Developmental changes in cognitive control

Temporal dynamics of task performance across trial sequences

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General discussion

THEME, OBJECTIVE AND MAIN FOCUS

The primary objective of this thesis was to contribute to our understanding of developmental changes in trial-by-trial performance adjustments from age 5 to young-adulthood. Flexible adjustment of behaviour in order to change quickly and flexibly to the demands of the environment is an essential part of cognitive control (Miller & Cohen, 2001; Zelazo et al., 2003). Cognitive control in general refers to processes that are important in non-routinized, complicated or novel situations. Flexibly controlling thoughts and behaviour is necessary for deciding to pay attention to something, making plans or derogate from it, creating a strategy, solving problems or adjusting one's behaviour after making an error. The main question of this thesis focussed on these underlying control processes and how they develop from childhood to adulthood. In this thesis a broad distinction was made between proactive and reactive control, both components of the dual-mechanisms of control (DMC) framework (Braver, 2012). Reactive control refers to the detection and resolution of an interfering event *after* its onset, reflecting bottom-up reactivation of task goals; proactive control refers to top-down processing mechanisms that rely upon the anticipation and prevention of interference *before* it occurs (Braver, 2012). Recently, Munakata et al. (2012) suggested that children initially engage control in response to external signals (*reactive* control) before they are capable recruiting cognitive control *proactively*. Both control processing mechanisms reflect those changes that occur across trials in adjusting performance based on detection and resolution of recently incurred actions or interference because of conflicting stimulus inputs (see Jacoby et al., 1999; Purmann et al., 2009; Ridderinkhof, 2002). Hence, the focus in this thesis was on the temporal dynamics of task performance across trial sequences (trial-by-trial) rather than average performance across trial blocks. The developmental changes associated with three types of trial-by-trial sequences were central in this thesis: i.e., *sequential effects* (Chapter 2 and 3), effects relating to *performance monitoring and adjustment* (Chapter 4), and those related to *conflict monitoring* and *adaