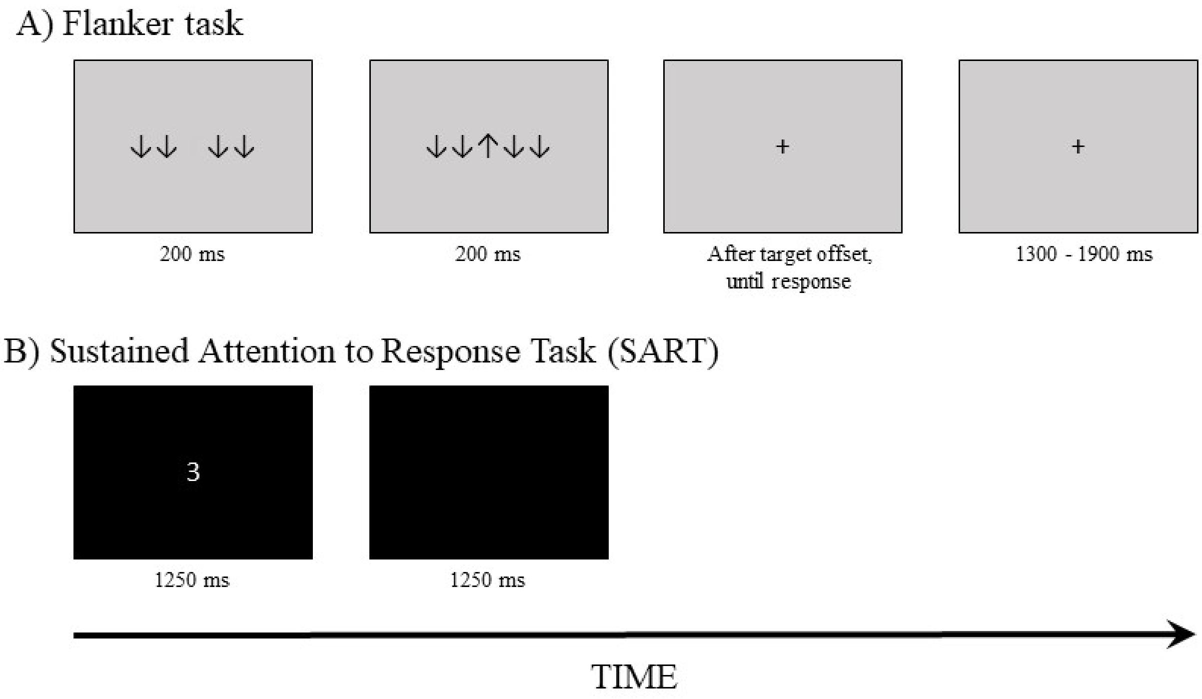


Figure 4.1 - Task designs in the study. A) Design of the flanker task. Participants had to identify the direction of the central arrow. An incongruent trial is pictured. B) Design of the Sustained Attention to Response Task (SART). Participants had to press SPACE every time a digit appeared (Go trials) except if the digit was 3 (No Go trial, pictured).

4.2.2.2 Sustained Attention to Response Task

The design of the SART was identical to that described in Chapter 3 (Fig. 4.1B). Participants had to press the SPACE bar every time a digit between 1 and 9 appeared on screen, except if that number was 3. In other words, digits 1, 2, and 4 to 9 were identified as Go stimuli, and the number 3 was identified as the No Go stimulus. With the exception of number identity, Go and No Go trials were identical. There were two blocks of 131 trials, resulting in a total of 262 trials. The two blocks were separated by a short self-paced break. Out of the 262 trials, 224 (85.5%) were Go trials, and 28 (10.69%) were No Go trials. On the remaining 10 trials (3.82%) instead of a digit, participants saw the following probe question until they responded: "Please choose the one option below that best describes your experience with the task just now" (see Gyurkovics et al., 2018; Jackson & Balota, 2012). The options were: "I was thinking about the task", "My mind was blank”, “My mind drifted to things other than the task, but I wasn’t aware of it until you asked me”, and “While doing the task I was aware that thoughts about other things popped into my head”; corresponding to on-task thoughts, space outs, zone outs, and tune outs respectively (Smallwood et al., 2007). Trials were intermixed pseudo-randomly, so that targets (No Go trials) were never preceded or immediately followed by another target or a probe. Proportions of different trial types were identical across the two blocks. On digit trials (Go or No Go trials), a digit in white was presented on black background in the centre of the screen for 1250 ms. The stimulus was then followed by an intertrial interval of 1250 ms, during which a blank black screen was presented. No performance feedback was provided during the experimental blocks. The two experimental blocks were preceded by three practice blocks. In the first, participants completed 9 trials (1 target), and received feedback on their performance after each one. In the second one, participants similarly completed 9 trials with feedback, however, this time a probe question was also added. In the final practice block, 9 trials and a probe appeared, with no feedback. As such, this practice block was identical to the experimental blocks except in duration. All tasks were programmed using the Psychtoolbox extension (Brainard, 1997; Kleiner, Brainard, & Pelli, 2007) in MATLAB R2014b.

4.2.3 Procedure

4.2.3.1 Tasks

After obtaining informed consent, including parental consent as well in the case of adolescents, participants first completed the Positive and Negative Affect Schedule (PANAS; Watson et al., 1988) for the first time (PANAS1). After that they were set up for the EEG recording (see below), and completed the flanker task which lasted approximately 25-30 minutes. Upon completion of the task, the EEG recording was terminated and the electrode cap removed. Participants then completed the PANAS for a second time (PANAS2), along with a self-rated measure of pubertal development

(Carskadon & Acebo, 1993), as is standard practice in our lab. Finally, the SART was administered, which lasted approximately 10-15 minutes. Participants also completed the Mind-Wandering Questionnaire (MWQ; Carriere et al., 2013), either before or after the SART (counterbalanced). Altogether, one experimental session lasted about 75-90 minutes.

4.2.3.2 EEG recording and pre-processing

EEG was recorded using a Biosemi ActiveTwo 64-channel EEG System (Amsterdam, the Netherlands). Electrodes were fitted according to the 10-20 system. EEG data was digitised by Biosemi ActiView software, at a sampling rate of 2048 Hz. The continuous data was subsequently down-sampled to 512 Hz off-line. The down-sampled data was then pre-processed and analysed using the EEGLAB 14.1.2 and ERPLAB 5.0 MATLAB toolboxes (Delorme & Makeig, 2004; Lopez-Calderon & Luck, 2014) and custom MATLAB scripts available on the OSF page of the project.

First, data was re-referenced to the average of all electrodes, and high-pass filtered using an infinite impulse response (IIR) Butterworth filter with a half-amplitude cut-off of 1 Hz to remove low frequency noise such as drifting caused by sweating. Then, the CleanLine plugin (Mullen, 2012) was used to attenuate 50 Hz noise originating from sources of alternating current (AC) in the environment, such as power lines. In the next step, channels containing excessive amounts of noise as determined by visual inspection were removed (average number of channels removed per participant: 4.29 ± 1.79), and an independent component analysis (ICA) was run to identify blink- and eye movement-related activity. Components representing these were subtracted from the data. The output of the ADJUST toolbox for artefact removal (Mognon, Jovicich, Bruzzone, & Buiatti, 2011) was used to help identify potential noise components. Finally, previously removed channels were interpolated using spherical spline interpolation (Perrin, Pernier, Bertrand, & Echallier, 1989).

After these steps, continuous data was segmented into 1200 ms long epochs beginning 400 ms before presentation of the target arrow (and thus 200 ms before presentation of the distractors) and concluding 800 ms after target presentation. Baseline activity from the period -400 ms to -200 ms was subtracted from the resulting epochs. Any epochs with voltage deflections exceeding ± 150 μV were removed from the data. Epochs where the participant's eventual response was incorrect and epochs immediately following error trials were also removed from the data. Epochs were classified into four categories based on current trial congruency (congruent vs. incongruent) and previous trial congruency (congruent vs. incongruent).

Table 4.1 shows the mean number of epochs left in each condition for the two groups after screening. The F- and p-values correspond to ANOVAs contrasting the means between groups. Adolescents had significantly fewer trials in all but one condition, however, all conditions contained a reasonably high number of trials (> 130).

Table 4.1 - Mean number of epochs (*SD*) in each condition and in each group. Maximum trial number for each condition is 160.

	Early adolescents	**Young adults**	**F**	**p**
iI	139.7 (16.57)	150.966 (12.173)	8.81	0.004
iC	143.067 (14.482)	151.931 (12.071)	6.5	0.014
cI	142.167 (14.849)	151.241 (11.125)	7.02	0.01
cC	148.3 (9.858)	153.414 (11.645)	3.32	0.074

Note: iI = incongruent preceded by incongruent; iC = congruent preceded by incongruent; cI = incongruent preceded by congruent; cC = congruent preceded by congruent. The degrees of freedom were (1,57) for all ANOVAs.

After artefact removal, epoched data were Laplacian transformed by using the laplacian_perrinX() MATLAB function created by Cohen (2014b). This transformation is a spatial filter that attenuates spatially broad features of the data, by subtracting the sum of activity across all electrodes weighted by inter-electrode distances from the activity of each electrode (Cohen, 2014b). This improves topographical localization and attenuates volume conduction effects, therefore it optimizes data for connectivity analyses (e.g., ISPC; Gulbinaite et al., 2014). Volume conduction, the spreading of current in every direction across a conductive material, introduces artefactual similarities between voltages at nearby electrodes, therefore it needs to be accounted for before connectivity can be investigated.

4.2.4 EEG analyses

4.2.4.1 Analysis in the time domain - ERPs

Electrode FCz was chosen as the electrode of interest in all analyses based on previous studies focusing on the N2 (e.g., Clawson et al., 2013, 2017; Clayson & Larson, 2011a; 2011b; 2013; Danielmeier, Wessel, Steinhauser, & Ullsperger, 2009; Larson et al., 2012; Riesel, Klawohn, Kathmann, & Endrass, 2017; Yeung et al., 2004) and cognitive control-related time-frequency effects (e.g., Cavanagh et al., 2009; Gulbinaite et al., 2014) in which the FCz has been the most commonly investigated electrode. Scalp topography of grand-average ERPs and power were also inspected visually to confirm the choice of electrode. For ERP analyses, a trial-by-trial variant of the adaptive mean procedure was used to quantify event-related changes in brain activity (Clayson, Baldwin, & Larson, 2013). In this procedure, first a local peak is identified in the time window of interest for each individual trial of each participant, and then the mean amplitude is extracted from a smaller time window around the identified peak, resulting in a peak latency and a mean amplitude value for every trial. This was preferable to the simple mean amplitude procedure (i.e., averaging down amplitude values across a fixed time window for every trial) because we were not forced to use the same time window for every participant. This would have been problematic in case there was a latency difference between groups in the peak of the N2 component which would make it difficult to find a single time window that effectively captures the component in both groups. In our study, the time window for (negative) peak identification was 200 ms to 350 ms after target presentation based on visual inspection of grand-averaged ERPs (Fig. 4.2A, previous studies have used similar time windows, see e.g., 210 to 340 ms in Li, Liu, & Shi, 2019). Mean amplitude was then taken from a smaller time window within this greater window, starting 15 ms pre-peak and ending 15 ms post-peak, on every trial. As peak identification can be susceptible to high frequency noise (e.g., a random fluctuation could be identified as the local peak, instead of the deflection reflecting the true signal), segmented EEG data was low-pass filtered for time domain analyses, using an IIR Butterworth filter with a half-amplitude cut-off of 30 Hz.

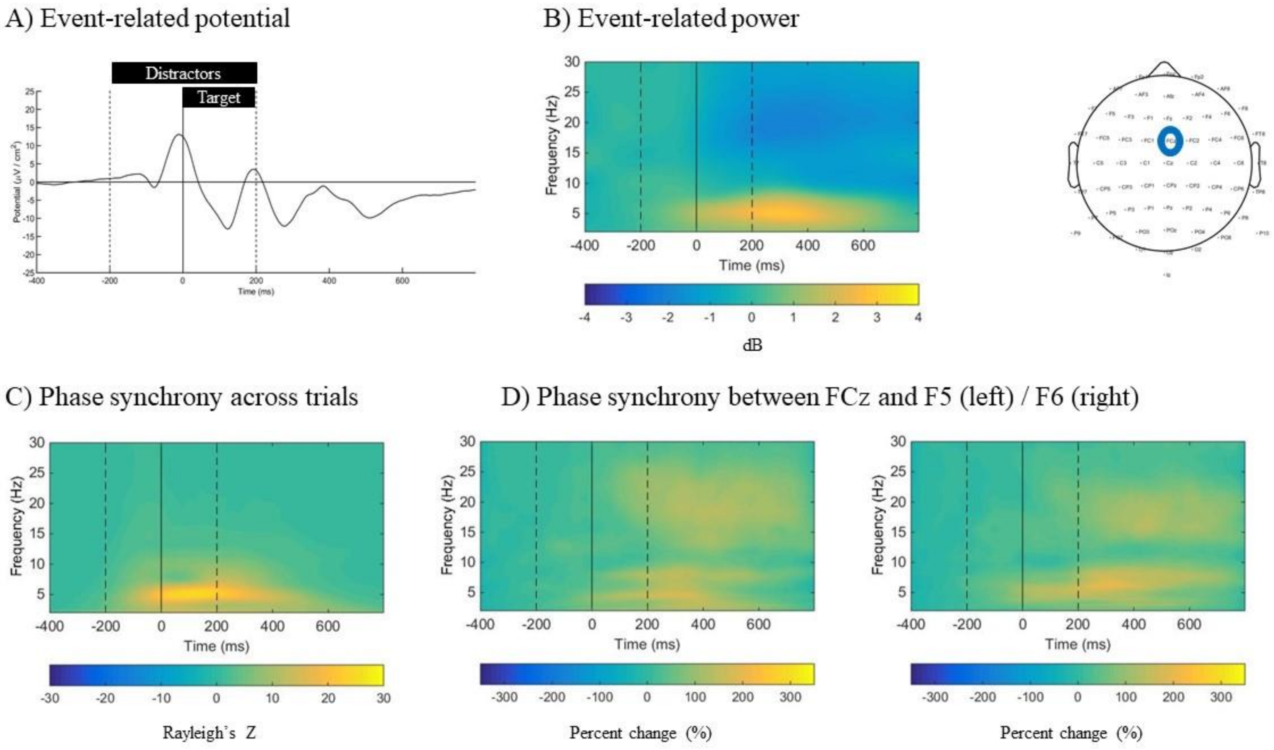


Figure 4.2 - A) Grand average event-related potential (ERP) waveform in the time domain. B) Grand average power at the trial level. C) Grand average inter-trial phase clustering (ITPC) across trials as a function of time. D) Grand-average inter-site phase clustering (ISPC) between electrode FCz and electrodes F5 (left) / F6 (right) at the trial level. On all figures the first dashed line indicates the onset of the distractors, the bold line at time 0 the onset of the target, and the second dashed line the offset of both the target and distractors.

4.2.4.2 Analysis in the time-frequency domain - power and phase synchrony

Power. For time-frequency analyses, epoched data were transformed to the time-frequency domain via Morlet wavelet convolution. A Morlet wavelet is a sine wave windowed by a Gaussian taper (Cohen, 2014b). Time-frequency information can be gleaned from the EEG signal by taking the Fourier transform (power spectrum) of the epoched data and multiplying it with the Fourier transform of Morlet wavelets of different frequencies, and then computing the inverse Fourier transform of the product spectra. Power values are then obtained from the resulting complex signal by squaring the length of the complex vector at each time point in each frequency. In our study, 30 frequencies were used, logarithmically spaced between 2 Hz and 30 Hz, and the width of the Gaussian tapers (i.e., the number of cycles of the taper used to create the Morlet wavelet) increased with the frequency, from 3 to 10, to ensure that frequency precision was similar across frequencies. Finally, power was normalized using a decibel (dB) transform (dB power = 10 × log 10[power/baseline]) where baseline activity represented the average power across all trials from -400 ms to -200, i.e., the first 200 ms of the epoch, before the appearance of the distractor arrows. This transforms the data to the same scale across different conditions and subjects, thereby facilitating comparisons.

To quantify event-related changes in power, a strategy similar to the adaptive mean strategy introduced above for ERPs was used. Peak post-target power was identified for each participant on every trial within a time window of 0 ms to 500 ms, and in the frequency band ranging from 2 to 10 Hz (Cohen, 2014b). The time window was determined after visual inspection of grand average power (Fig. 4.2B). After maximal power was found, a time window extending 25 ms before and 25 ms after the peak time-frequency point was identified. Power was then averaged down in this window, across a band of frequencies stretching ± ~ 2 Hz around the frequency of the maximum power value. Thus, at the end of the procedure we had information about the a) latency of maximal post-target power, b) the frequency of maximal post-target power, and c) the mean power in a time window surrounding this maximal value for every trial.

Inter-trial phase clustering. For ITPC analyses, the same time-frequency domain transformation procedure was run as described above (Morlet wavelet convolution), but instead of extracting power values for every trial, the similarity of the phase angles of oscillations at each time point across trials in a given condition was quantified by determining how clustered they are in polar space. Data was aggregated within a condition because ITPC is not defined for a single trial as it reflects cross-trial phase synchrony. Consequently, every participant had 4 ITPC values (instead of as many as the number of trials), corresponding to the four conditions (cC, cI, iC, iI). In general, an ITPC value of 0 indicates no phase synchrony, i.e., the phase angles of the different trials are uniformly distributed in polar space at time point N, there is no clustering; whereas a value of 1 would mean phase angles are identical across trials, meaning perfect synchronization. For analyses, conditional values were extracted using a strategy similar to the one described for ERPs and power: first, a sample-level time window was defined based on the grand average data (Fig. 4.2C, covering frequencies from 2 to 10 Hz, and time points from 0 ms to 400 ms post-target), then for each participant and each condition, the maximum ITPC value was identified within this larger window, and a smaller window of the same parameters described above for power analyses was defined around it. The mean ITPC within this latter window was used in further analyses. To avoid the potential biasing effect of slight differences in trial number across conditions (e.g., due to the removal of error and post-error trials), ITPC values were transformed to Rayleigh's Z by squaring the raw ITPC values and multiplying them by the number of trials in the given condition (Cohen, 2014b). While this changes the scale of the measure (it is no longer bound by 1), it does not change its interpretation, i.e., larger values mean more clustering, and thus, more consistency across time.

Inter-site phase clustering. As mentioned in the Introduction (Section 4.1), ITPC and ISPC are analogous measures, but for ISPC analyses, the distribution of phase angle differences between two electrodes is examined in the polar space. The actual phase lag between electrodes is unimportant, the magnitude of ISPC is dependent only on the *consistency* of phase difference values between the electrodes across trials at a given time point. If consistency is high, i.e., phase angle differences are clustered around a value, ISPC will be high too (with a maximum of 1), and if phase angle differences are distributed randomly, with no clustering, ISPC will be low (with a minimum of 0). In the current study, phase differences were calculated between electrode FCz (seed) and electrodes F5 and F6, representing the dorsolateral prefrontal cortex based on previous work (Cavanagh et al., 2009; Gulbinaite et al., 2014). Similarly to ITPC, ISPC values were also extracted from condition-aggregated data, resulting in 4 ISPC values for each participant, and for each electrode pair (FCz – F6, and FCz – F5). ISPC values were quantified using the same strategy described above for ITPC: a sample-level time window was established based on the grand average ISPC plot (Fig. 4.2D, here ranging from 0 ms to 500 ms) in the frequency band of interest (2-10 Hz), and then smaller windows of interest were identified within this larger window for each condition and each participant, in a manner identical to the ITPC analyses. ISPC values were also converted to Rayleigh's Z.

4.2.5 Statistical analyses

Behavioural data was analysed using a similar strategy to our previous study. To clean the data, RTs shorter than 150 ms were removed. This resulted in the removal of only 0.37% of trials in the flanker and 2.49% of trials that had RTs in the SART. Then outliers, identified as trials with RTs beyond 3 SDs of the participant's mean were also removed. This resulted in the removal of further 1.01% and 1.31% of trials in the flanker and the SART, respectively. For RT analyses in the flanker task, error trials and trials immediately following error trials were also removed. For accuracy analyses, no trials were removed.

For the flanker analysis, a general linear mixed-effects model with variables Previous Congruency (0: congruent, 1: incongruent), Current Congruency (0: congruent, 1: incongruent), and Age Groups (0: adults, 1: adolescents) and their interactions as predictors was run, with RT as the outcome, using the “lme4” package in R (Bates et al..2015). The structure of the random effects was determined by inspecting the Akaike Information Criteria (AIC) of models with random effects structures of different complexity, as in Chapters 2 & 3. Significance of terms in the model with the lowest AIC value was determined using the Anova() function of the “car” R package (Fox & Weisberg, 2019).

A similar generalized linear mixed effects model was run for accuracy analyses with trial level accuracy as the outcome. Similarly to our previous study, for the sake of brevity accuracy analyses of the conflict tasks will only be presented if they in any way contradict or complement RT analyses.

Data from the SART was analysed by similar general and generalized linear models, but with Trial Type (0: Go, 1: No Go), Age Group, and their interaction as predictors.

Group differences in MW frequency in the SART and the relationship between CSE magnitude and MW frequency were investigated with generalized linear mixed-effects models. In these analyses, binary dummy variables indicating whether a given thought report category was chosen in response to a probe question or not were the outcome variables, in a fashion identical to the strategy used in our previous study. The

CSE magnitude variable in these analyses was created by using the following equation for every participant: (cI – cC) – (iI – iC) where each letter combination refers to the mean RT of that condition.

ERP data and time-frequency power data were analysed using general linear mixed-effects models with predictors identical to the one investigating RT. However, in these analyses, the outcomes were trial-level mean amplitude and trial-level mean power. EEG data was analysed this way to maintain a consistent analytic strategy across behavioural and neural observations. For neural findings, however, multilevel models might be disadvantageous because single-trial ERPs and oscillatory changes might be subtle, thus trial-by-trial estimations of amplitude and power might increase noise and decrease power (e.g., on the single trial level, noise might have a bigger effect on where peak amplitude / power is than in aggregated data).

For this reason, neural results were also analysed by running the adaptive mean amplitude and adaptive mean power calculations on data aggregated across different conditions, resulting in four values for each participant (amplitude/power in the iC condition, in the cC condition, etc.) instead of as many as the number of trials per participant. Note that this is not equivalent to averaging down the trial-level data obtained for power and amplitude because in those data sets the location of the peak differs from trial to trial from the peak of the aggregated data. In essence in these condition-aggregated analyses we calculated the adaptive means of average activity per condition, instead of the average of the adaptive means within a condition. These conditional means were then analysed via a mixed ANOVA, with Age Group as a between-subject factor and Previous Congruency and Current Congruency as within-subject factors. ITPC and ISPC values were only analysed this way as these measures were not defined on the individual trial level, therefore using a mixed-effects approach was not necessary. For the sake of brevity, analyses of peak latency for the various outcomes are not reported because we formulated no *a priori* hypotheses about these measures, and because using peak latency is discouraged - at least in the time-domain - due to the measure’s high susceptibility to noise (Clayson et al., 2013).

For each participant, two neural CSE indices were also calculated using the same equation as in the behavioural analyses, but with adaptive mean amplitude and adaptive mean power (from the ANOVA-type analyses) instead of mean RT. These indices were then correlated with the behavioural CSE index using Kendall’s τ, and were also entered into separate generalized mixed-effects models as predictors with MW frequency as outcome to investigate whether the CSE-MW relationship can be observed on the neural level as well. Finally, the relationship between ITPC and behavioural variability was examined by correlating the conditional ITPC values with the corresponding conditional coefficients of variation (CV, RT SD / mean RT), e.g., iI ITPC with iI CV.

The alpha level was set to .05 in all analyses.

4.3 Results

4.3.1 Behavioural findings

4.3.1.1 Conflict task performance

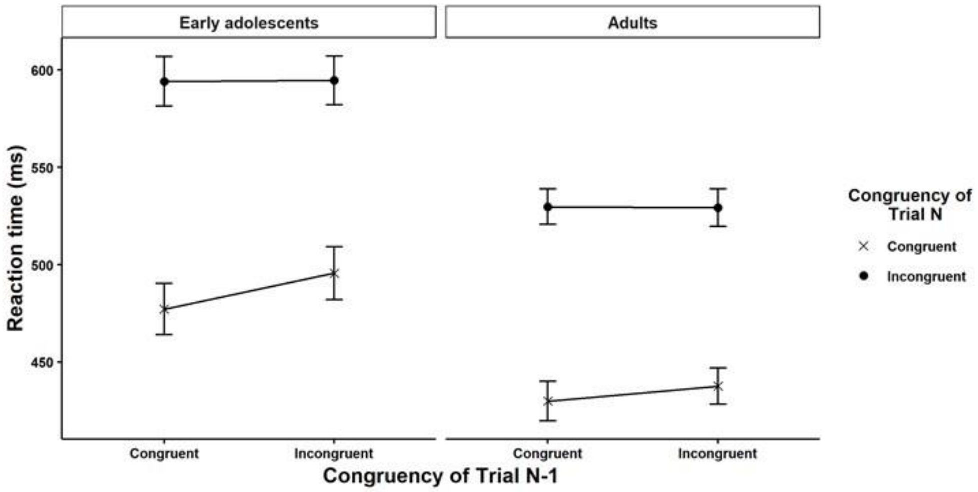
First, we report the findings of the linear mixed-effects models investigating behavioural performance on the flanker task across groups. Table 4.2 summarizes the two models of interest, one with raw RT as the outcome and the other with standardized RT to control for baseline speed differences across groups. The CSE is the Previous Congruency × Current Congruency interaction, and it is significant in both models. While there is a small age effect in the magnitude of the CSE in raw RT whereby the size of the effect is smaller in adults than in early adolescents (Fig. 4.3), this effect is no longer present after controlling for the speeding of RT as a function of age. In accordance with our previous findings (Chapter 3), there is an age-related increase in the size of the congruency effect (Age Group × Current Congruency) in standardized RT.

Table 4.2 - Terms from the two general linear mixed-effects models investigating flanker task performance in raw and standardized RT across age groups.

Model (AIC value)	**Raw RT** (436972.9)		**Standardized RT** (90405.1)	
	$\chi^2(1)$	**p**	**$\chi^2(1)$**	**p**
Congruency (C)	1047.438	<.001	922.436	<.001
Previous Congruency (PC)	39.001	<.001	42.37	<.001
Age Group	16.469	<.001	4.588	0.032
C × PC (CSE)	37.439	<.001	48.245	<.001
C × Age Group	3.748	0.053	15.204	<.001
PC × Age Group	7.919	0.005	3.912	0.048
C × PC × Age Group	5.499	0.019	1.746	0.186

Note: CSE = congruency sequence effect, AIC = Akaike Information Criterion. For both the raw RT and the standardized RT analyses, the model with random slopes for the main effect of C per participant was selected over models with slopes for the PC × C interaction, or no random slopes at all. The AIC values of the competing models were: 436986.4 and 437287.9, respectively, in the raw RT analysis, and 90408.9 and 90933.6, respectively, in the standardized RT analysis.

A) Congruency sequence effect (CSE) in raw RT



B) Congruency sequence effect (CSE) in standardized RT

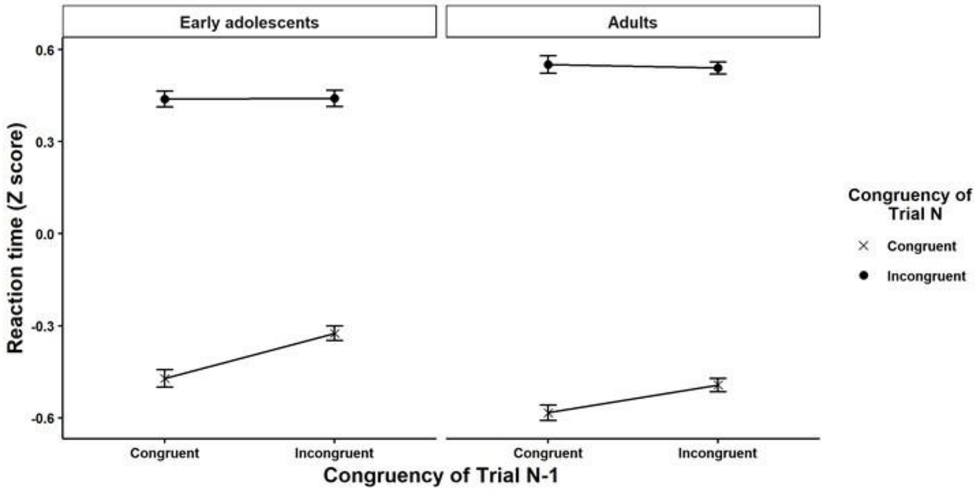


Figure 4.3 - The effect of congruency as a function of previous trial congruency, or the congruency sequence effect in raw (A) and standardized RT (B) in the flanker task. Error bars represent +/- 1 SE.

4.3.1.2 Go/No Go task performance and mind-wandering

Performance on the SART Go/No Go task was investigated next. Descriptive data from this task and the results of the models investigating performance are summarized in Tables 4.3 and 4.4, respectively. For both raw RT and accuracy, main effects of Age

Group and Trial Type were found, along with an Age Group × Trial Type interaction. Early adolescents were slower and more error prone than young adults. All participants were more accurate on Go trials than on No Go trials, and this difference was significantly bigger in early adolescents than in young adults. Participants were also slower on correct Go trials than on incorrect No Go trials, a difference that was amplified in early adolescents in raw RT. The Age Group × Trial Type interaction, however, was no longer significant after controlling for baseline speed differences (standardized RT analyses).

Table 4.3 - SART task performance indices – means (*SD*s) – for early adolescents and young adults.

	Early adolescents	**Young adults**
Go RT	547.28 (71.11)	428.74 (50.76)
No Go RT	439.65 (67.05)	374.19 (74.53)
Go zRT	0.02 (0.01)	0.01 (0.01)
No Go zRT	-0.62 (0.41)	-0.54 (0.57)
Go Accuracy	0.97 (0.05)	0.998 (<0.01)
No Go Accuracy	0.70 (0.17)	0.84 (0.14)

Table 4.4 - Terms from the linear mixed-effects models investigating SART performance in raw RT, standardized RT, and accuracy across age groups.

Model (AIC value)	**Raw RT** (163125.2)		**zRT** (36295.9)		**Accuracy** (3282.2)	
	$\chi^2(1)$	**p**	**$\chi^2(1)$**	**p**	**$\chi^2(1)$**	**p**
Trial Type	115.996	<.001	113.844	<.001	224.374	<.001
Age Group	48.483	<.001	0.279	0.597	26.207	<.001
Trial Type × Age Group	6.812	0.009	<.001	0.996	13.161	<.001

Note: AIC = Akaike Information Criterion. For the raw RT and accuracy analyses, models with no random slopes were selected. For the standardized RT analysis, the model with random slopes for Trial Type by participant was selected. The AIC values for the competing models in the raw RT, standardized RT, and accuracy analyses were 163127.1, 36299.9, and 3335.2, respectively.

As intraindividual variability was strongly affected by age in our previous study (Chapter 3), behavioural variability, as indicated by the coefficient of variation (CV) of Go RTs (Go RT SD / mean Go RT) was examined in the current sample too. Replicating previous findings, it was significantly higher in early adolescents compared to young adults (with means of 0.31 ± 0.06 vs. 0.20 ± 0.05, respectively), $F(1, 56) = 69.39$, $p < .001$.

Examining MW frequency during the SART (Fig. 4.4), we failed to replicate our previous finding of age-related differences in the frequency of MW with awareness, $\chi^2(1) = .713$, $p = .399$; $OR = .798$, 95% CI[.463, 1.361]. The effect of Age Group was not significant for any of the other probe response types either. In accordance with the analysis presented in Chapter 3, an overall-MW category was created once more by combining reports of MW with and without awareness. This analysis was suggested by a reviewer (Dr Mike Kane) for the manuscript of the paper presented in Chapter 3, after data analysis has already taken place for the present study. As such, all analyses concerning overall-MW were only conducted to make the Results sections of these two studies consistent, but were otherwise unplanned. This analysis also revealed no effect of age. The effect of Age Group on trait-level spontaneous and deliberate MW frequency (as measured by the MWQ) failed to reach significance as well (all *p*s > .05).

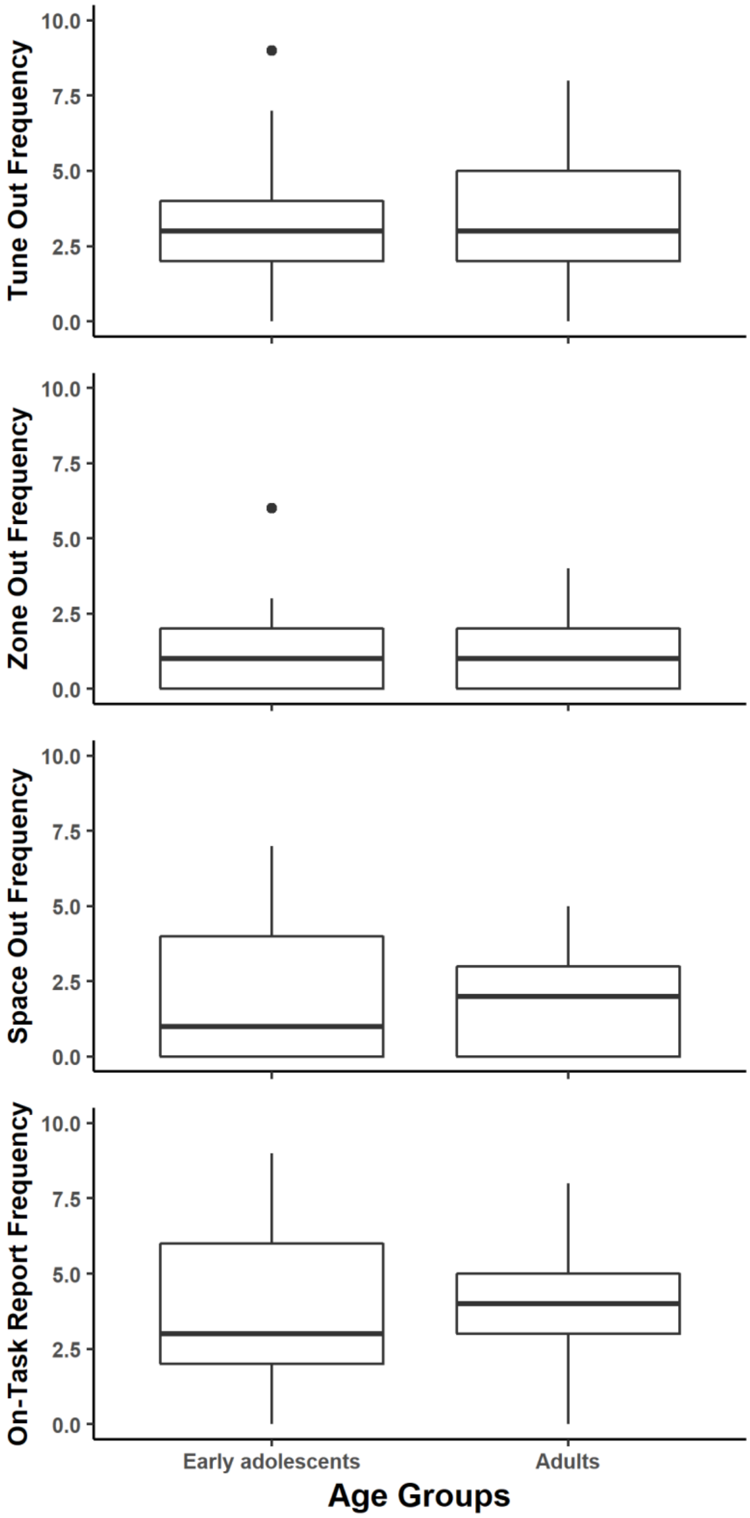


Figure 4.4 - Box-plots of the frequencies of different categories of thought reports across age groups during the Sustained Attention to Response Task (SART).

Finally, we replicated our previous finding that the magnitude of the CSE predicts MW frequency across age groups. It positively predicted on-task report frequency in both raw RT, $\chi^2(1) = 6.07$, $p = .014$; *OR* = 1.020, 95% CI[1.004, 1.038], and standardized RT, $\chi^2(1) = 4.21$, $p = .040$; *OR* = 5.605, 95% CI[1.064, 31.430]. It was negatively related to MW with awareness in both, $\chi^2(1) = 9.93$, $p = .002$; *OR* = .977, 95% CI[.962, .991], for raw RT and $\chi^2(1) = 6.69$, $p = .010$; *OR* = .135, 95% CI[.027, .617], for standardized. Similar relationships appeared for overall-MW as well, $\chi^2(1) = 5.77$, $p = .016$; *OR* = .983, 95% CI[.968, .997], for raw RT and $\chi^2(1) = 4.44$, $p = .035$; *OR* = .204, 95% CI[.044, .909], for standardized

Similarly to our previous study's findings, no hypothesized behavioural index of MW (accuracy and RT variability in the SART) correlated with MW frequency in our sample. However, the Spontaneous subscale of the MWQ (measuring unintentional MW frequency in everyday life) negatively predicted on-task report frequency, $\chi^2(1) = 8.94$, $p = .003$; *OR* = .734, 95%CI[.592, .899], and positively zone out (MW without awareness) frequency during the SART, $\chi^2(1) = 6.23$, $p = .013$; *OR* = 1.457, 95% CI[1.096, 2.011].

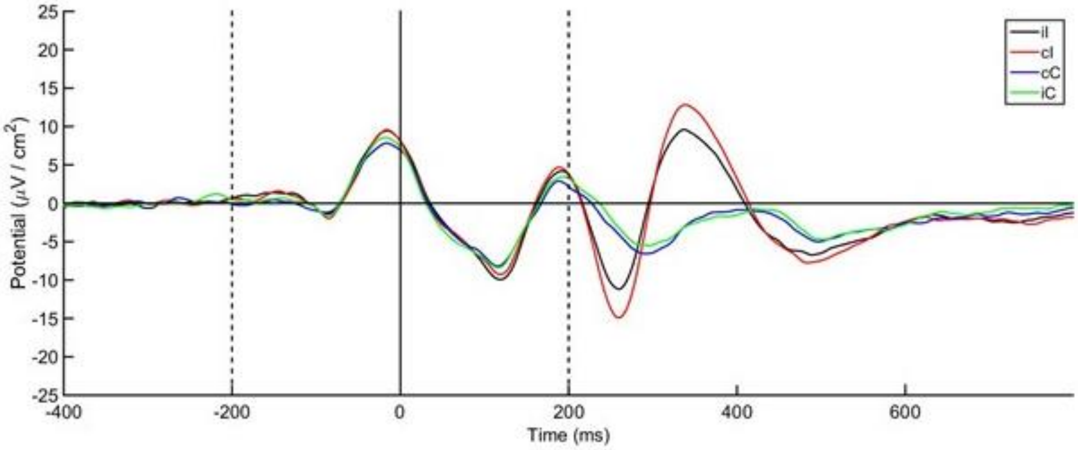
4.3.2 EEG results

Next, neural data was examined to see if the neural correlates of conflict detection and conflict signalling processes differ between adolescents and adults.

4.3.2.1 Event-related potential analyses – N2 component

As a first step, data was investigated in the time domain. Stimulus-locked ERPs at electrode FCz for all four conditions (cI, iI, cC, iC), in both age groups are depicted in Figures 4.5 and 4.6. Statistical analyses (Table 4.5) revealed a main effect of Current Congruency as a greater negative deflection was observed on incongruent trials compared to congruent trials in the N2 time range (Fig. 4.7). The Previous Trial Congruency × Current Congruency interaction was also significant, suggesting the presence of the CSE. Neither effects were modulated by age, although Age Group had a significant main effect, as early adolescents showed greater negative deflections than adults in the N2 time window across conditions. The corresponding ANOVA analysis conducted on condition-aggregated data corroborated these findings (Table 4.6).

A) Event-related potentials at electrode FCz in adults



B) Event-related potentials at electrode FCz in adolescents

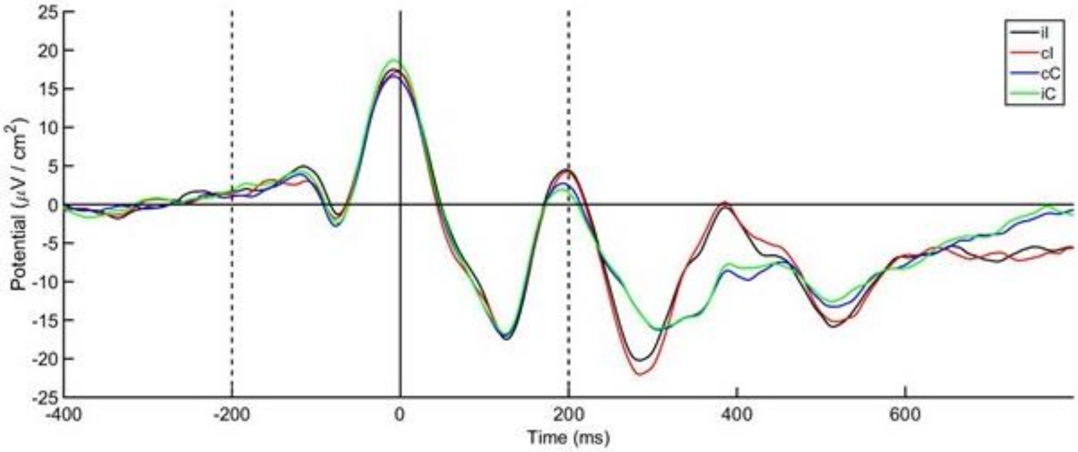


Figure 4.5 - Event-related potentials at electrode FCz as a function of previous trial congruency and current trial congruency in the two age groups. On both figures the first dashed line indicates the onset of the distractors, the bold line at time 0 the onset of the target, and the second dashed line the offset of both the target and distractors. iI = incongruent trials preceded by an incongruent trial; cI = incongruent trials preceded by a congruent trial; iC = congruent trials preceded by an incongruent trial; cC = congruent trials preceded by a congruent trial.

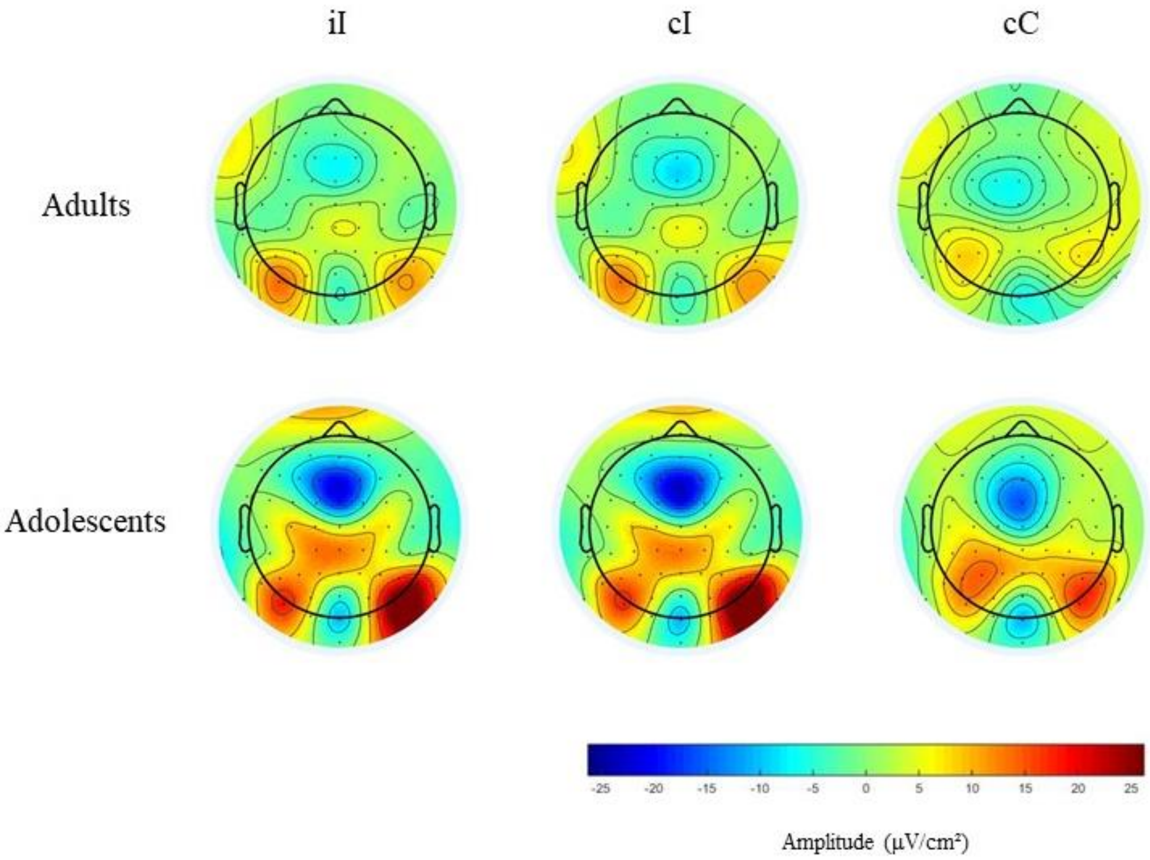


Figure 4.6 - Scalp topography of mean amplitude calculated from a 30-s time-window around the group-specific grand-average peak latency (280 ms for adults, 300 ms for adolescents). iI = incongruent trials preceded by an incongruent trial; cI = incongruent trials preceded by a congruent trial; iC = congruent trials preceded by an incongruent trial; cC = congruent trials preceded by a congruent trial.

Table 4.5 - Terms from two general linear mixed-effects models investigating the neural correlates - N2 amplitude and theta power at electrode FCz - of flanker task performance across age groups.

Model (AIC value)	**N2 amplitude** (333689.1)		**Theta power** (172555)	
	$\chi^2(1)$	**p**	**$\chi^2(1)$**	**p**
Congruency (C)	50.113	<.001	137.883	<.001
Previous Congruency (PC)	13.883	<.001	12.161	<.001
Age Group	127.219	<.001	31.501	<.001
C × PC (CSE)	10.276	0.001	18.536	< .001
C × Age Group	2.589	0.108	3.35	0.067
PC × Age Group	0.042	0.837	0.31	0.578
C × PC × Age Group	0.003	0.955	2.557	0.11

Note: CSE = congruency sequence effect, AIC = Akaike Information Criterion. For both analyses, the model with random slopes for the interaction of C × PC per participant was selected over models with slopes for the main effect of C only, or no random slopes at all. The AIC values of the competing models were: 333690.6 and 334027.7, respectively, in the N2 analysis, and 172563 and 172983, respectively, in the theta power analysis.

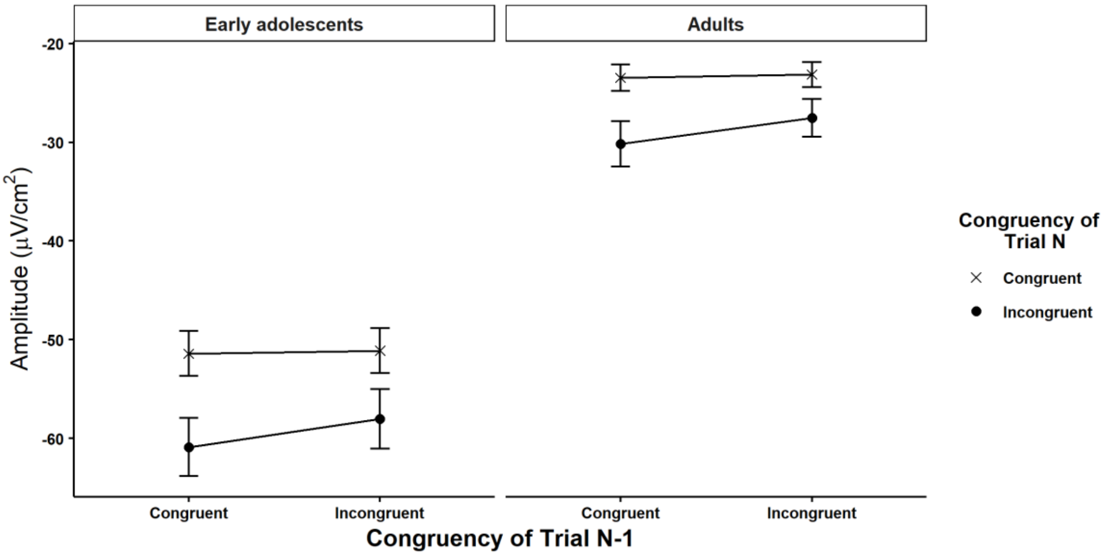


Figure 4.7 - The effect of congruency as a function of previous trial congruency, or the congruency sequence effect, on mean amplitude at electrode FCz in the time domain. Error bars represent +/- 1 SE.

Table 4.6 - The results of the ANOVAs examining N2 amplitude, theta power, and inter-trial phase clustering (ITPC) in the flanker task across age groups.

	N2 amplitude			**Theta power**			**ITPC**		
Term	**F**	**p**	**η_p^2**	**F**	**p**	**η_p^2**	**F**	**p**	**η_p^2**
Congruency (C)	43.13	< .001	0.822	132.66	< .001	0.97	23.15	< .001	0.759
Previous Congruency (PC)	10.55	0.002	0.116	27.88	< .001	0.373	0.85	0.361	0.012
Age Group	32.83	< .001	0.925	0.19	0.665	0.1	7.16	0.01	0.641
C × PC (CSE)	7.73	0.007	0.119	28.32	< .001	0.332	1.32	0.255	0.023
C × Age Group	0.35	0.558	0.036	5.09	0.028	0.557	5.69	0.021	0.437
PC × Age Group	0.79	0.377	0.01	0.31	0.58	0.007	1.43	0.236	0.021
C × PC × Age Group	0.03	0.86	0.001	3.55	0.065	0.06	0.07	0.797	0.001

Note: CSE = congruency sequence effect. η_p^2= partial eta squared. All degrees of freedom were (1,57).

4.3.2.2 Event-related changes in midfrontal theta power

In the time-frequency domain, oscillatory power was analysed first. Changes in power at different frequencies across time in different conditions in the two groups at electrode FCz are shown in Fig. 4.8, with corresponding scalp topographies in Fig. 4.9. As can be seen, power increased in the theta band following the presentation of incongruent compared to congruent targets. The main effect of Current Congruency was significant (Table 4.5). A CSE was also observed (Fig. 4.10). Furthermore, early adolescents showed higher power on average than young adults. The corresponding ANOVA did not detect this latter effect; however, it did reveal a significant Age Group × Congruency interaction (Table 4.6). Early adolescents showed a smaller congruency effect than young adults in this analysis.

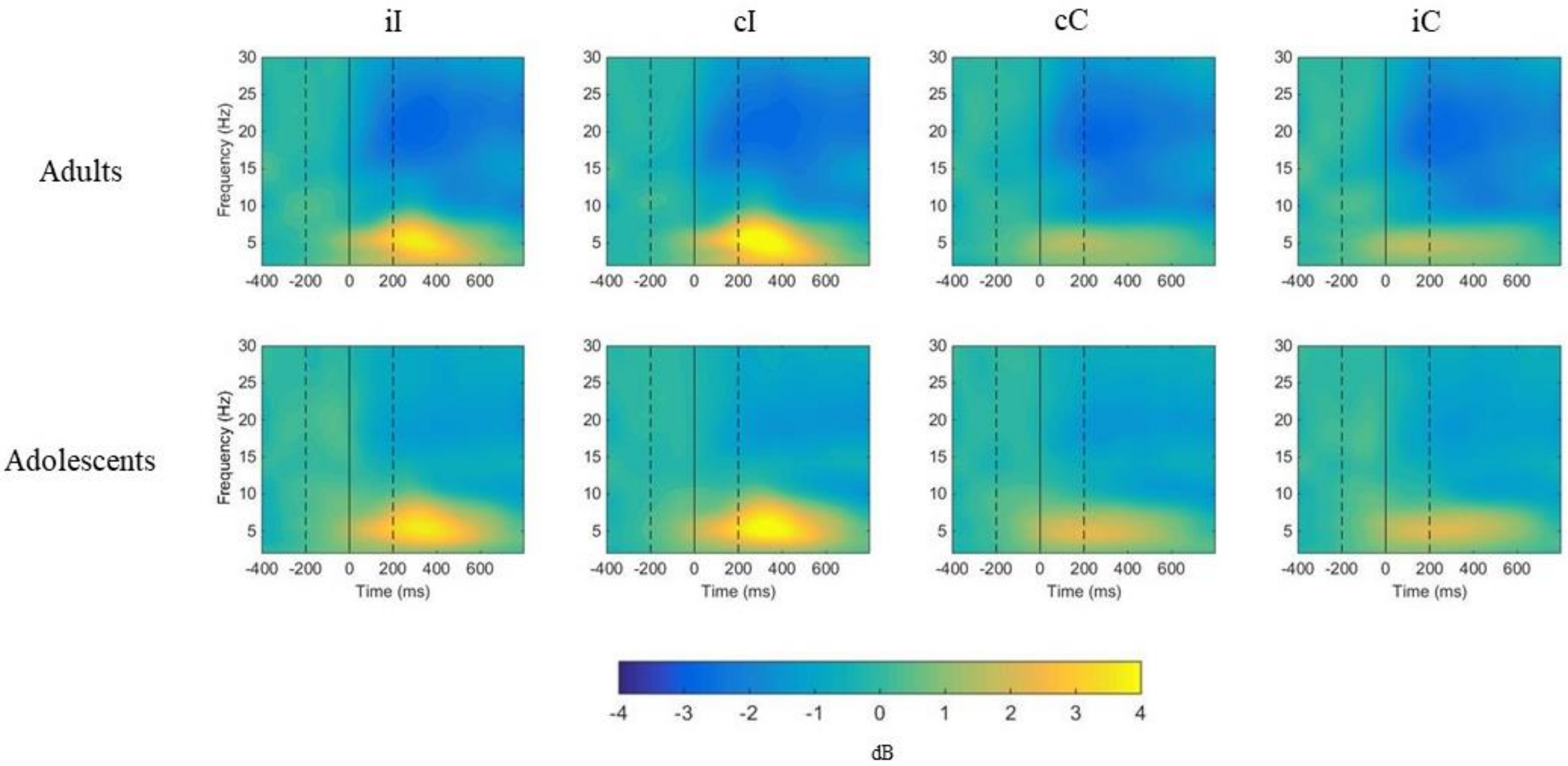


Figure 4.8 - Event-related power at electrode FCz as a function of previous trial congruency and current trial congruency in the two age groups. On all figures the first dashed line indicates the onset of the distractors, the bold line at time 0 the onset of the target, and the second dashed line the offset of both the target and distractors. iI = incongruent trials preceded by an incongruent trial; cI = incongruent trials preceded by a congruent trial; iC = congruent trials preceded by an incongruent trial; cC = congruent trials preceded by a congruent trial.

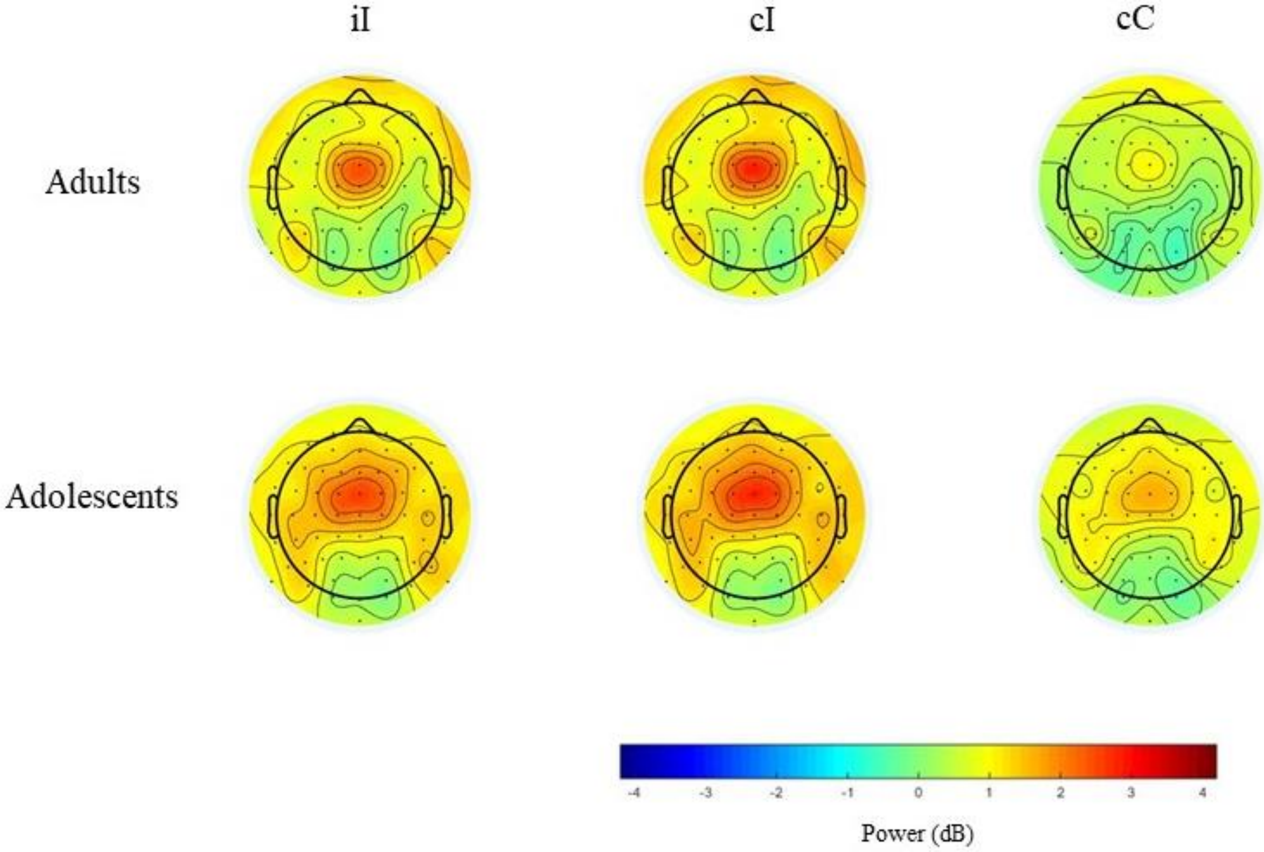


Figure 4.9 - Scalp topography of mean power across 4-7 Hz and between 0 and 500 ms. iI = incongruent trials preceded by an incongruent trial; cI = incongruent trials preceded by a congruent trial; iC = congruent trials preceded by an incongruent trial; cC = congruent trials preceded by a congruent trial.

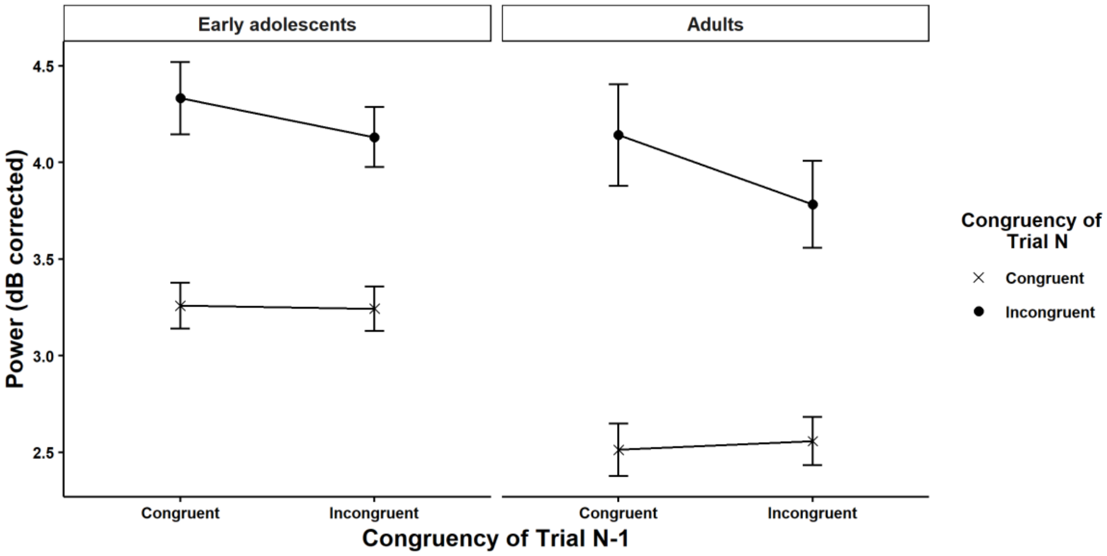


Figure 4.10 - The effect of congruency as a function of previous trial congruency, or the congruency sequence effect, on mean theta power at electrode FCz. Error bars represent +/- 1 SE.

4.3.2.3 Phase synchrony across trials

The temporal consistency of theta oscillations across trials was investigated next, as measured by ITPC. ITPC values across time-frequency points in the four conditions and across the two groups are shown in Figure 4.11, with corresponding scalp topographies in Fig. 4.12. Cross-trial synchrony increased on incongruent compared to congruent trials in the theta band, however this increase was significantly smaller in early adolescents compared to young adults (Fig. 4.13). This was due to higher temporal synchronization on incongruent trials in adults than in early adolescents ($p < .001$). Relatedly, there was a main effect of age because adults were found to show higher synchronization on average compared to early adolescents. No CSE was observed in this outcome measure. For the full results of the ANOVA, see Table 4.6.

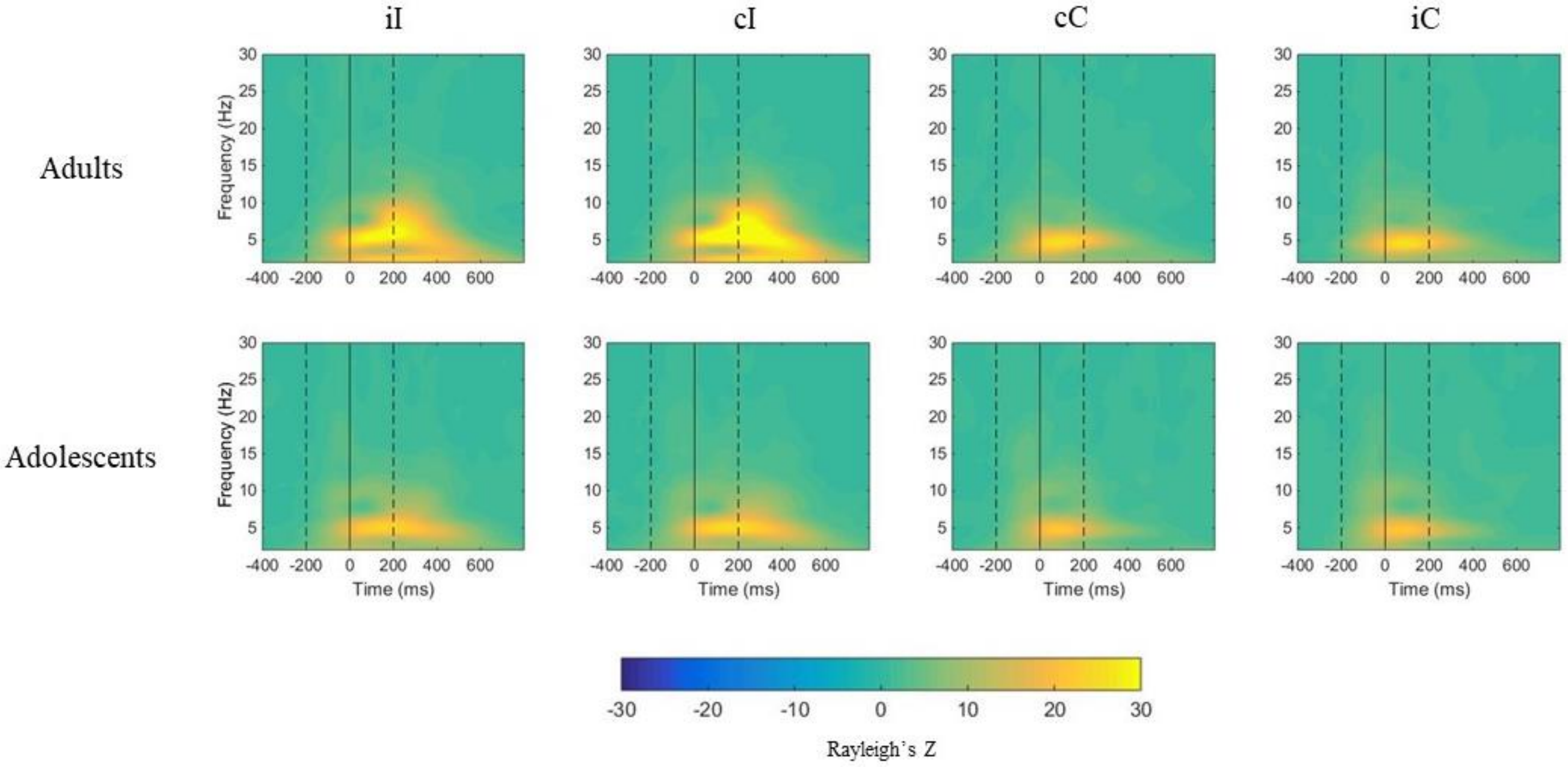


Figure 4.11 - Inter-trial phase clustering (ITPC) at electrode FCz as a function of previous trial congruency and current trial congruency in the two age groups. On both figures the first dashed line indicates the onset of the distractors, the bold line at time 0 the onset of the target, and the second dashed line the offset of both the target and distractors. iI = incongruent trials preceded by an incongruent trial; cI = incongruent trials preceded by a congruent trial; iC = congruent trials preceded by an incongruent trial; cC = congruent trials preceded by a congruent trial.

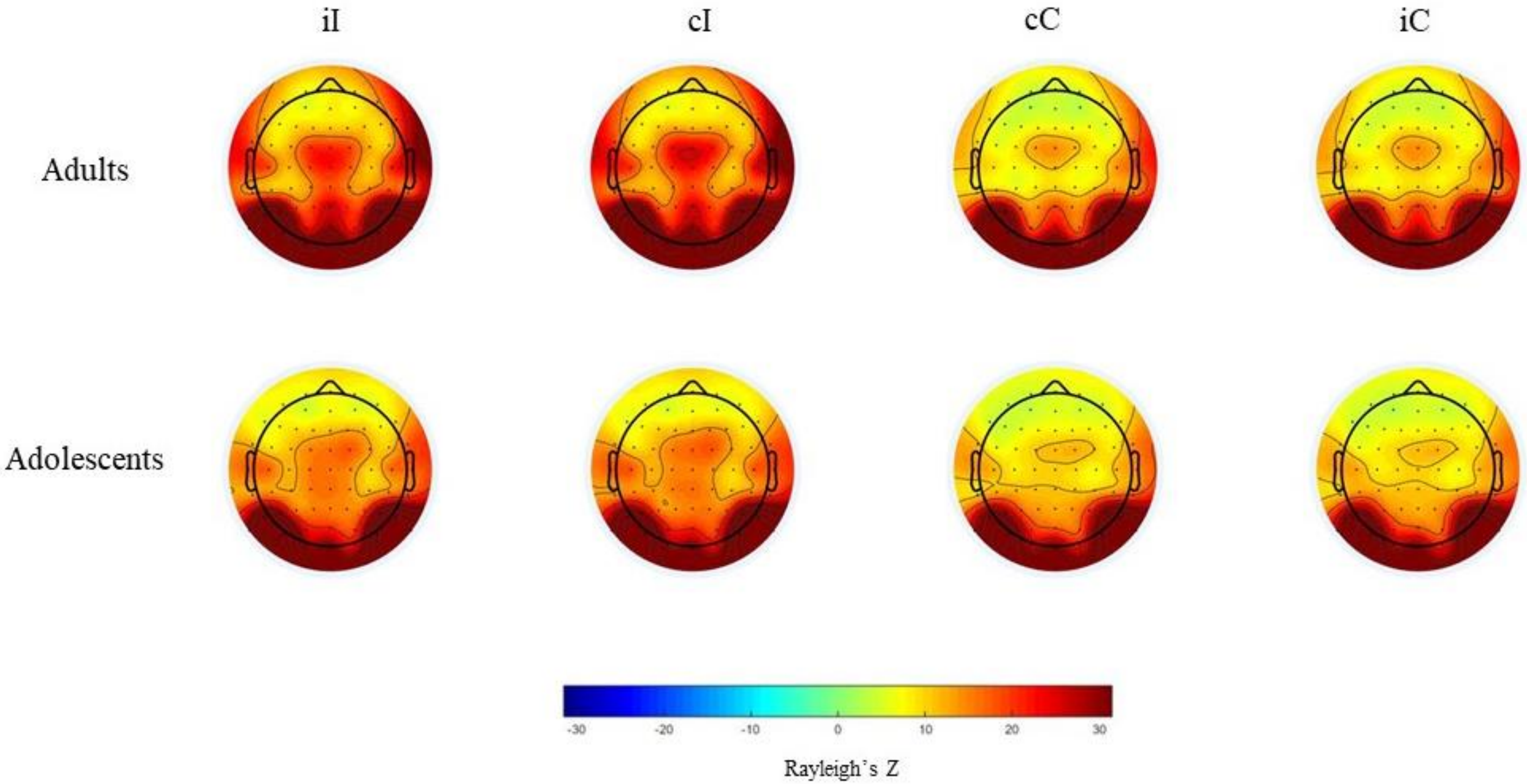


Figure 4.12 - Scalp topography of mean ITPC values across 4-7 Hz and between 0 and 400 ms. iI = incongruent trials preceded by an incongruent trial; cI = incongruent trials preceded by a congruent trial; iC = congruent trials preceded by an incongruent trial; cC = congruent trials preceded by a congruent trial.

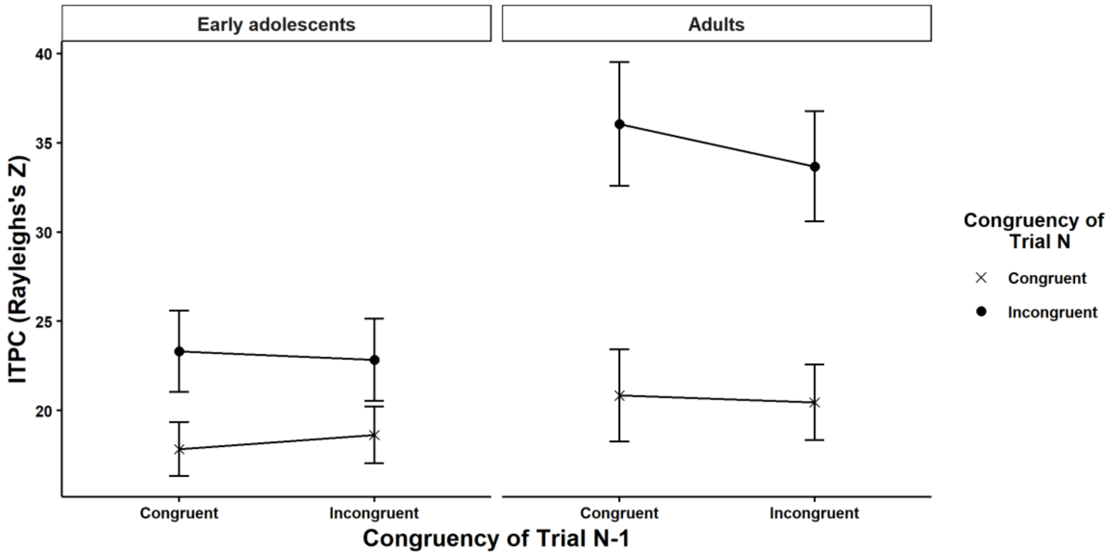


Figure 4.13 - The effect of congruency as a function of previous trial congruency, or the congruency sequence effect, on mean theta ITPC at electrode FCz. Error bars represent +/- 1 SE.

4.3.2.4 Phase synchrony across electrodes

ISPC values across the two groups for both the FCz-F5 and the FCz-F6 electrode pairs are shown in Figures 4.14A and 4.14B, respectively, with corresponding scalp topographies in Fig. 4.15. Figures 4.16A and 4.16B show the patterns of the adaptive mean ISPC values used in statistical analyses. A 2 (Current Congruency) × 2 (Previous Congruency) × 2 (Age Group) × 2 (Channel, referring to the target electrodes F5 and F6) mixed ANOVA was run to investigate ISPC values. Results showed a clear congruency effect across electrodes, suggesting that synchronization between midfrontal and lateral frontal sites is greater on incongruent compared to congruent trials. A main effect of previous congruency was also found. These two effects did not interact (no CSE was observed), and neither was modulated by age group or channel (Table 4.7).

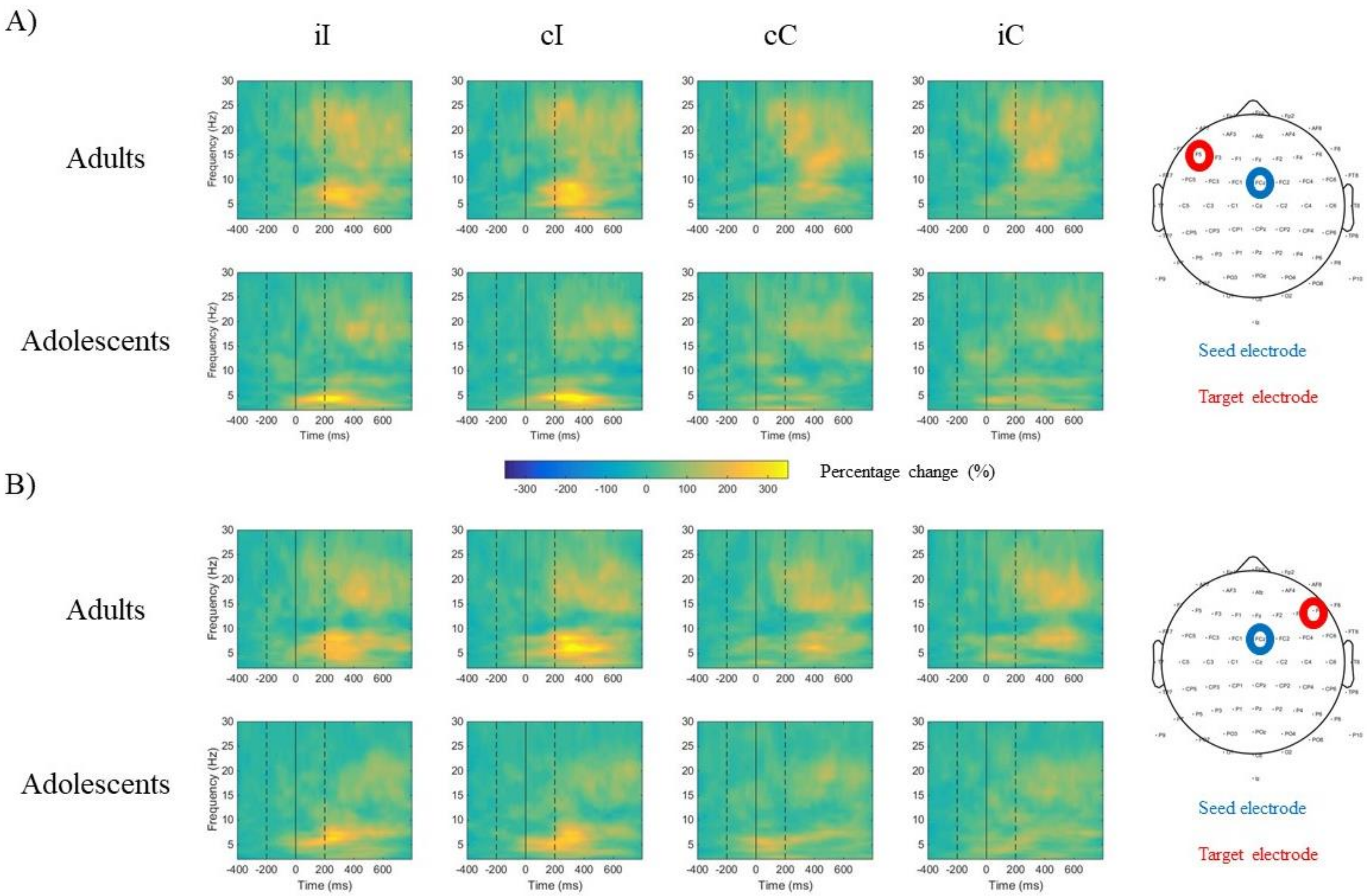


Figure 4.14 - Inter-site phase clustering (ISPC) between electrode FCz and electrodes F5 (A) and F6 (B) as a function of previous trial congruency and current trial congruency in the two age groups. On both figures the first dashed line indicates the onset of the distractors, the bold line at time 0 the onset of the target, and the second dashed line the offset of both the target and distractors. Values are expressed as percentage change compared to a pretrial baseline (-400 to -200 ms). iI = incongruent trials preceded by an incongruent trial; cI = incongruent trials preceded by a congruent trial; iC = congruent trials preceded by an incongruent trial; cC = congruent trials preceded by a congruent trial.

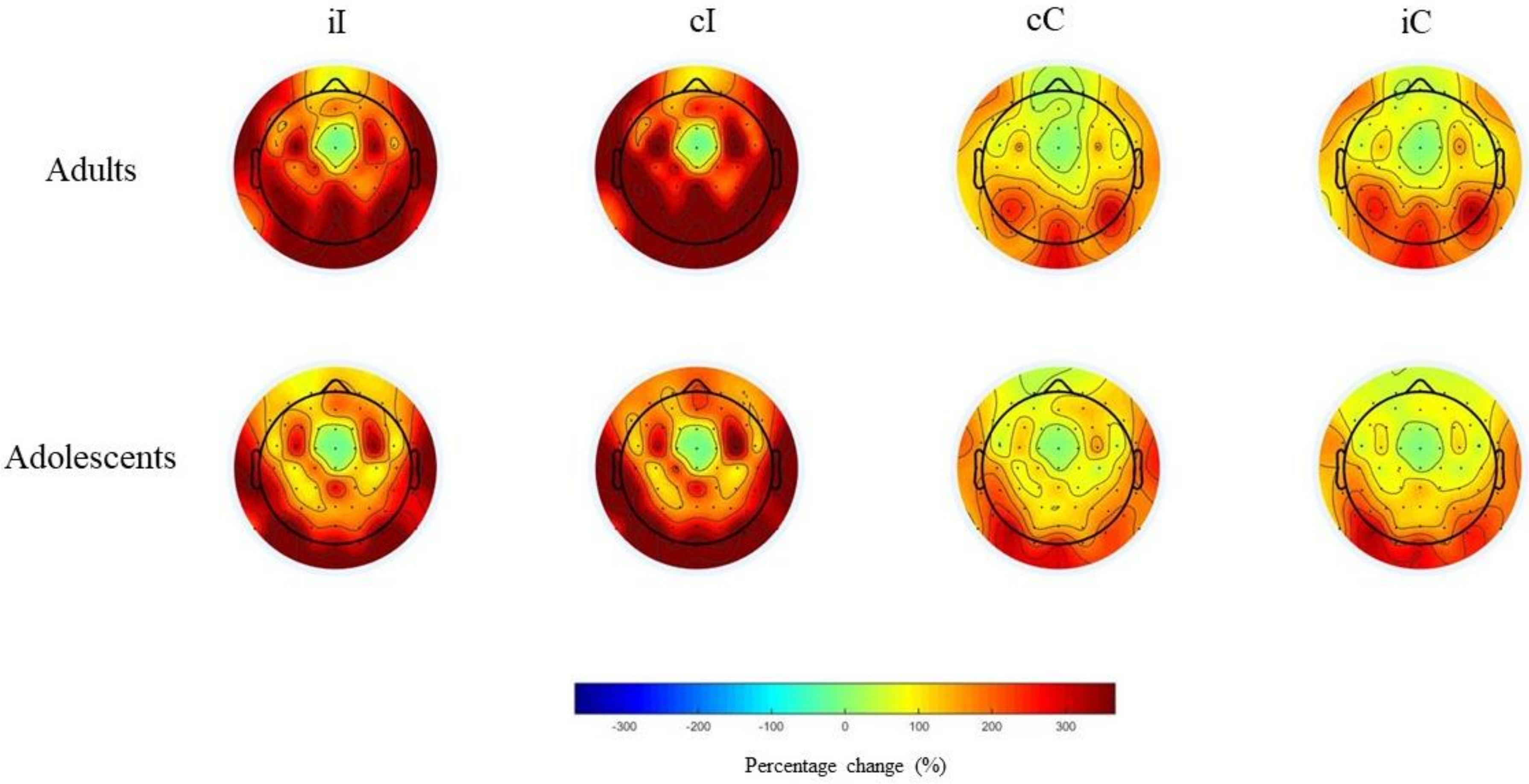
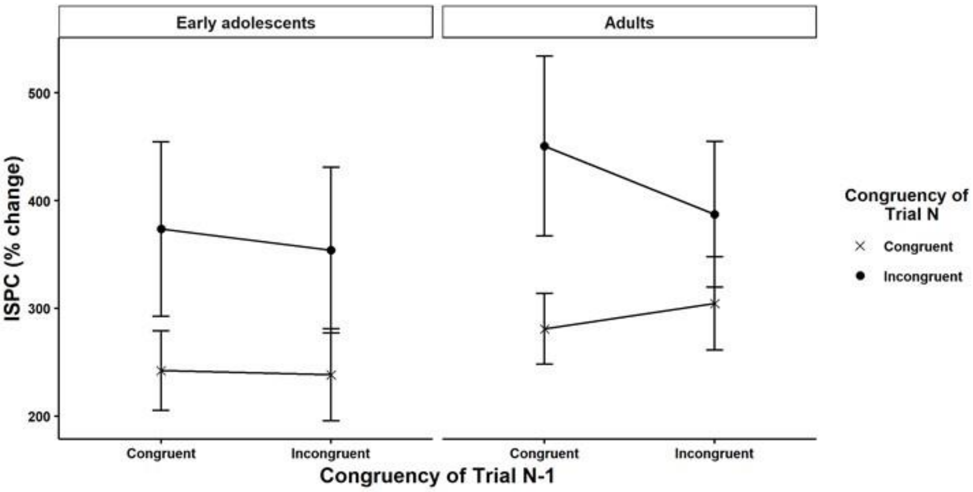


Figure 4.15 - Scalp topography of mean ISPC between electrode FCz and all other electrodes, across 4-7 Hz and between 0 and 500 ms. Values are expressed as percentage change compared to a pretrial baseline (-400 to -200 ms). iI = incongruent trials preceded by an incongruent trial; cI = incongruent trials preceded by a congruent trial; iC = congruent trials preceded by an incongruent trial; cC = congruent trials preceded by a congruent trial.

A) Connectivity between midfrontal and left lateral sites (FCz – F5)



B) Connectivity between midfrontal and right lateral sites (FCz – F6)

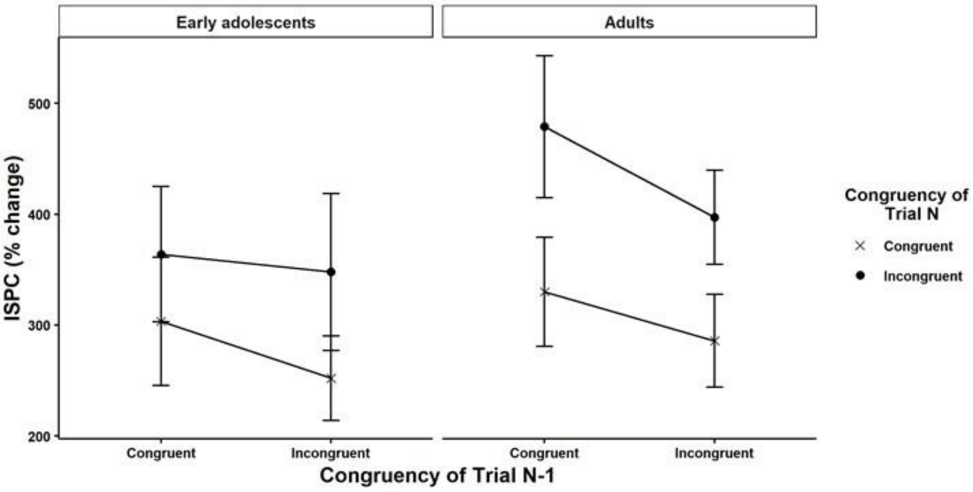


Figure 4.16 - The effect of congruency as a function of previous trial congruency, or the congruency sequence effect, on mean theta ISPC between electrode FCz and electrodes F5 (A) and F6 (B). Values are expressed as percentage change compared to a pretrial baseline (-400 to -200 ms). Error bars represent +/- 1 SE.

Table 4.7 - The result of the ANOVA examining functional connectivity - inter-site phase clustering (ISPC) - in the flanker task across age groups.

	ISPC		
	F	**p**	**η_p^2**
Congruency (C)	15.26	< .001	0.512
Previous Congruency (PC)	6.22	0.016	0.076
Age Group	1.06	0.307	0.195
Channel (Chan)	0.14	0.705	0.02
C × PC (CSE)	0.62	0.433	0.013
C × Age Group	0.22	0.641	0.015
PC × Age Group	0.54	0.465	0.007
C × PC × Age Group	1.23	0.272	0.025
C × Chan	0.23	0.631	0.009
PC × Chan	1.55	0.22	0.021
Chan × Age Group	0.001	0.977	< .001
C × PC × Chan	0.73	0.398	0.013
C × Age Group × Chan	0.32	0.573	0.012
PC × Age Group × Chan	0.17	0.684	0.002
C × PC × Age Group × Chan	<.001	0.989	< .001

Note: CSE = congruency sequence effect, η_p^2= partial eta squared. The seed electrode was FCz, and the two target electrodes (channels) of interest were F5 and F6. All degrees of freedom were (1,57).

4.3.2.5 Brain-behaviour correlations

First, the relationship between the CSE at the neural level and the CSE at the behavioural level was investigated. The correlation between the power-based (time-frequency domain) CSE and the RT-based CSE did not reach significance (Kendall's τ = 0.04, p = .62). A weak positive relationship was detected between the ERP-based (time-domain) CSE and the RT-based CSE, Kendall's τ = 0.20, p = 0.024, suggesting that people with higher CSEs in the time-domain also showed higher CSEs in RT. The relationship was similar across age groups (τ = 0.21 for adolescents, and τ = 0.17 for adults; comparison of the Fisher Z-transformed correlations revealed no significant difference between the two, *p* > .05).

Next, the relationships between MW frequency and the neural data CSEs were analysed. Time-frequency domain CSE was found to have a weak, *positive* association with the frequency of MW with awareness during the SART, $\chi^2(1) = 5.11$, $p = .024$; *OR* = 1.520, 95% CI[1.051, 2.217]. This did not interact with age. No other relationships were found.

Finally, behavioural variability was negatively related to ITPC values in all conditions (Kendall's τs of - .35, - .15, - .30, and - .14 for iI, iC, cI, cC, respectively), but the associations only reached statistical significance in the two incongruent conditions, iI and cI, (p < .001, and p = .001, respectively). These correlations did not differ significantly between groups.

4.4 Discussion

In the present study, we investigated the neural correlates of conflict-related dynamic changes in cognitive control, as indicated by the CSE, in young adolescents and adults, using a confound-minimized version of the classic flanker task. Our main objective was to examine whether age-related changes are apparent in the ability to flexibly modulate control at the neural level, which is to be expected given the protracted maturation of control-related brain areas (Gogtay et al., 2004; Ordaz et al., 2013). We focused on midfrontal neural correlates of control processes, such as the N2 ERP component and theta oscillatory power as these have clearly been implicated in the detection of conflict in previous studies (e.g., Cohen, 2014b; Larson et al., 2014), and have been found to show sequential modulation, that is, the CSE. We used two analytic strategies for the neural data, one focusing on trial-level signals and one on condition-averaged signals. We will only interpret effects in depth if both strategies yielded the same results, and will discuss potential reasons why they might disagree. With both strategies, the CSE was found in the N2 component and midfrontal theta power in our study as well, and to the best of our knowledge this is the first demonstration of the effect in these measures using a confound-minimized version of a classic conflict task (the flanker task). The CSE, however, was not modulated significantly by age in either measure. As a secondary aim, we also replicated our previous finding that the magnitude of the CSE in the flanker task negatively predicts the frequency of MW in a separate task. The implications of these findings for theories of the CSE and MW are discussed.

4.4.1 Cognitive control at the behavioural level

At the behavioural level, early adolescents were slower than young adults, in accordance with previous findings. The CSE pattern was present in both groups in RT, and when raw untransformed reaction times were analysed, early adolescents showed a bigger effect than young adults, contrary to our predictions. This age-related effect, however, was no longer reliable after controlling for the baseline speed difference between groups by standardizing RTs. This pattern of results perfectly matches the findings of Smulders et al. (2018) who found that the magnitude of the CSE decreases as a function of age between 7 and 25 years in three different tasks, but this age-related decline disappears after controlling for response speed differences. However, the authors concluded that the CSE was mostly a product of bottom-up associative priming in their study as opposed to top-down control because in their designs feature repetitions were allowed to occur in the trial sequence, leading Smulders et al. to suggest that the developmental trend was due to changes in these mechanisms. In our study feature repetitions were controlled for *a priori*, thus bottom-up effects are unlikely to explain the CSE. Importantly, however, we concur with Smulders et al. (2018) in that whatever the mechanism behind the effect is (top-down control modulation or bottom-up priming/learning) it matures at a similar rate as processes responsible for translating a stimulus into a response, as suggested by the non-significant developmental effect after controlling for speed. It is important to keep in mind, however, that the lack of a significant finding cannot be interpreted as evidence for the lack of an effect, as more highly powered studies might still be able to observe developmental changes in the future. As in Chapter 3, the most cautious interpretation is to say that there appear to be no substantial and robust age differences after controlling for general age-related speeding.

Behavioural performance on the SART was also largely in line with predictions, with adolescents showing slower, more error prone, and more variable performance than adults (e.g., Braet et al., 2009; Carriere et al., 2010), supporting the notion that response inhibition is still maturing at the beginning of adolescence (e.g., Shulman et al., 2016). On a methodological level, our findings support the conclusion of Smulders et al. (2018) that baseline speed differences cannot be ignored when analysing the effect of within-subject conditions on response latencies. In the current study, two apparent developmental changes in performance disappeared after controlling for such differences – the age effect observed in the CSE in the flanker task, and the seemingly disproportionate speeding on No Go errors in adolescents compared to adults in the SART. This demonstrates that one must be cautious in interpreting raw RT effects in developmental studies. However, caution must also be exercised when looking at transformed RTs – in our studies for instance, the standardization procedure created what is most likely to be an "illusory" age-related increase in the size of the congruency effect in the flanker. As described in Chapter 3, the most parsimonious explanation of this effect is that it occurred due to higher intra-individual variability in adolescents "shrinking" the size of the congruency effect when such variability (*SD*) is used to standardize RTs.

In sum, the behavioural findings of the present study are generally in line with those of the previous study (Chapter 3), and suggest that even though early adolescents still do not perform at adult levels on cognitive control tasks, as indicated by slower and more error prone responses on both the flanker and the SART, there are no *substantial* age differences in the ability to dynamically modulate cognitive control above and beyond the maturation of basic cognitive processes, e.g., stimulus-to-response translation.

4.4.2 Cognitive control at the neural level

At the neural level, we investigated age- and conflict-related changes in midfrontal activation in both the time domain, as represented by the N2 ERP component, and the time-frequency domain where we focused on theta oscillations. In both domains, conflict had a robust effect: amplitude of the N2 was greater on incongruent trials compared to congruent trials (Larson et al., 2014), and both the power and temporal consistency of theta oscillations increased in the midfrontal region on incongruent compared to congruent trials (Cohen, 2014a; Cohen & Donner, 2013; Hanslmayr et al., 2008; Nigbur et al., 2011, 2012). Synchronization between midfrontal and lateral frontal sites also increased in response to conflict (Cohen, 2014a; Cohen & Cavanagh, 2011; Gulbinaite et al., 2014; Hanslmayr et al., 2008). In sum, the purported neural markers of cognitive control were all modulated by response conflict. All of these modulations occurred before a correct response was made, suggesting that midfrontal regions are indeed involved in conflict resolution processes, possibly in the detection of conflict (e.g., the ACC; Botvinick et al., 2001, 2004) or more generally, signals of need for control (Cavanagh & Frank, 2014; Cavanagh & Shackman, 2015), and that theta rhythm generation is a key aspect of the oscillatory activity supporting these processes (Cohen, 2014a). The ISPC findings also show that theta oscillations were involved in the communication between midfrontal and lateral frontal regions (Cohen & Cavanagh, 2011; Gulbinaite et al., 2014; Hanslmayr et al., 2008), possibly reflecting the signalling of the need for control deployment on incongruent trials.

Some aspects of the neural data also showed dynamic, conflict-related cross-trial modulations. The CSE pattern was detectable in the N2 component and in midfrontal theta power; in fact, it was the strongest in this latter measure. As far as we are aware, this is the first demonstration of midfrontal theta CSE using a confound-minimized conflict task. As such, our findings provide important further support to the idea that midfrontal theta reflects control-related processes (e.g., Clayton et al., 2015; Cohen, 2014a) as the CSE cannot be explained by lower-level mechanisms, such as feature repetitions or distractor-target contingencies in our sample. The CSE, however, was not reliable in either phase synchrony measure. In the case of inter-trial phase clustering (ITPC), this could mean that the occurrence of conflict on the previous trial does not affect the temporal coordination of control processes on the current trial, it merely impacts the size of the neuron population firing, as indicated by the power findings. The lack of a CSE in inter-site phase clustering (ISPC), our measure of functional connectivity, is more surprising, given the conflict monitoring theory's clear predictions regarding communication between midfrontal and lateral frontal sites (the ACC and the DLPFC to be exact) being impacted by trial history as well as the current trial. It is possible that this modulation was too subtle and would have been detected in a more highly powered design - this is true of the ITPC effect as well -, and it also cannot be ruled out that our *a priori* choices of lateral frontal sites (electrodes F5 and F6) were not ideal, although they were guided by previous studies (Cavanagh et al., 2009; Gulbinaite et al., 2014). Interestingly, topographical maps of functional connectivity across the scalp (Fig. 4.15) revealed no clear frontal sites of highly increased connectivity in the time window we specified. Future studies are needed to explore when (e.g., in the peri-response period, Cohen & Cavanagh, 2011; vs the post-stimulus period, Gulbinaite et al., 2014) and where midfrontal-to-lateral-frontal communication can be best observed in the flanker and other tasks, if at all.

Importantly, the congruency effect and the CSE were not significantly modulated by age in either N2 amplitude or theta power, paralleling our behavioural findings. Adolescents showed greater ERP amplitudes and higher theta power across conditions than adults (possibly reflecting the common finding that - absolute - power in lower frequencies decreases with age, e.g., Cragg et al., 2011; Marek et al., 2018), but the effect of age was not clearly evident on conflict-related modulations in all analyses. In the ANOVA analysis, but not in the LME, there was a weak interaction between age and the effect of current trial congruency in midfrontal theta power (Fig. 4.10), which was also mirrored by a similar interaction in ITPC values (Fig. 4.13, discussed in more detail below), whereby adolescents showed a smaller congruency effect than adults. Future studies are needed to investigate if these patterns are replicable, however if they are, they are not clearly in line with the notion that adolescents are more susceptible to conflict than adults on the neural level (Hämmerer et al., 2014), rather, they suggest that adolescents may not respond to the occurrence of conflict adequately, potentially due to some limitation of their conflict detection system posed by their still-maturing cognitive control networks (e.g., a lack of available neural resources due to inefficient resource allocation), leading to smaller differentiation between congruent and incongruent trials. It is unlikely that the reduced congruency effects reflect more optimized neural performance in adolescents (e.g., stronger control resulting in less interference), given that these age effects were not accompanied by faster or less error-prone responses to incongruent trials on the behavioural level in adolescents compared to adults. The observed effects could instead mean that early adolescents were unable to recruit adequate control processes when conflict occurred, or they engaged such processes even when that was unnecessary, on congruent trials (for a similar idea see Chevalier et al., 2013). This could also provide an alternative explanation for the reduced congruency effect in adolescents in standardized RT. Importantly, it appears that even though the two age groups differed somewhat in how they responded to current trial conflict on the neural level, both groups then modulated control levels similarly – or more precisely, not significantly differently - in response to the conflict signal as suggested by the CSEs in ERP amplitude, theta power, and RT that did not interact with age.

Next, let us examine our findings concerning the temporal consistency of neural oscillations, as measured by ITPC. ITPC was modestly, but significantly related to intraindividual variability in RT as captured by the coefficient of variation on correct trials, especially in more demanding (i.e., incongruent) conditions, providing some support to the idea that the consistency of stimulus-locked neural signals is associated with variability of performance (Papenberg et al., 2013), although of course causality cannot be inferred from our correlational findings. Similarly to behavioural variability, ITPC was also significantly different between age groups. This was expected based on previous findings showing that both behavioural and neural variability decreases with age (e.g., Liu et al., 2014; Papenberg et al., 2013). As mentioned above, this main effect of age was qualified by an age by current trial congruency interaction: the phases of theta waves in the midfrontal region varied more strongly on incongruent trials in adolescents than in adults, but not on congruent trials where the two groups did not differ. This suggests that adolescents may not be able to temporally coordinate their control processes in demanding conditions as efficiently as adults do. Liu et al. (2014) reported a similar pattern of findings in a Go/No Go task, whereby ITPC only increased in mid- and late adolescents (11-18) as a function of effort but not in younger children (8-11), although in their design the manipulation of effort was confounded with time on task.

Finally, there was no age effect in functional connectivity (ISPC) between frontal and lateral frontal sites, providing no clear support for the idea that network integration, the functional collaboration of different networks in the brain is still undergoing changes during adolescence (Luna et al., 2015). It is important to note, however, that ISPC on the current trial is interpreted as change in connectivity after target presentation compared to a pre-target baseline, to facilitate the investigation of within-subject changes in response to shifts in control demands (in accordance with previous studies, e.g., Gulbinaite et al., 2014). As such, our results probably underestimate the between-group differences in absolute connectivity in our sample. It is, however, also possible that functional connectivity is already fairly adult-like during task performance in the regions we focused on. Investigating 14-31 year-olds in an EEG study, Marek et al. (2018) found increased functional *de*coupling between multiple regions of interest covering the whole scalp as a function of age during rest, which was especially prominent at midfrontal regions. During a working memory task, however, no age-related changes could be observed in phase-based connectivity. Hwang, Hallquist, & Luna (2012) did observe increases in functional connectivity between brain regions from adolescence to adulthood, but these were less pronounced and more posterior in location than changes from childhood to adolescence. Consequently, it is possible that the frontal cortico-cortical connections examined in our sample already show mature connectivity by the start of adolescence during task performance.

4.4.2.1 Summary of neural findings

Using a confound-minimized version of the flanker task, we replicated previous findings showing current trial conflict-related modulations of neural activity both in the time domain (N2 ERP component) and the time-frequency domain (midfrontal theta power, cross-trial, and cross-site phase synchronization), underlining the role of frontocentral regions and slow, theta band oscillations in conflict monitoring. These conflict-related effects were further modulated by previous trial congruency, showing conflict-induced control adjustments (CSE) in the amplitude of the N2 component and midfrontal theta power. Maturation generally had a modest effect on conflict-related processes on the neural level, although the smaller congruency effect in the power and consistency of midfrontal theta oscillations in adolescents compared to adults in ANOVA-style analyses suggests that adolescents might have trouble flexibly recruiting and temporally coordinating these processes in response to increased task demands on the current trial. Conflict, however, is reliably detected, and used to modulate control levels on the following trial in both age groups, as suggested by the presence of comparable CSEs.

The findings that the congruency effect was smaller in adolescents than in adults in certain neural measures and that the CSE was not significantly modulated by age mean that we found no support for our original hypothesis that adolescents experience conflict to a greater extent than adults, but are unable to translate this into adequate control modulations (Hämmerer et al., 2014). This is in accordance with some previous studies that have also found no evidence of greater conflict sensitivity in younger age groups in the amplitude of the N2 (e.g., Ladouceur et al., 2004, 2007). Furthermore, we found no clear support for the idea that communication between subnetworks of control is still immature in adolescence (Luna et al., 2015) because functional connectivity was comparable across age groups in our study. It is possible, however, that in future studies using larger samples clearer refinement of flexible control regulation abilities across adolescence could be observed. It would be especially interesting to examine age-related changes in theta power, as conflict-related dynamic adjustments were very pronounced in theta oscillations in our sample, possibly because time-frequency analyses capture aspects of neural activity that could be relevant to conflict-processing but are not measurable by ERPs (e.g., power that is not phase-locked to stimulus presentation, Cohen & Donner, 2013).

4.4.2.2 A note on analytic approaches

On a statistical note, we found that the multilevel modelling approach using single-trial information and the ANOVA approach using condition-aggregated data did not always yield identical results, as alluded to in Section 4.4.2. It is possible that combining an adaptive mean process, i.e., identifying local peaks for every trial and extracting the mean amplitude/power values in a time interval around that peak, with multilevel (LME) modelling is suboptimal because individual trial-level observations will be noisy, more so than if peaks were identified in aggregated data, and this might obscure potential true effects. This is an empirical question, and future simulation studies might be best suited to answer it. In the discussion of our results, we noted effects that were not corroborated by both approaches, so they can be interpreted accordingly, with caution.

4.4.3 Cognitive control and mind-wandering

In contrast to our previous study, no age difference was observed in the frequency of MW with or without awareness. The cognitive resource account of MW (Smallwood & Schooler, 2006) posits that maintaining an off-task train of thought requires cognitive resources, thus individuals who have more resources at their disposal are more likely to MW. This idea was indirectly supported in our previous study where the frequency of MW increased as a function of age. However, further analysis of the age effect revealed that it was driven by a difference between late adolescents (18-20 year-olds) and early adolescents (12-13 year-olds) with the latter mind-wandering less. The difference between adults (25-27 year-olds) and early adolescents was not prominent. In our current study, only these two age groups were investigated, thus it is possible that the lack of an age effect stems from the fact that early adolescents and adults tend to report similar rates of MW. This could mean that the increase in MW rate in late adolescence observed in the previous study was due to factors other than the maturation of cognitive resources across age. One such factor might be that late adolescents in Chapter 3 who were primarily undergraduate students might have had more university-related off-task thoughts primed by the testing environment (i.e., a university building). This idea is in line with the control failures × current concerns account of MW (McVay & Kane, 2009, 2012) which suggests that MW typically results from an inability of cognitive control to defend goal-relevant processing from competing, task-unrelated thoughts, and that MW rates increase with the number of competing thoughts. Naturally this interpretation would imply that early adolescents and late adolescents in our previous study were mostly comparable in terms of cognitive control capacity, and *only* differed substantially in the number of competing thoughts they had, otherwise more mature control in late adolescents could have offset the greater propensity to MW triggered by the greater number of intruding thoughts. This assumption may not be tenable, questioning the validity of this interpretation.

Finally, we replicated our previous finding that the magnitude of the CSE in RT is negatively associated with the frequency of MW in the SART. This effect was again driven by reports of tune outs, or MW with awareness. This successful replication suggests that this relationship was not merely a spurious finding due to chance in our previous study. One interpretation of this association could be that a larger CSE reflects better reactive control, and such control helps individuals stay on task, or return to the task once their attention has started to wander. Potential alternative interpretations of this finding will be discussed in the following chapter which presents a study designed to further understand the relationship between the mechanisms supporting the CSE and MW.

4.4.4 Conclusion

In conclusion, the present study found sequential modulation of conflict-related effects (CSE) in the amplitude of the N2 ERP component and midfrontal theta power using a confound-minimized conflict task, underlining the importance of midfrontal regions and theta oscillations in conflict detection processes. These effects were not consistently modulated by age, supporting the conclusion in Chapter 3 that the ability to reactively regulate control is present early on in development, and extending it by showing that developmental effects only appear in some outcome measures in the neural data, using certain analytic strategies. These mostly suggest smaller differentiation between low- and high-conflict trials in adolescents compared to adults. We also replicated our finding that the magnitude of the CSE is related to MW frequency across age groups, suggesting that cognitive control might be involved in the regulation of MW. No age effects were found in MW frequency in this study.

Chapter 5 - The Relationship Between the Congruency Sequence Effect and Mind-Wandering

Abstract

In Chapters 3 and 4, the magnitude of the congruency sequence effect (CSE) in a flanker task was found to negatively predict the frequency of mind-wandering (MW) in a Go/No Go task. We hypothesize that this is because larger CSEs represent more efficient reactive control engagement, and such control might help keep participants on task. In the present study, we examined if the mechanisms generating the CSE (potentially reactive control adjustment) interact with the mechanisms behind MW when the two are measured within the same task. To this end, 42 healthy undergraduates (mean age = 22.45, SD = 4.98) completed a confound-minimized flanker task with frequent thought probes embedded into the trial sequence. Probes asked if participants were on task or if they engaged in intentional or unintentional MW. We analysed performance on flanker trials preceding the probes and categorized these trials as on-task or MW trials according to the response given on the following probe. We found no significant difference in the magnitude of the CSE between on-task and MW trials. As such, our findings do not suggest a robust interaction between the mechanisms behind the CSE and MW, contrary to the findings of Chapters 3 and 4. The potential reasons for this discrepancy are discussed. Exploratory findings in our sample suggest that working memory capacity (WMC) might interact with the CSE-MW relationship, providing a clear hypothesis for future large scale studies.

5.1 Introduction

In my final study, I investigated the relationship between the congruency sequence effect and mind-wandering in more depth. The two phenomena were found to be related in two of my previous studies, therefore a third experiment was designed to learn more about the nature of this relationship.

The term “mind-wandering” (MW) has been used to describe a wide variety of mental phenomena that may not share one key defining feature (Seli, Kane et al., 2018, however see Christoff et al., 2018). One prototypical form of MW, however, is task-unrelated thought, mental content that is unrelated to the completion of the task at hand (Smallwood & Schooler, 2006). In the current chapter, I will be using the term to refer to this specific type of MW (unless noted otherwise).

As described briefly in Chapter 3, there are two major accounts of the mechanisms supporting MW: the attentional resource account (Smallwood & Schooler, 2006), and the control failure × current concerns account (McVay & Kane, 2010). The former suggests that MW is a re-direction of attention from goal-relevant information to internally generated content, and maintaining it requires executive resources. This account can easily explain fundamental findings such as that MW decreases as a function of task difficulty and task demands (Forster & Lavie, 2009; Seli, Konishi, Risko, & Smilek, 2018; Smallwood, Obonsawin, & Reid, 2003; Thomson, Besner, & Smilek, 2013) and with age (Giambra, 1989, 2000; Gyurkovics et al., 2018; Jackson & Balota, 2012; Maillet & Schacter, 2016; Maillet et al., 2018; Seli, Maillet et al., 2017), because both increasing task difficulty and increasing age decrease the amount of resources available for MW.

The control failure × current concerns account on the other hand, suggests that MW is a consequence of inadequate levels of cognitive control that cannot defend goal-directed cognition from competing thoughts, for example those brought on by the current, task-unrelated concerns of the individual. In this framework, the task difficulty-MW relationship is thought to result from lower levels of attentional control in easier tasks compared to more demanding tasks that then lead to more lapses of attention. This account is supported by studies that show a weak but replicable negative relationship between working memory capacity (WMC) and MW (Kane et al., 2007, 2017; McVay & Kane, 2009, 2012; Randall, Oswald, & Beier, 2014; Robison, Gath, & Unsworth, 2017; Unsworth & McMillan, 2014). Although the two frameworks might appear to be incompatible, attempts have been made to integrate them for example by differentiating between different aspects of MW that could be affected by either resource availability or control failures (e.g., its maintenance vs. its initiation; Smallwood, 2013) or by differentiating between subtypes of MW (e.g., intentional or unintentional, see below; Seli, Kane et al., 2018).

As discussed in previous chapters, one indicator of cognitive control deployment in tasks involving cognitive conflict may be the sequential modulation of interference caused by task-irrelevant stimuli, known as the congruency sequence effect (CSE; Gratton et al., 1992). The CSE is hypothesized to index dynamic adjustments in attentional control levels in response to changing task demands (as proposed by Botvinick et al., 2001, 2004), possibly through the active suppression of the distractor-related irrelevant response (Grant & Weissman, 2019; Weissman et al., 2014). Given this attentional interpretation of the effect, how might it be related to episodes of inattention, as indicated by MW frequency? The two frameworks outlined above make different predictions. First, the resource account makes no clear prediction because the link between cognitive resources and the mechanisms behind the CSE has not been researched extensively thus far. Two highly powered studies (Meier & Kane, 2013; Unsworth et al., 2012) found no relationship between WMC and CSE magnitude. Other studies, however, suggest that there might be a weak negative relationship, i.e., higher WMC individuals might show smaller CSEs (Aschenbrenner & Balota, 2015; Keye, Wilhelm, Oberauer, & van Ravenzwaaij, 2009), maybe because the level of their attentional control is already higher throughout the task and there is no need for additional modulation in response to conflict to maintain adequate performance. Taken together these findings could lead one to predict either no relationship between the CSE and MW frequency because the mechanisms behind the CSE might not compete for the same resources MW might use, or a negative relationship between CSE magnitude and MW frequency because those who have the most resources available for MW might show smaller CSEs than lower WMC individuals.

Based on the same findings regarding WMC and CSE magnitude, the control failures × current concerns account would either predict the independence of the CSE and MW, or a positive relationship between the two if lower WMC individuals do indeed show bigger sequential modulation *and* are also more inclined to MW. The cited studies that found a negative relationship between WMC and the CSE, however, all contained confounds that make it hard to interpret the CSE patterns observed in those tasks as control-related phenomena. Thus it might be more reasonable to consider the control mechanisms that are proposed to be behind the CSE directly, and examine how these might be related to MW frequency. If the CSE truly reflects conflict-induced control adjustments, the size of the effect could indicate the efficiency of *reactive* control, i.e., control deployed *in response to* changes in task demands (Braver, 2012), with larger CSEs suggesting a more flexible finetuning of control levels to meet the demands of goal-directed behaviour than smaller CSEs. Reactive control has been found to be negatively related to the propensity to MW (Stawarczyk et al., 2014). Consequently, individuals showing larger CSEs might be less likely to MW due to a better ability to monitor the demands of the task and reactively deploy control when necessary. Although this account also invokes efficiency of control processes, it is not clearly a corollary of the control failure × current concerns theory as that account primarily focuses on maintaining goals in an active state which is related to proactive (preparatory, sustained) aspects of control, not reactive.

Our finding reported in Chapters 3 and 4 that the magnitude of the CSE in the flanker negatively predicted the frequency of MW in a separate Go/No Go task may thus reflect that larger CSEs mean better reactive control which, in turn, results in a higher likelihood of staying on task maybe via defending task focus from internal distractions when they occur. Alternatively, reactive control might help to redirect attention to the task once it has wandered away, as hypothesized by Drescher et al. (2018). These authors also found a negative association between the CSE in a flanker task and behavioural MW frequency, albeit it did not reach statistical significance presumably due to lower power. We favour these reactive control-related explanations of the relationship over resource-based accounts because, as stated above, previous studies establish no clear association between cognitive resources and confound-minimized CSE magnitude therefore a control mechanism based explanation is more parsimonious.

Our findings thus far have provided insight into the relationship between the CSE and MW frequency at the global level – i.e., people who tend to MW less show higher control adjustments. This, however, does not directly address whether the mechanisms involved in the two phenomena interact during task performance. It is, therefore, important to look beyond this individual difference approach, and investigate the interaction of the two processes at the local (i.e., trial) level by examining whether the magnitude of the CSE is different during MW episodes compared to periods when the participant is focused on the task. In the present study, we set out to investigate this by asking participants to complete a flanker task with random thought probes and then analysing their performance on trials immediately preceding either on-task or off-task (MW) reports. We hypothesized that if the previously reported CSE-MW association reflects an effect of the mechanisms generating the CSE (e.g., reactive control deployment) on MW, or vice versa: the processes behind an MW episode impact an individual's ability to modulate their control adequately, then the CSE should be smaller on pre-MW report trials compared to pre-on-task report trials (e.g, because both a small CSE and an MW episode could reflect a low level of reactive control). As a further extension of the previous two studies, participants were also asked to differentiate between intentionally and unintentionally engaged MW in their responses, both at the state and at the trait level as well. This distinction is important because the two types of MW, which have been conflated in the previous two studies, are impacted differentially by different task difficulty manipulations – with intentional MW (IMW) always decreasing but unintentional MW (UMW) sometimes increasing and sometimes decreasing as a function of difficulty (Seli, Konishi, et al., 2018; Seli et al., 2016) – suggesting that different control mechanisms and resources may be behind the initiation and maintenance of the two. *A priori* we would expect UMW to have a bigger effect on behavioural performance and have a tighter relationship with CSE magnitude because that is more likely to reflect a type of MW where self-generated mental content competing with goal-relevant stimuli captures attention (i.e., a failure of attentional control) as opposed to a strategic reallocation of resources from task to MW.

A design similar to ours was used by Thomson et al. (2013) who presented MW probes in pure blocks of congruent and incongruent trials in a Stroop task, and observed a reduction of MW frequency in the incongruent blocks compared to the congruent blocks, suggesting that when more cognitive control is required, participants engage in off-task thinking less frequently. However, when only performance on the five trials immediately preceding a probe were analysed, probe response (on-task vs. MW) did not interact with the congruency effect nor did it affect reaction time or accuracy, i.e., performance was similar on pre-MW and pre-on-task trials. The authors concluded that there were no behavioural costs of MW because participants are able to modulate how much off-task thought they engage in based on the amount of resources “left over” by task demands. Although no distinction was made in this study between IMW and UMW, the language of this conclusion suggests that this would more likely hold for IMW (a more controlled form of MW that potentially reflects a careful “titration” of attention between the task and other thoughts) than UMW, which in turn would suggest that changes in behaviour might be more evident during UMW episodes compared to IMW. In the light of these previous findings, the present study was designed to examine a) if thought report response has an effect on congruency in the flanker task using a design where the two trial types are randomly intermixed (as opposed to the blocked design of Thomson et al., 2013), b) if the magnitude of the CSE differs between episodes of on-task and off-task thought as suggested by the findings reported in Chapters 3 and 4 (relationship at the local level), and if yes, whether the intentionality of the off-task thought episode modulates this effect, and c) if we can replicate our previous finding that the amount of MW reported during a task is predicted by the magnitude of the CSE in the task (relationship at the global level), and if yes, whether this relationship differs between UMW and IMW. Finally, we also included a measure of WMC to estimate the executive resources at the participant’s disposal. This enabled us to examine the relationship between WMC and the CSE, and WMC and different types of MW frequency, however these questions were not of central interest thus the sample size was not determined with these correlational analyses in mind.

5.2 Method

We report how we determined our sample size, all data exclusions (if any), all manipulations, and all measures in the study. Data files and the analysis script for this study are available on the Open Science Framework at the following URL: https://osf.io/yaj36/.

5.2.1 Participants

Forty-two healthy adult participants completed the tasks (mean age = 22.45, SD = 4.98; 32 females). No participants in this final sample reported any psychiatric or neurological problems, however, two additional participants were removed due to neurological problems. Participants were undergraduate and postgraduate students at the University of Sheffield. Every volunteer received £10 or course credits as compensation for their time taking part. The study was approved by the Ethics Committee of the Department of Psychology, University of Sheffield.

We aimed to collect a minimum of forty participants to match typical sample sizes in the experimental literature (e.g., Exp. 2 of Thomson et al., 2013, a study with similar design). We aimed to increase the power of our design by including a high number of MW probes (78, see below, in the next section) and by using multilevel (or linear mixed-effects) analyses instead of standard ANOVAs.

5.2.2 Materials

5.2.2.1 Complex span task

To measure working memory capacity, participants completed a complex span task. In this task, participants were presented a sequence of two-digit numbers in black, and their task was to memorize these numbers. Each black number was followed by a single blue digit between 1 to 9, but never 5, and the participant had to indicate whether this number was bigger or smaller than the number 5. As such, two-digit black numbers (the memoranda) alternated with single blue digits (choice-reaction time task). Participants saw the memoranda for 1000 ms, and the blue digits until they responded using either the left arrow (smaller than 5) or the right arrow (bigger than 5). After 3 to 5 memoranda had been presented, participants were prompted to recall the black numbers in order of presentation by typing them in and confirming their response by pressing Enter. The next series of memoranda were then presented after an ITI of 2100 ms.

Participants completed 4 trials of each memorandum series length (3, 4, and 5) in a pseudorandom order that was fixed across participants. A unit-weighted partial-credit scoring system was used to evaluate performance (Conway et al., 2005). Unit weighting means that each memorandum series, regardless of its length has the same weight in the calculation of the final capacity score. This is achieved by calculating the proportion of correctly recalled elements within a series on each trial, and then averaging these scores, so each trial's contribution varies between 0 and 1. Partial-credit scoring means that participants receive credit for every correctly recalled item even if the other items in that series are recalled incorrectly. As such, for instance, recalling 2 elements in the correct position from a 4-element long series would mean a score of .5 for that trial, and recalling 2 elements from a 5-element series would mean .4. WMC data of participants who did not reach 85% accuracy on the digit classification task was excluded (1 participant).

5. 2.2.2 Flanker task

Similarly to previous studies, participants completed a confound-minimized arrow flanker task, in which they had to identify the direction of the central arrow – up, down, left, or right - out of a string of five arrows displayed in the centre of the screen. The four flanking arrows could point either in the same direction as the central target (congruent trials), or in a different direction (incongruent trials). The proportion of congruent trials was 50%, and the number of observations in the four within-subject conditions of interest (iI, cI, cC, and iC where i/I is incongruent and c/C is congruent, and lowercase letters indicate the congruency of the previous trial and upper case letters indicate the congruency of the current trial) was balanced. The same strategy was used as in previous studies to avoid feature repetition and contingency learning confounds: the four arrow directions were broken up into two sets of two, and features in one set were used exclusively on odd trials whereas features in the other were used exclusively on even trials.

As a novel addition to the paradigm, the trial sequence also contained probe questions concerning the mental contents of the participant at the time of the probe. Specifically, they were asked “What were you JUST thinking about?”, and were provided the following response options: A) the task, B) my performance, C) intentional mind-wandering, or D) unintentional mind-wandering, corresponding to on-task thought, task-related interference (TRI), intentional MW, and unintentional MW, respectively. Participants were given detailed descriptions of each mental state before the start of the task. The probes were randomly intermixed with arrow trials with the constraint that there always be at least 5 flanker trials between two probes.

The task started with 18 practice trials (16 flanker trials and 2 probe questions). Feedback was given after every flanker trial during the practice session. After that participants completed 7 blocks of 97 flanker trials. In even numbered blocks, 10 probes were intermixed with the flanker trials, while in odd numbered blocks, the number of probes was 12. This was done to maximize the number of probes across blocks while also attempting to minimize the chance of the appearance of probes becoming too predictable due to the abovementioned constraint. In total, participants responded to 78 probes and completed 679 flanker trials.

On each flanker trial, a fixation cross was displayed for 500 ms, followed by a blank screen for 200 ms. After this, the target and the flanker arrows were presented simultaneously for 3000 ms, or until a response was made. Stimuli were presented in black on a grey background. Similarly to Chapters 3 and 4, participants had to indicate the direction of the target arrows by pressing the 2, 4, 6, or 8 keys on the numeric keypad to respond down, left, right, or up, respectively. Participants were asked to use the index finger of their dominant hand. Following the target stimulus, a blank screen was presented for 750 ms if the response to the target was correct. On incorrect trials an error message was displayed for 750 ms instead of the blank screen, saying either 'ERROR' if the participant pressed an incorrect key, or 'TOO SLOW' if the participant failed to respond within the response deadline. Then, the next trial started after an ITI of 250 ms. On probe trials, participants had a maximum of 15 seconds to respond to the question, after which the flanker task continued as before.

5.2.3 Procedure

After obtaining informed consent, participants first completed the complex span task, followed by the flanker task. Participants also completed the Mind-Wandering Questionnaire (MWQ; Carriere et al., 2013) that measures everyday frequency of deliberate (intentional) and spontaneous (unintentional) MW. This was done either before or after the behavioural task, counterbalanced across participants. The whole session lasted approximately 55-60 minutes.

5.2.4 Statistical analyses

Prior to analyses, RTs shorter than 150 ms were removed. This resulted in the removal of only 0.08% of trials. Then outliers, identified as trials with RTs beyond 3 SDs from the participant's mean were also removed. This resulted in the removal of a further 1.94% of trials. For RT analyses, error and post-error trials were also removed. For accuracy analyses, no trials were removed.

The main hypothesis concerning the effect of mind-wandering on the CSE was analysed through a series of linear mixed-effects models using the "lme4" R package (Bates et al., 2015). First, thought probe responses were categorized as either on-task

(“task” response) or off-task (every other response), then the four flanker trials immediately preceding each thought probe were selected for analysis. The CSE was analysed in these trials and the modulating effect of MW was investigated by classifying each four-trial sequence as either on-task or off-task depending on the nature of the thought report that immediately followed them (e.g., if a participant responded “on-task” on Probe N, flanker Trials N-5 to N-1 were all coded as “on-task” trials). The basic model of interest thus contained the predictors Previous Congruency (PC, coded as congruent: 0, incongruent: 1), Current Congruency (CC, congruent: 0, incongruent: 1), and Thought Content (TC, on-task: 0, off-ask: 1), and RT as the outcome. Trial Number was also included as a covariate of no interest because MW rates are known to covary with time on task (e.g., Thomson, Seli, Besner, & Smilek, 2014). To probe the effect of different types of MW on the CSE, three further models were run in which the nature of the Thought Content variable was modified: in the first model, all off-task thought (TRI, IMW, UMW, coded as 1) were contrasted with on-task thought (coded 0), as described above. Then, intentional MW (IMW, coded 0) and unintentional MW (UMW, coded 1) trials were contrasted with each other. In the third model, on-task trials (0) were contrasted with IMW (1), and in the final model, on-task (0) and UMW (1) trials were contrasted. TRI was not the focus of any research question and was thus analysed only in a strictly exploratory manner, contrasted with on-task thought.

Accuracy rates were analysed in the same manner using generalized linear-mixed effects models with trial-level accuracy as the outcome.

To investigate whether the magnitude of the CSE across all trials correlated with the frequency of MW within the task, 3 generalized linear mixed-effects models were run. In all models the predictor variable was the magnitude of the CSE (calculated as (cI-cC)-(iI-iC) as in Chapters 3 & 4), and the outcome variables were binary dummy variables indicating whether the response to a given probe was on-task or not (in the first model), IMW or not (in the second model), and UMW or not (in the third model). In all mixed-effects models Type II ANOVA tables generated by the Anova() function from the “car” package (Fox & Weisberg, 2019) are reported. In the generalized LME analyses odds ratios (ORs) are also reported.

A general LME was run to explore the effect of working memory capacity (WMC) on the CSE in RT, using all flanker trials from the task, and specifying WMC as a subject-level variable. The term of interest was the PC × CC × WMC interaction. A series of generalized LMEs were also run to examine the effect of WMC on accuracy rates and on different types of MW. The logic of these latter analyses was identical to the generalized LMEs described in the previous paragraph, however the magnitude of the CSE was replaced by WMC as the predictor of interest.

5.3 Results

5.3.1 Mind-wandering frequency in the task

Across the entirety of the task, UMW probe reports occurred with the highest frequency, 33.25% (± 17.30%). On-task thought reports made up 31.00% (± 20.92%) of all probe responses, IMW 23.32% (± 16.86%), while TRI accounted for only 12.43% (± 9.14%).

5.3.2 CSE as a function of MW subtype

Figure 5.1 shows the CSE in RT as a function of different probe responses (thought contents), and Table 5.1 contains the terms of four general linear mixed-effects models with RT as the outcome. The models differ in which MW contrast they show (e.g., on-task blocks vs. general off-task blocks; IMW vs. UMW, etc.). As can be seen, reported thought content had no significant effect on behaviour. No main effect of a MW contrast or any interaction including a MW contrast is significant. In fact, the only two effects that are consistently significant across models are the main effects of Current Congruency and Trial Number. The CSE (Previous Congruency × Current Congruency interaction) is only significant in the two models containing the largest number of observations, i.e., the two most highly powered models (On vs. Off, and UMW vs. On).

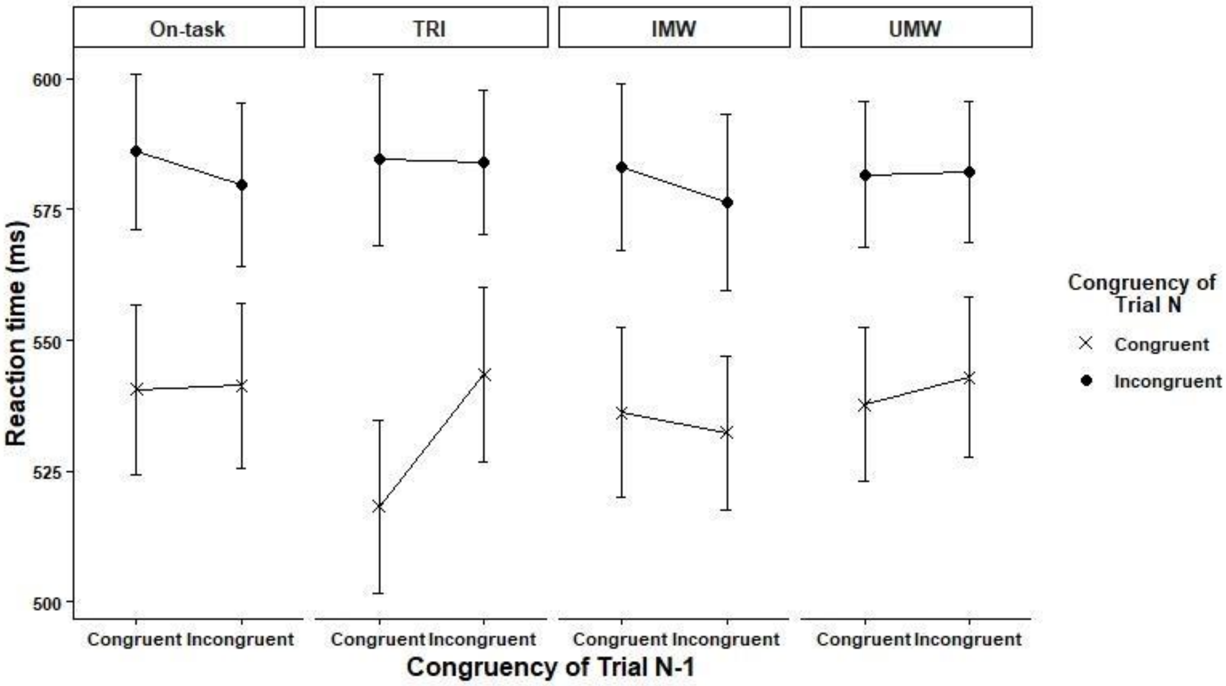


Figure 5.1 - The congruency sequence effect in RT as a function of different thought report categories. TRI = Task-Related Interference, IMW = Intentional Mind-Wandering, UMW = Unintentional Mind-Wandering. Error bars represent ± 1 SEM.

Table 5.1 - Results of the general linear mixed-effects models investigating the effect of thought report categories on RT.

	On vs. Off		**IMW vs. UMW**		**IMW vs. On**		**UMW vs. On**	
	$\chi^2(1)$	**p**	**$\chi^2(1)$**	**p**	**$\chi^2(1)$**	**p**	**$\chi^2(1)$**	**p**
Congruency (C)	137.775	< .001	120.301	< .001	103.618	< .001	129.08	< .001
Previous Congruency (PC)	0.567	0.451	0.386	0.534	0.493	0.483	1.801	0.18
Thought Content (TC)	3.446	0.063	0.615	0.433	0.679	0.41	3.45	0.063
Trial Number	273.667	< .001	172.909	< .001	133.738	< .001	203.093	< .001
C × PC	9.393	0.002	3.356	0.067	3.159	0.076	8.133	0.004
C × TR	0.042	0.838	0.635	0.426	0.588	0.443	0.002	0.968
PC × TR	0.076	0.783	3.743	0.053	1.292	0.256	1.15	0.284
C × PC × TR	0.023	0.879	0.499	0.48	0.532	0.466	0.015	0.904

Note: The Akaike Information Criterion (AIC) values of the selected models from left to right are 157325.5, 89364.82, 85832.1, and 100805.2. All models contain random slopes for congruency. Models without random slopes or with random slopes for the CSE interaction all had higher AIC values. The contrasts in the top row are denoted by the term TC in each model. IMW = Intentional Mind-Wandering, UMW = Unintentional Mind-Wandering.

Following the same logic, generalized linear mixed-effects models with accuracy as the outcome (Table 5.2) found that participants were more error prone when they were off task compared to when they were on task, *OR* = 2.47, 95% CI [.544, 11.166], $\chi^2(1)$ = 9.81, *p* = .002, an effect that was likely driven by participants being more error prone during UMW trials than during reportedly on-task trials, *OR* = .29, 95% CI [.061, 1.426], $\chi^2(1)$ = 7.09, *p* = .008 (Fig. 5.2).

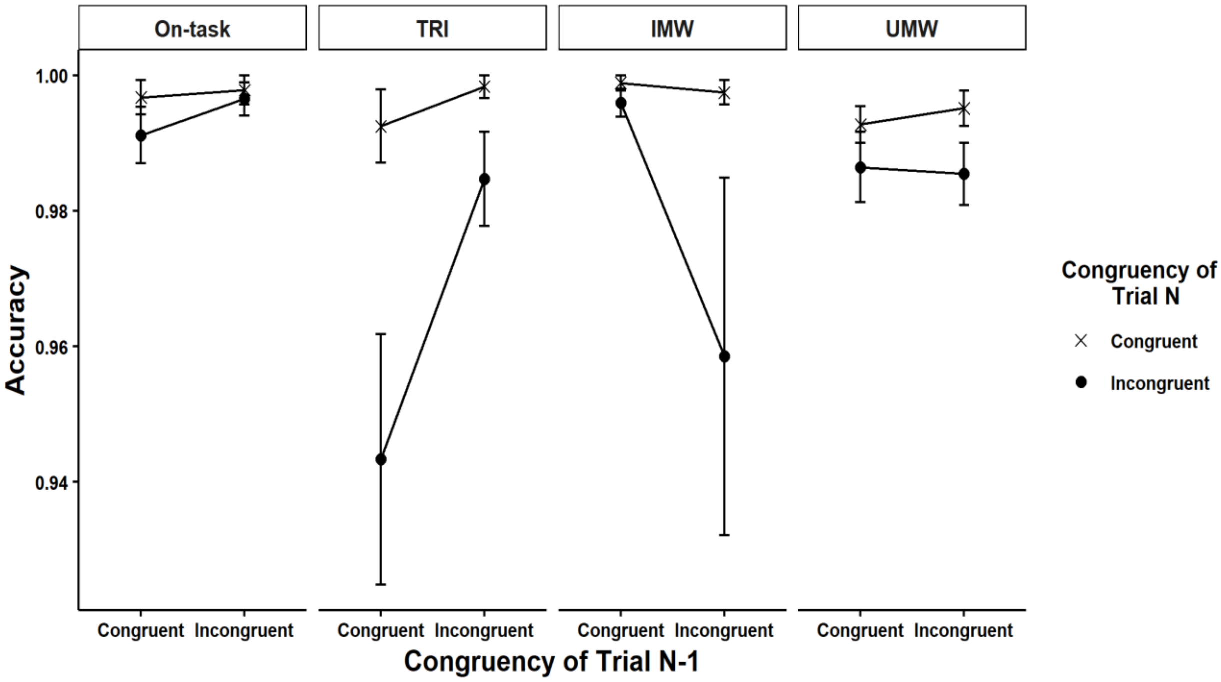


Figure 5.2 - The congruency sequence effect (CSE) in accuracy as a function of different thought report categories. TRI = Task-Related Interference, IMW = Intentional Mind-Wandering, UMW = Unintentional Mind-Wandering. Error bars represent ± 1 SEM.

Table 5.2 - Results of the generalized linear mixed-effects models investigating the effect of thought report categories on accuracy.

	On vs. Off		**IMW vs. UMW**		**IMW vs. On**		**UMW vs. On**	
	$\chi^2(1)$	**p**	**$\chi^2(1)$**	**p**	**$\chi^2(1)$**	**p**	**$\chi^2(1)$**	**p**
Congruency (C)	25.135	< .001	9.662	0.002	7.87	0.005	8.953	0.003
Previous Congruency (PC)	1.306	0.253	0.427	0.514	< .001	0.994	0.342	0.559
Thought Content (TC)	9.809	0.002	2.535	0.111	0.435	0.51	7.094	0.008
Trial Number	1.861	0.172	1.189	0.276	0.526	0.468	1.285	0.257
C × PC	0.360	0.549	1.164	0.281	0.002	0.966	1.095	0.295
C × TR	< .001	0.999	0.238	0.626	0.043	0.835	0.34	0.56
PC × TR	0.9	0.343	0.910	0.34	3.277	0.07	1.422	0.233
C × PC × TR	0.094	0.759	0.374	0.541	< .001	0.998	0.39	0.532

Note: The Akaike Information Criterion (AIC) values of the selected models from left to right are 1011.9, 601.0, 341.0, and 589.1. All models contain random slopes for congruency. Models without random slopes or with random slopes for the CSE interaction all had higher AIC values. The contrasts in the top row are denoted by the term TC in each model. IMW = Intentional Mind-Wandering, UMW = Unintentional Mind-Wandering.

As a next step, the relationship between CSE magnitude calculated across all trials and MW frequency across all blocks was investigated. Contrary to our predictions and to previous findings, the CSE was not significantly related to on-task thought, IMW, or UMW frequency, *OR* = .997, 95% CI [.974, 1.020], $\chi^2(1) = .07$, *p* = .788; *OR* = 1.001, 95% CI [.977, 1.025], $\chi^2(1) < .01$, *p* = .952; *OR* = 1.005, 95% CI [.987, 1.023], $\chi^2(1) = .35$, *p* = .557, respectively. We also explored the association between CSE magnitude and TRI frequency, however it is important to keep in mind that we had formulated no *a priori* hypothesis regarding TRI in particular. A weak negative relationship was found, *OR* = .984, 95% CI [0.967, 1.000], $\chi^2(1) = 4.04$, *p* = .045.

The trait MW variables – the scores of the Deliberate MW and Spontaneous MW subscales of the MWQ – did not interact with the CSE either, however, Deliberate MW scores negatively predicted on-task reports, *OR* =.679, 95% CI [.530, .868], $\chi^2(1) = 9.95$, p = .002, and positively predicted IMW reports, *OR* =1.481, 95% CI [1.136, 1.945], $\chi^2(1) = 8.70$, p = .003, providing some support for the validity of the thought report responses in our task. Spontaneous MW was not found to be associated with any of the state MW variables.

5.3.3 The relationship of WMC with MW and CSE

Table 5.3 summarizes the findings of the linear mixed-effects models investigating the relationship between WMC and behavioural performance (RT and accuracy). WMC showed a negative relationship with RT, but it did not interact with either the congruency effect or the CSE, both *p*s > .5.

Table 5.3 - Results of the general linear mixed-effects models investigating the effect of working memory capacity (WMC) on RT and accuracy.

	Reaction time		**Accuracy**	
	$\chi^2(1)$	**p**	**$\chi^2(1)$**	**p**
Congruency (C)	165.834	< .001	46.318	< .001
Previous Congruency (PC)	0.106	0.745	0.577	0.448
WMC	8.715	0.003	0.056	0.813
C × PC	8.091	0.004	< .001	0.997
C × WMC	0.309	0.578	0.004	0.947
PC × WMC	0.056	0.813	0.137	0.712
C × PC × WMC	0.216	0.642	0.226	0.634

Note: The Akaike Information Criterion (AIC) values of the selected models from left to right are 291311.2 and 1799.8. All models contain random slopes for congruency. Models without random slopes or with random slopes for the CSE interaction all had higher AIC values.

Next, the relationship between WMC and MW were examined. Similarly to the CSE analyses, WMC was not significantly related to on-task thought, IMW, or UMW frequency, *OR* =1.748, 95% CI [.160, 19.481], $\chi^2(1) = .22$, $p = .641$; *OR* =1.796, 95% CI [.134, 24.352], $\chi^2(1) = .21$, $p = .648$; and *OR* =.262, 95% CI [.041, 1.639], $\chi^2(1) = 2.14$, $p = .144$, respectively. We explored the association between WMC and TRI frequency as well, and no significant relationship was found, *OR* =4.094, 95% CI [.674, 27.623], $\chi^2(1) = 2.39$, $p = .122$.

5.3.4 Exploratory analyses

To explore which thought report categories may be of most interest for future studies investigating the relationship between MW and behavioural performance, we investigated how the effect of different MW contrasts on flanker trial performance changes as a function of the trial's distance from the probe. If one assumes that trials closer to a probe are more likely to happen during the mental state reported on the probe, any true mental state-related effect on cognitive processes should get bigger the fewer trials we go back from Probe N. To test this idea, the factor Trial Position (coding whether a given flanker trial is 1, 2, 3, or 4 back from Probe N) and its interactions with all other terms were added as predictors to the linear mixed-effects models investigating the effects of MW on RT and accuracy. No significant interactions involving MW and Trial Position were found in any of the models.

Next, we explored how the impact of MW on performance changes as a function of WMC. No clear *a priori* hypotheses had been formulated for these analyses, and every reported relationship should be interpreted in the light of this.

The effect of interest was the four-way interaction between Previous Congruency × Current Congruency × Thought Content × WMC. Just like in previous analyses, there were multiple different Thought Content variables. The resulting models are summarized in Table 5.4.

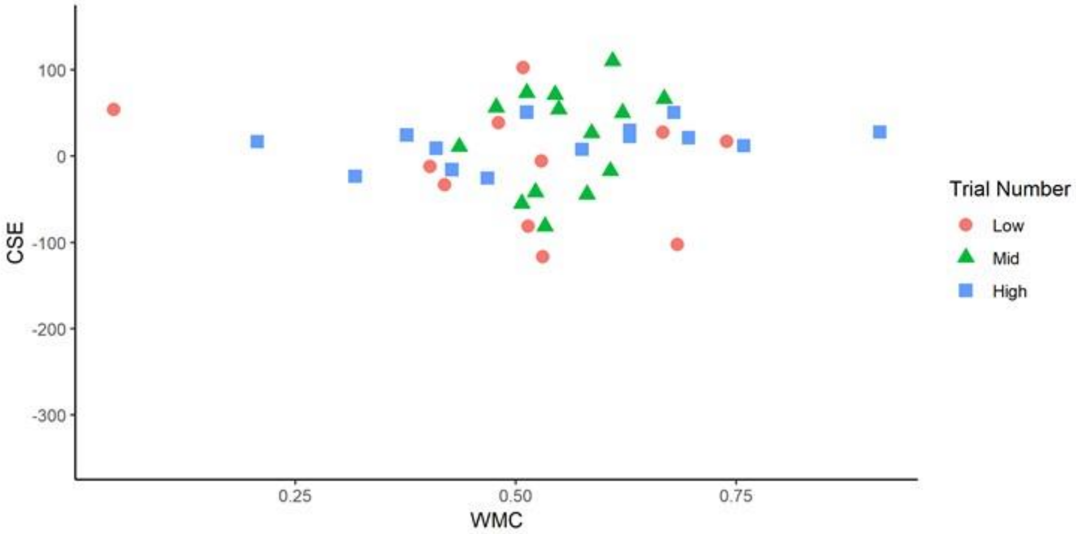
Table 5.4 - Results of the general linear mixed-effects models investigating the effect of thought report categories and working memory capacity (WMC) on RT.

	On vs. Off		**IMW vs. UMW**		**IMW vs. On**		**UMW vs. On**	
	$\chi^2(1)$	**p**	**$\chi^2(1)$**	**p**	**$\chi^2(1)$**	**p**	**$\chi^2(1)$**	**p**
Congruency (C)	143.875	< .001	123.356	< .001	109.189	< .001	132.095	< .001
Previous Congruency (PC)	0.854	0.355	0.249	0.618	0.179	0.672	1.873	0.171
WMC	8.581	0.003	5.26	0.022	7.663	0.006	9.275	0.002
Thought Content (TC)	3.644	0.056	0.254	0.614	0.688	0.407	3.086	0.079
Trial Number	331.267	< .001	201.166	< .001	144.096	< .001	232.444	< .001
C × PC	11.235	0.001	3.89	0.049	3.580	0.058	10.627	0.001
C × WMC	0.223	0.637	0.707	0.401	0.349	0.555	0.352	0.553
PC × WMC	0.677	0.411	0.1	0.752	0.335	0.563	2.061	0.151
C × TR	0.508	0.476	0.714	0.398	1.33	0.249	0.222	0.638
PC × TR	0.001	0.976	2.903	0.088	1.695	0.193	0.408	0.523
WMC × TR	4.448	0.035	1.862	0.172	5.632	0.018	0.53	0.467
C × PC × WMC	0.538	0.463	3.846	0.05	0.442	0.506	0.045	0.832
C × PC × TR	0.1	0.752	0.692	0.405	0.943	0.332	0.026	0.872
C × WMC × TR	1.247	0.264	0.075	0.784	3.004	0.083	1.236	0.266
PC × WMC × TR	0.812	0.367	0.819	0.365	1.796	0.18	0.046	0.831
C × PC × WMC × TR	3.158	0.076	2.001	0.157	6.82	0.009	1.586	0.208

Note: The contrasts in the top row are denoted by the term TC in each model. IMW = Intentional Mind-Wandering, UMW = Unintentional Mind-Wandering.

A significant four-way interaction was found *only* when Thought Content represented the contrast between being on-task and intentionally mind-wandering (IMW vs. On). This is visualized in Fig. 5.3 which shows CSE magnitude as a function of WMC for both on-task and IMW trials. As can be seen, there is a negative relationship between CSE and WMC in the IMW trials but not in on-task trials. In the figure, participants are categorized based on the mean number of trials they had across the four PC × CC conditions that contribute to the calculation of the CSE during on-task and IMW episodes. This was done to illustrate that while participants with low trial counts do seem to be driving the effect, participants with higher trial counts also show similar patterns.

A) The CSE-WMC relationship during on-task episodes



B) The CSE-WMC relationship during IMW episodes

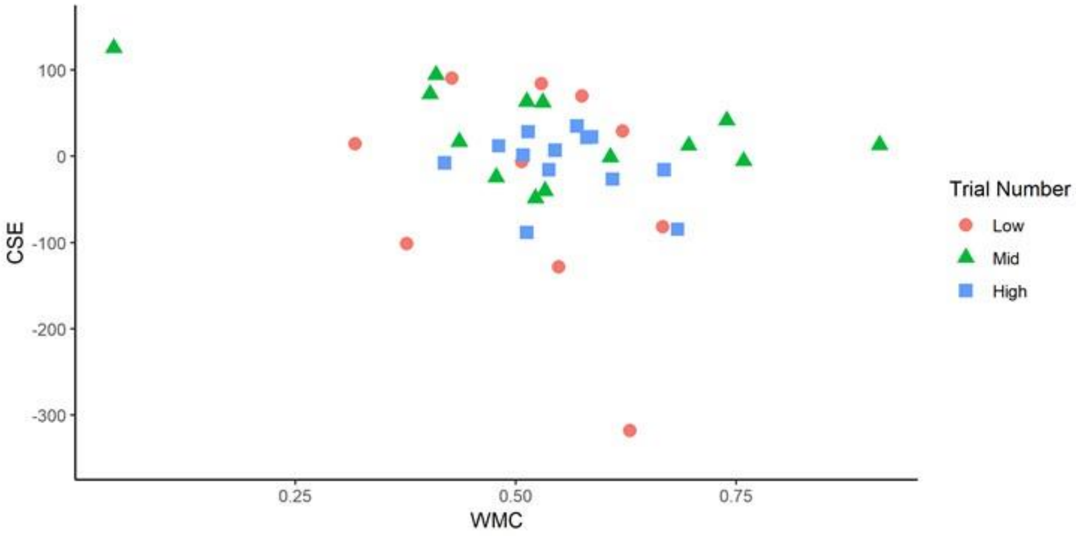


Figure 5.3 - The interaction between the congruency sequence effect (CSE), intentional mind-wandering, and working memory capacity (WMC). Trial number groups are based on the tertiles of the distribution of the mean trial number across conditions in the sample. IMW = Intentional Mind-Wandering.

Finally, just like in Chapters 3 and 4, we combined the two categories representing MW (here those are IMW and UMW) to create an overall MW category. As was mentioned in Chapter 4, this was a suggestion by a reviewer (Dr Mike Kane) for Chapter 3 that was received after analysis has already been completed for the present chapter, as such analyses including this category were *not* planned. No significant results were found when all of the above analyses were repeated with overall MW (or the contrast between on-task thoughts and overall MW) as the outcome / independent variable, except for a significant positive relationship between overall MW frequency and Deliberate MW scores, *OR* =1.370, 95% CI [1.074, 1.749], $\chi^2(1) = 6.69$, p = .010.

5.4 Discussion

In this experiment, we investigated how different types of mind-wandering are related to the magnitude of the CSE in a flanker task. In addition to an individual difference approach examining the correlation between CSE magnitude and the frequency of different types of MW reports similar to Chapters 3 & 4, we also contrasted performance on trials that likely occurred during different types of MW with performance on trials that likely occurred during task focus. Although our two previous studies (Chapters 3 & 4) found a negative relationship between CSE magnitude in the flanker task and the frequency of MW reports in a separate task, no such relationship was found in the current sample when both were measured in the same task. Similarly, no effect of MW was found on behavioural performance when on-task and off-task runs of trials were contrasted. Exploratory analyses, however, revealed some promising avenues for future research.

We failed to replicate the finding of the previous two studies (Chapters 3 & 4) that MW frequency is negatively correlated with CSE magnitude across participants. There are several differences between the design of the previous studies and the design of the current study that might account for this null finding. Most importantly, in the current study thought probes were embedded into the flanker task itself, instead of the CSE and MW frequency being measured in separate tasks. The trial sequence interruptions inherent in the thought probe method could have impacted the CSE in some way. While most explanations of the CSE consider changes triggered by the immediately preceding trial (e.g., Duthoo et al., 2014a; Hommel et al., 2004; Schmidt & Weissman, 2016), some recent findings suggest that trial history may have a longer lasting effect on performance or that trial history beyond Trial N-1 needs to be taken into account as well when considering performance on Trial N. For instance, Rey-Mermet & Meier (2017) found that the lengthening of response times following incongruent trials compared to following congruent trials (post-conflict slowing) can last for several trials after a conflicting trial, and is not only detectable on the immediately following trial in a variety of conflict tasks. Using the Stroop task, Jiménez & Méndez (2013, 2014) found that the congruency effect on Trial N decreased as a function of the number of preceding incongruent trials which they interpreted as evidence that the effect of conflict accumulates progressively over longer runs of trials. Thus trial history beyond the immediately preceding trial might have an effect on current trial control levels. This is also in line with the findings of Aben, Verguts, & Van den Bussche (2017) who found that although the effect of preceding trial congruency on current trial congruency decreases as a function of distance from Trial N, trials beyond Trial N-1 still exert some influence on Trial N. Altogether these findings suggest that interrupting the trial sequence every 6-7 trials might have interfered with the mechanisms generating the CSE (e.g., it might have reset the mechanism keeping track of average conflict across trial history) weakening the effect and changing what it reflects, to some extent. Alternatively, unpredictable but frequent interruptions might have discouraged participants from engaging proactive (sustained and anticipatory) control mechanisms making their performance more reactively driven than in previous studies. This change in mechanisms might have affected the CSE-MW relationship too.

Interruptions might also have affected propensity to MW. Participants might have been brought back to the task by every disruption, and in the short time window that typically separated probes in the task they may have been less likely to re-start MW. This notion was not supported in a recent experiment by Robison, Miller, & Unsworth (2019) who found no difference in behavioural indices and MW frequency between a rare- and a frequent-probe version of a Go/No Go task, and is also not supported by the fact that participants reported being on-task slightly less frequently in the current study than in either one of our previous ones (31% vs 37-40%) which had significantly fewer probes and thus, disruptions. This task-related difference in frequency is particularly interesting given that task difficulty is known to decrease MW rates (Seli et al., 2016; Seli, Konishi et al., 2018) and the current task was more difficult than the simple Go/No Go task used in previous studies because participants had to ignore irrelevant information and decide which out of 4 response options is the correct one. It is, however, worth noting that the current task was longer than the previous tasks (approx. 40 minutes vs. 15 minutes), and on-task reports tend to decrease as a function of time (e.g., Smallwood, Baracaia, Lowe, & Obonsawin, 2003; Smallwood et al., 2007; Thomson et al., 2014). Accordingly, on-task rates in the first block only of the current task were comparable to previously reported rates (37.8%). This rate, however, is still not higher than previous rates coming from a substantially easier paradigm.

One other feature of the current design that could explain differences between the previous and current findings is that different probe responses were used, in order to gain more information about the intentionality of MW (Seli et al., 2016). While in previous studies, participants could either categorize their thoughts as on-task, MW with or without awareness, or mind-blanking; the latter three categories were replaced by intentional or unintentional MW and task-related interference (TRI) in the current task. Mind-blanking was dropped due to its low incidence in previous studies, and TRI was added because it is a transitional type of cognition that is halfway between on-task and MW thus it might contaminate other thought category reports if it is omitted (Robison et al., 2019). This might also explain the difference in on-task rates across our studies: when this option is not available (like in our previous two studies) participants will classify some task-related evaluative thoughts (TRI) as on-task, and some as off-task (Robison et al. estimate the proportion of misclassified TRI thoughts to be 2/3 and 1/3, respectively), inflating the proportion of these other categories. Interestingly, there was a weak *negative* relationship between TRI frequency and CSE magnitude in the present study that had not been originally hypothesized. This would only be in line with previous findings if we assumed that misclassified TRIs were driving the correlation between CSE magnitude and MW frequency in those studies. This appears unlikely given Robison et al.'s finding that TRIs are more frequently misclassified as on-task thought (the frequency of which was positively or not related to the CSE in previous studies) than MW. Therefore, this tentative relationship would need to be replicated before a full interpretation can be offered. However, one speculative idea could be that participants who are more preoccupied by their performance are performing closer to their own ceiling throughout the whole task and there is less room for modulation in the magnitude of the congruency effect. It is also possible that the meaning of TRIs is different in a flanker task than in a Go/No Go task, and that the misclassification rate reported by Robison et al. for a Go/No Go task would be different for a more complex task such as the flanker.

One further difference between previous studies and the current one lies in the composition of the samples used. The current sample contained healthy adults only (following the terminology of our developmental studies, a mixture of young adults and late adolescents), while in the previous two studies, the age range was substantially wider. However, age group did not interact with the CSE-MW relationship in either one of those studies, nor did it have an effect on CSE magnitude or MW frequency separately (except for Chapter 3, where an age effect on MW was found, but failed to replicate in Chapter 4). As such, this is unlikely to be a significant contributing factor to our null finding.

With the exception of a slight decrease in accuracy during UMW episodes compared to on-task performance, we found no significant MW-behaviour relationships on the trial level either, that is, performance was largely similar during on-task episodes and off-task episodes of various kinds. This is somewhat surprising in the light of our previous findings linking the MW to CSE magnitude as discussed above, but it fits well with the relatively mixed literature on the behavioural costs of MW in general. While the majority of studies show that MW impacts performance in a variety of tasks (e.g., McVay & Kane, 2009, 2012; Randall et al., 2014; Seli, 2016; Seli, Cheyne, & Smilek, 2013; Smallwood, Baracaia et al., 2003; Smallwood et al., 2007; in certain analyses Thomson et al., 2014), some find no significant association between performance and reported task focus (e.g., Gyurkovics et al., 2018; Varao-Sousa & Kingstone, 2019; also see Chapters 3 & 4). Importantly, Thomson et al. (2013) found no behavioural costs associated with being off-task vs being on-task in a Stroop task, and suggested this was because participants were able to titrate how much of their resources they can allocate to MW while also maintaining adequate performance. Our study provides support for this idea, using a more powerful design and analysing a wider range of potential behavioural indices that may have been affected (the CSE in addition to mean RT, accuracy, and the congruency effect). A more parsimonious and cautious interpretation of our findings could be that the mechanisms behind performance on the flanker task and the mechanisms behind different types of MW do not appear to compete for the same resources in our sample, if they require cognitive resources at all. Importantly, however, it is unwise to over-interpret a null finding as it could merely reflect a lack of adequate statistical power to detect a subtle effect, instead of the lack of an actual effect.

In an effort to elucidate the nature of the mechanisms behind the two phenomena, we also investigated the associations between WMC and the CSE, and between WMC and different types of MW. No significant associations were found. In the case of the CSE, this is not surprising given previous, substantially more highly powered studies that also found WMC and the CSE to be unrelated (Meier & Kane, 2013; Unsworth et al., 2012). It is however important to keep in mind that our study was not adequately powered for conclusive correlational analyses, thus further studies need to be conducted that investigate the relationship between the magnitude of the confound-minimized CSE in different tasks – as the mechanisms behind the effect might be task-specific, see the Discussion of Chapter 3 – and WMC, in a large sample. While the studies by Meier & Kane (2013) and Unsworth et al. (2012) were highly powered, they used only one task each (Stroop and flanker, respectively), and their design contained confounds or additional manipulations that may have impacted the nature of control mechanisms recruited for the CSE (e.g., proportion congruency manipulation, see also Aben et al., 2017).

The lack of a clear relationship between WMC and any type of MW is more surprising given the wealth of high-powered findings linking the two (e.g., McVay & Kane, 2009, 2012), and is most likely explained by a lack of power to detect this association in the current sample. Consequently, our findings provide no support for or against either the cognitive resource account of MW or the control failure account.

Finally, a set of exploratory analyses were also conducted on the data. These analyses were not planned *a priori*, and were only run to generate hypotheses for future research. First, we examined whether the effects of MW on performance differ as a function of the distance of flanker trials from the probe. The rationale for this analysis was that trials closer to a probe are more likely to fall into the thought content episode reported on that particular probe (e.g., IMW) than trials further away, thus if type of thought interacts with cognitive control mechanisms, thought content related effects might get bigger the closer a trial is to the probe. We found no reliable evidence of such an effect, although it is important to note that this was a complex four-way interaction that our sample may have been underpowered to detect.

Next, another four-way interaction was also explored, namely between the CSE (itself a two-way interaction), thought content, and WMC. We found that in our sample the magnitude of the CSE is negatively correlated with WMC during IMW episodes but was unrelated to it when on-task. If future studies replicate this effect, that will have important implications for our understanding of both the CSE and MW. It is possible, albeit speculative that when no resources are allocated to MW (i.e., during on-task episodes), everyone regardless of WMC has sufficient capacity to deal with the occurrence of conflict using either proactive or reactive strategies or a mixture of both. However, when MW is engaged intentionally, consuming resources (for the theoretical argument that IMW might reflect a resource-dependent type of MW whereas UMW might be a consequence of control failures, see Seli, Kane, et al., 2018), the strategy participants employ to maintain adequate performance may be more dependent on the amount of resources available for the individual. High WMC individuals might be more likely to use a proactive strategy than low WMC individuals (Redick, 2014; Redick & Engle, 2011) leading to a smaller CSE because control levels are set to be high across trials, regardless of their congruency. This might account for the negative relationship between CSE magnitude and WMC. This would suggest that a bigger CSE might indicate a lack of proactive preparation for conflict, instead of the efficiency of reactive control deployment under these circumstances. Due to the theoretical importance of this question future studies with more observations per participant are necessary to address it, until then it cannot be ruled out that the significance of this interaction is merely a result of a highly complex model overfitting a relatively small sample. Our findings provide a clear hypothesis for such future studies.

In conclusion, using a large amount of thought probes in a conflict task with a large number of observations per condition, we found no clear relationship between performance and attentional state. Specifically, MW was not related to the magnitude of the CSE either at the global level or at a more local level. This goes against our previous findings that the magnitude of the CSE is negatively related to MW frequency in a different task. Potential reasons for this discrepancy include a difference in the number of interruptions caused by the probes and in the response options provided by the probes between the previously used and the current tasks. We conclude that future studies using a longer task with more probes should investigate how the intentionality of MW affects conflict resolution performance, and how this interacts with working memory capacity.

Chapter 6 - General Discussion

The studies reported in this thesis were designed to investigate the determinants and correlates of dynamic adjustments of cognitive control, with a special emphasis on the developmental trajectory of such adjustments on both the behavioural and neural levels. Dynamic adjustments of control were operationalized as the congruency sequence effect (CSE), the phenomenon that the effect of task-irrelevant distracting information in conflict tasks is smaller following conflicting (incongruent) compared to non-conflicting (congruent) trials (Gratton et al., 1992). This is commonly interpreted to be a consequence of the upregulation of cognitive control in response to the occurrence of conflict (Botvinick et al., 2001, 2004).

The main focus of my studies was the investigation of the CSE across adolescence. I focused on this period of life in particular because cognitive control abilities are still thought to be undergoing maturation across the second decade of life (Shulman et al., 2016). This assumption is supported not just by previous findings examining adolescent behavioural performance on control tasks, but also by studies of brain function and structure, which suggest that control-related areas (e.g., the prefrontal cortex or the anterior cingulate cortex) are still maturing through this period, often into adulthood (e.g., Casey et al., 2005; Gogtay et al., 2004; Ordaz et al., 2013; Luna et al., 2010, 2015; Shulman et al., 2016). Based on this notion, I expected to find age-related differences, possibly increases, in the magnitude of the CSE, a control-related effect, across adolescence.

In the first developmental study (Chapter 3), participants from four age groups, ranging from early adolescents (12-13 year-olds) to young adults (25-27 year-olds) older than the latest proposed endpoint of adolescence (24; Sawyer et al., 2018) completed two conflict tasks, the flanker task and the Simon task. Both were designed specifically to examine the CSE, as such, potential learning and memory confounds (see e.g., Duthoo et al., 2014a) that could have complicated the interpretation of the effect were controlled for. The CSE was observed in both tasks, however, no significant age differences in its pattern or magnitude were found, even after controlling for baseline response speed differences between groups.

The next study (Chapter 4) was designed to investigate the neural mechanisms supporting the CSE across age with the help of EEG. Two groups, early adolescents (ages 12-14) and young adults (ages 25-27) completed a single, confound-minimized conflict task, a modified flanker task where distractors preceded the target, while their neural activity was recorded. Data was analysed in 3 domains: 1) behavioural performance, 2) the time domain of the neural data, as represented by the N2 ERP component, and 3) the time-frequency domain of the neural data, specifically midfrontal theta power, temporal consistency of theta, and functional connectivity with other sites. While strong effects of congruency were found in all outcomes, along with CSEs in some outcomes (RT, N2 component, theta power), no significant age differences were observed in the majority of measures once again. Analysis of condition-aggregated data did suggest, however, that adolescents show smaller congruency effects in both theta power and cross-trial synchronization than adults.

In both of these studies, participants also completed a Go/No Go task during which the frequency of task-unrelated thoughts (mind-wandering, MW) was measured via self-report. In the first study, MW frequency appeared to show a moderate increase as a function of age, in accordance with theories of MW that suggest it requires cognitive resources, however, this pattern did not replicate in the second study. Consequently, it is difficult to draw firm conclusions about developmental effects on MW frequency based on these two sets of findings.

I also presented two additional studies (Chapters 2 & 5) that did not investigate developmental research questions, but were focused on the determinants and correlates of the CSE, and were designed to learn more about the exact nature of the effect.

In the first study (Chapter 2), I investigated whether response conflict is an aversive signal in healthy young adults and late adolescents (undergraduates). This was based on the notion that control regulation following conflict, e.g., the mechanism that is hypothesized to be behind the CSE, is triggered by the transient negative affective state elicited by conflict, and is aimed at down-regulating the negative experience and avoiding further similar states (Dreisbach & Fischer, 2015; Saunders et al., 2017). An affective priming design was used in which congruent and incongruent Stroop stimuli were presented as primes for various durations, and were immediately followed by Chinese characters. Participants had to evaluate how negative/positive they found the target characters. We expected targets to be judged more negatively following incongruent compared to congruent primes due to incongruent primes eliciting negative affect and this spilling over into the evaluation of the target. This effect, although numerically present, was not statistically significant in our sample as such we were unable to demonstrate the aversive nature of response conflict.

Finally, in the study reported in Chapter 5, the relationship between MW and the CSE was examined more closely. Both of our previously described developmental studies (Chapters 3 & 4) suggested that across all ages, the frequency of MW during an unengaging Go/No Go task was negatively related to the magnitude of the CSE in the flanker task (but not the Simon in Chapter 3). In this final study, we attempted to replicate this finding in a sample of late adolescents and young adults (university students) by looking at the association between MW frequency and the CSE when both are estimated within the same task (the flanker), and to see if being on-task vs off-task (MW) had an effect on the size of the CSE. We failed to replicate the previously reported association, and we also observed no performance difference between on-task and off-task episodes in terms of the size of either the congruency effect or the CSE.

In the following sections these findings will be discussed in detail, separated into two general areas. First, the central research questions of my thesis will be discussed: the processes behind the confound-minimized CSE and how they change across adolescence (Chapters 3 & 4), followed by the discussion of additional aspects of the CSE such as its potential causes (Chapter 2) and its association with MW (Chapters 3,4, & 5).

6.1 The confound-minimized CSE and its developmental trajectory

The congruency effect was smaller in RT following incongruent compared to congruent trials in both Chapters 3 and 4, and in most models of Chapter 5 as well, meaning that the CSE was observed in these studies. Notably, it emerged in tasks in which the most common lower-level learning and memory effects that could have generated a CSE-like pattern (e.g., Hommel et al., 2004; Mayr et al., 2003; Mordkoff, 2012) were controlled for. Consequently, our findings provide strong support for the notion that higher level, cognitive control processes can also generate the effect (e.g., Botvinick et al., 2001; Weissman et al., 2017). Importantly, to the best of my knowledge, Chapter 3 described the first observation of the CSE in midfrontal theta-power using confound-minimized tasks, underlining the proposed central role of theta oscillations in cognitive control (Cohen, 2014a; Gratton et al., 2018). Our finding that the confound-minimized CSE was present in the amplitude of the N2 ERP as well replicates previous findings (Feldman & Freitas, 2018; Larson et al., 2016) and, along with the theta findings, highlights the importance of the midfrontal region (possibly the dACC in particular) in top-down control regulation. Both theta power and N2 amplitude are most likely indices of processes involved in the detection of conflict (Cohen, 2014a; Gratton et al., 2018; Larson et al., 2014) or more generally, the detection of signals of need for control (e.g., unexpected punishment; Cavanagh & Shackman, 2015). This is supported by our findings that they both peaked before correct response execution and were sensitive to the magnitude of conflict on a given trial. Previous studies have also shown that the generator of both midfrontal theta and the N2 is likely to be the ACC (Hanslmayr et al., 2008; Van Veen & Carter, 2002a), the region that plays the role of conflict monitor in the conflict monitoring theory (Botvinick et al., 2001). The conclusion that these neural markers reflect conflict detection is buttressed by the fact that our tasks were confound-minimized, therefore different trial types only (or presumably only) differed from each other in the amount of conflict, and not in the extent of feature overlap with the previous trial or distractor-target contingencies. In short, our findings suggest that theta oscillations and N2 amplitude are neural correlates of cognitive processes involved in top-down control regulation, and that the observed CSEs might be interpreted as modulations of such control processes.

Most importantly for the central question of my thesis, no significant age effects were found in the magnitude of the CSE in any outcome measure, except for a subtle decrease as a function of age in raw reaction times in Chapter 4 that disappeared after controlling for baseline speed differences between age groups. The most cautious conclusion we can draw from our null findings across studies is that developmental changes in the CSE are subtle if they exist. This naturally does not disconfirm the idea that cognitive control is still undergoing maturation in the adolescent period (Shulman et al., 2016) – indeed, performance on all control tasks got faster, more accurate, and less variable with age, and ANOVA-type analyses also suggested that adolescents show smaller differentiation between conflicting and non-conflicting trials in theta oscillatory dynamics, suggesting that certain aspects of control have still not reached adult levels by early adolescence, neither on the behavioural nor the neural level. Our findings do, however, suggest that the mechanism indexed by the CSE matures fairly early on: by approximately 12 years of age based on the findings reported in the thesis; and based on previous, albeit confounded findings, it may even be present as early on as age 5-6 (Ambrosi et al., 2016). Previous studies have also shown that different cognitive control processes mature at different speeds (e.g., Crone, Donohue, Honomichl, Wendelken, & Bunge, 2006; Ordaz et al., 2013), as such, it is reasonable to assume that while some control processes (e.g., rule representation or error processing; Crone et al., 2006) do not reach full maturity until late adolescence (or later), the process responsible for the CSE changes less substantially over the second decade of life. But what might this process be?

As mentioned at the beginning of this section, we favour a control-related explanation of the CSE, at least in our data sets. In general, control-related accounts explain the effect in terms of conflict adaptation: the adjustment (strengthening) of top-down control in response to response conflict (Botvinick et al., 2001; Duthoo et al., 2014a). The studies presented in this thesis were not designed to adjudicate between different sub-hypotheses within the top-down control account of the CSE concerning the exact mechanism of control adjustment (e.g., attentional shift, response modulation), however, our findings appear to be most consistent with a response modulation explanation. Briefly, this argues that control processes actively suppress the response activated by the distractor to a greater extent after conflicting compared to non-conflicting trials (Weissman et al., 2014, 2017; Weissman, Colter et al., 2015; Weissman, Egner et al., 2015). This suppression is even more pronounced when the distractor-related response is activated before the target response, leaving more time for control processes to act on it. Weissman et al. (2014) used this logic to explain why the CSE was bigger in the Simon task in their study than in either the Stroop or the flanker task: the automatic activation of the task-irrelevant response is faster in the Simon than in the other two tasks, leading to greater suppression. In Chapter 3, we also found that the CSE was greater in the Simon than in the flanker, lending indirect support to the response modulation idea (see also Gyurkovics et al., in principle acceptance).

Furthermore, our findings also provide some support to the idea that the mechanisms behind the CSE might be task-specific (Egner, 2008). The CSE did not correlate across the Simon and the flanker tasks in Chapter 3, and it also appeared to have different correlates depending on the task (the flanker CSE correlated with MW, the Simon CSE did not). Consequently, what mechanism the CSE reflects or how this mechanism is implemented may be dependent on the task one is using. It is possible that ultimately some type of episodic retrieval (Weissman et al., 2016) or associative learning mechanism (Abrahamse et al., 2016) is behind the generation of the effect, whereby different, concrete and abstract aspects of Trial N-1, e.g., the congruency level of the trial and the control setting used, are bound together into an episodic representation or associative network which then may be activated on Trial N, leading to performance changes based on the activated control setting. These frameworks would predict highly task-specific CSEs as the implementation of top-down control would depend on representations and networks that contain information specific to the task stimuli, response set, temporal structure, etc. of a given task. Importantly, the control setting that is bound to trial features in these accounts could still include the modulation of distractor-related responses (e.g., “suppress response X”), as such these frameworks do not invalidate the response modulation account, merely extend it.

Regardless of the specific mechanism, the top-down control accounts of the CSE typically interpret the effect as a manifestation of *reactive* control. In the terminology of the dual mechanisms of control theory (Braver, 2012; Braver, Gray, & Burgess, 2007) which differentiates between two modes of control, reactive control refers to control deployed in response to a stimulus, mobilized to address demands after they have occurred. Proactive control, in contrast, is engaged before stimulus onset, in preparation for the stimulus, and is assumed to be more demanding than reactive control. Previous developmental studies have shown that even children under the age of 6 employ reactive strategies spontaneously (as opposed to showing no control at all), with a shift towards the more frequent use of proactive control occurring sometime around the age of 6 (Chatham et al., 2009; Chevalier et al., 2015; Lucenet & Blaye, 2014). In light of these findings and the findings reported in the present thesis, it is possible that the CSE reflects a mode of control (reactive control) that is present early on in development, and while it might show improvements in precision or speed over the years, these improvements are not substantial after 12 years of age. Importantly, I do not and cannot claim that there are no improvements, merely just that they are likely to be small. Future studies could investigate if the magnitude of the CSE in confound-minimized tasks changes after age 6, as a shift from predominantly reactive control to more proactive control may lead to a *decrease* in CSE magnitude (although see Surrey et al., 2019 who failed to detect the CSE in RT in 9-12 year-olds, but found it in adults in a fairly confound-free design). This is because if control is engaged proactively in a conflict task, reactive adjustments may not be necessary to meet changing task demands. A less restrictive formulation of this idea could be that if proactive control is more available and more likely to be engaged, reactive adjustments may occur less frequently, leading to an overall smaller effect. However, it is also worth noting that engaging proactive control in a largely unpredictable task like the typical conflict tasks may be wasteful and counter-productive, thus, meta-control abilities, which also improve with age (Chevalier, 2015), might not favour proactive strategies in these contexts. In this case, the future studies proposed above would provide a glimpse into the refinement of purely reactive control across the early years of development.

Finally, it is important to note that other manifestations of conflict-induced adjustments of control beside the CSE have also been identified in the literature, such as various proportion congruency (PC) effects (Bugg & Crump, 2012). The most extensively researched of these is the list-wide proportion congruency (LWPC) effect, the finding that in conflict tasks, the congruency effect is smaller in trial lists that contain a higher proportion of incongruent than congruent trials (e.g., 80% vs 20%) than in lists where these proportions are reversed (Logan & Zbrodoff, 1979). This is hypothesized to reflect a global heightening of control in response to the higher probability of conflict (Botvinick et al., 2001; Bugg & Crump, 2012). Another PC effect is the context-specific proportion congruency (CSPC) effect which refers to the finding that when certain contextual cues (e.g., a location on the screen) are associated with different proportions of incongruent trials, these cues can also be used to modulate control settings, e.g., if trials appearing above fixation in a 50% incongruent task are more likely to be incongruent than trials appearing below, the congruency effect will be smaller for trials presented above fixation (the mostly incongruent location) than below (the mostly congruent location; Crump, Gong, & Milliken, 2006). Finally, individual stimulus features can also be associated with different proportions of incongruent trials, e.g., in the Stroop task, the color green could appear mostly on incongruent trials, whereas the color red could appear mostly on congruents. The congruency effect is then typically smaller on items containing mostly incongruent features than on items with mostly congruent features, resulting in an item-specific proportion congruency (ISPC) effect (Jacoby, Lindsay, & Hessels, 2003). These latter two effects are thought to reflect reactive adjustments of control driven by the contextual cue or the trial feature, respectively, however, their relationship with the CSE and with each other is still a topic of intense research and debate (Braem et al., 2019). Developmental studies investigating PC effects appear to be even more scarce than those looking at the CSE, although recently Surrey et al. (2019) found that 9-12 year-olds show similar LWPC and CSPC effects to young adults, suggesting that control adjustments driven by contextual cues (e.g., list type and location) are online by this age (albeit, as mentioned above, they did not find a CSE in RT in the younger age group, only in accuracy rate). Importantly, learning and memory related confounds can contaminate these effects as well (Braem et al., 2019), therefore, rigorously designed developmental studies of different aspects of control dynamics are crucial in order to learn more about age-related changes in the ability to adjust control levels to task demands.

6.2 What drives top-down control mobilization?

Thus far I have discussed the proposed mechanism of the CSE, and its potential developmental trajectory. Next I would like to examine what drives the effect. In Chapter 2, I introduced the hypothesis that the CSE occurs as a form of emotion regulation due to the aversive nature of the signal elicited by conflict (Dreisbach & Fischer, 2015), and used an affective priming paradigm to investigate the core assumption of this idea, namely that conflict is aversive. I failed to replicate the findings of Fritz & Dreisbach (2013, 2015) who demonstrated that neutral stimuli are more likely to be judged negatively following incongruent compared to congruent trials. The original finding was taken to suggest that conflict elicits a negative affective state which is then carried over to the neutral stimulus impacting its evaluation. Importantly, a null finding such as ours cannot be interpreted as evidence for the lack of an effect, as such the most conservative conclusion that can be drawn is that our results were inconclusive. Based on our findings, however, the size of the effect if it exists is likely to be small, therefore future studies should attempt to replicate the original findings with larger samples or more observations per condition, possibly in conjunction with a Bayesian statistical approach, thereby confirming or invalidating the original account. As such, it is probably most prudent to consider why control mobilization occurs in the CSE an open question. The main reason behind the failure to replicate the effect was probably the slight alterations in design compared to the original study (Fritz & Dreisbach, 2015), thus, our findings could provide valuable insight about the expected effect size of affective priming by conflict stimuli in various paradigms, and the design parameters most conducive to its occurrence (e.g., fixed prime duration, simple binary valence evaluations).

6.3 Mind-wandering and the CSE

For my final study, I investigated a potential correlate of the CSE: MW. This study was motivated by the empirical finding from Chapter 3, replicated in Chapter 4, that the magnitude of the CSE in the flanker task correlated negatively with self-reported MW frequency in a Go/No Go task. While this association was not the main focus of any of those studies, the study in Chapter 5 was designed to investigate it in more depth as it had the potential to yield interesting observations about the mechanisms of both the CSE and MW. In this final study, MW frequency was measured within the flanker task itself. Flanker CSE magnitude and MW frequency were unrelated in this design, regardless of the nature of MW (intentional vs. unintentional). Consequently, future studies are necessary to confirm if the mechanisms of the CSE interact with the mechanism behind MW as suggested by Chapters 3 and 4, or not robustly as suggested by the final study. If they confirm the former, that could mean that reactive control abilities – that may be indexed by the CSE, as described above – play a role in regulating how much time one spends in MW, and/or how often MW episodes occur. Furthermore, our findings suggest a complex interaction between cognitive resources (working memory capacity), the intentionality of MW, and task demands (the congruency of current and previous trials). As the statistical model that yielded this interaction was a) exploratory and b) highly complex, providing more than a tentative interpretation of this interaction would be risky until future studies replicate it. One clear benefit of Chapter 5 is that it has generated novel hypotheses for future research. Future studies might also investigate neural activity in a combined cognitive control/MW paradigm similar to the one introduced in Chapter 5, as MW has also been shown to disrupt theta oscillations, albeit in a perceptual task (Baird, Smallwood, Lutz, & Schooler, 2014).

A final finding of the present thesis that deserves closer scrutiny is the inconsistently observed age effect in MW frequency. In Chapter 3, it was observed that late adolescents (18-20 year-olds) reported significantly more off-task thoughts than early adolescents (12-13 year-olds), and numerically than any other group. Originally this was interpreted as being in line with the predictions of the cognitive resource account of MW (Smallwood & Schooler, 2006) which posits that MW is a resource-intensive process, thus it is likely to become more frequent as a function of development as the amount of available cognitive resources increases. However, no age related increases in MW frequency were found subsequently in Chapter 4 where only early adolescents (12-14 year-olds) and young adults (25-27 year-olds) were contrasted. This raises at least two possibilities: 1) either the first or the second set of results was due to random chance, therefore future studies are needed in this area, and 2) there is something special about the late adolescent (mostly undergraduate) age group leading to a spike in MW there. Although this explanation is highly speculative, it is possible that they had more university-related concerns that competed with task-relevant thoughts in the university testing setting than any other group (e.g., McVay & Kane, 2012). Developmental studies in which the number of current concerns is measured alongside MW frequency could potentially address this research question.

6.4 Limitations

The most important limitation of the studies presented in this thesis is the lack of consensus in the literature on what exactly the magnitude of the CSE represents. Larger CSEs might be associated with better, more flexible reactive control or a relative failure of proactive control, while smaller CSEs could indicate a rigid control system unable to adjust, or high levels of proactive control. There are two reasons why we interpreted our findings from a "larger CSE means more flexible control" perspective: 1) previous studies have found effects that are more consistent with this interpretation, at least in the Simon and flanker tasks (e.g., the CSE gets smaller with age at the other end of the lifespan; Aschenbrenner & Balota, 2017), and 2) the random (or pseudorandom) nature of conflict tasks is not conducive to proactive control, as it has been suggested in Section 6.1. As such, it is unlikely that CSE magnitude would – only - reflect proactive strategies.

A second limitation concerns task design in CSE studies. Although every care was taken to control for well-established learning and memory related confounds, it is still possible that some confounds remained and the effect does not, in fact, reflect top-down control or reflects other mechanisms as well in addition to that. One such mechanism could be learning of the temporal structure of the tasks (Schmidt, 2013; Schmidt & Weissman, 2016), although empirical support for this idea is inconsistent at the moment. Furthermore, cognitive control research is an extremely dynamic field, and it is possible that future studies will identify new confounds even in confound-minimized designs that researchers working now could not have anticipated. In fact, not long before the completion of this chapter, a new study was published which argues that even in designs where Trial N never shares any features with Trial N-1 (like ours) feature overlap between Trial N and Trial N-2 might still affect behaviour (Erb & Aschenbrenner, 2019).

Two further limitations concern the developmental studies presented in Chapters 3 & 4. First, our studies were not designed to investigate gender differences in the developmental trajectory of cognitive control. This could be an important avenue to explore in future studies as gender differences might emerge in the neural correlates of cognitive control in adolescence (e.g., Alarcón, Pfeifer, Fair, & Nagel, 2018; Schulte et al., 2019, although see Ordaz et al., 2013). Second, in both of our developmental studies we employed a between-subject, cross-sectional design to investigate age-differences, due to practical constraints (e.g., available time and funding). As age groups could potentially differ in other important variables beside age, longitudinal studies would provide the ultimate test of the developmental trajectory of cognitive control across adolescence. These, however, are scarce at the moment (e.g., Montez et al., 2017; Ordaz et al., 2013).

Another general limitation across the studies presented in this thesis, and indeed, across much of the MW literature concerns the self-report nature of MW measures. It is impossible to tell whether participants, especially younger ones, reported their thought contents accurately. Inaccurate reporting could be a consequence of metacognitive deficits and/or an unwillingness to admit when one’s mind has wandered away from the task. Neither of these can be ruled out based on our findings, although the second alternative appears unlikely due to the generally high rates of MW reporting across tasks (often close to or above 50% of probes). Notably, probe measures of MW are widely used (e.g., Robison et al., 2019; Weinstein, 2018), and have been validated in young and older adults using eye-tracking (Frank et al., 2015). Nevertheless, it would be important to establish that such reports are also valid in adolescents. This is made more difficult by the fact that different types of MW have not been clearly linked to different behavioural costs and signatures yet.

6.5 Concluding remarks

In the present thesis, I outlined 4 empirical studies that investigated different aspects of the CSE, a hallmark effect of the cognitive control literature. All paradigms were designed to exclude common confounds that could have complicated the interpretation of the effect, as such I believe it is reasonable to assume that the CSE in our studies represented top-down control modulation (at least in part). The main focus of my research was to investigate if and how the ability to dynamically modulate attention, as indexed by the magnitude of the CSE changes across adolescence, a period of life when control related brain regions, brain networks, and the communication between such networks are still thought to be undergoing maturation. In accordance with models of cognitive development, performance on tasks of cognitive control and sustained attention did get better as a function of age, however, no robust age effects were found in the CSE in either behavioural or neural data, although some findings provide clear hypotheses for future research, suggesting, for instance that developmental neuroscientists might gain important insights from the investigation of theta oscillatory dynamics during control tasks on how adolescents respond to conflict compared to adults. All in all, based on our data it appears that the ability to reactively adjust control levels does not change substantially after the age of 12. This contributes to our understanding of cognitive development by suggesting that not all forms of cognitive control are clearly immature during adolescence. Future studies could also investigate if dynamic control adjustments might appear deficient in adolescents under conditions that might affect adolescent cognition to a greater extent than adults, e.g., in the presence of peers, or using emotional task stimuli (Shulman et al., 2016).

Our findings also contribute to the understanding of the CSE. The observations that the effect differs in magnitude between the Simon and the flanker tasks, does not correlate across tasks, and has different correlates in the two tasks (Section 3.4.3) all suggest that the mechanisms behind the CSE could be task-specific at least to a certain extent. The negative correlation between MW frequency and CSE magnitude in the flanker task is an intriguing finding, and it strongly suggests that at least in this task, larger CSEs mean better reactive control efficiency, although the fact that we were unable to replicate this relationship in a third study cautions against any strong interpretations of the association. Understanding this relationship more clearly would be an important step as currently little is known about the real-world correlates of the CSE. Some forms of cognitive control have been linked to academic performance (e.g., Checa & Rueda, 2011; Hirsh & Inzlicht, 2010; Veroude, Jolles, Knežević et al., 2013), but how generalizable these associations are across tasks and different experimental effects, remains to be seen.

Finally, our studies raise at least two important methodological points. First, based on the findings of Chapter 4 and Smulders et al. (2018), it appears advisable to control for group differences in basic response speed in developmental studies when the focus is on within-subject modulations of RT because general age-related speeding might mask real effects or create illusory effects. Second, it would be important to assess in future simulation studies how noisy adaptive mean estimates are in EEG data sets on a trial-by-trial level for different components and whether this potential noisiness could offset any increase in analytical power compared to condition-aggregated data (e.g., due to switching from simple ANOVAs to linear mixed-effects models).

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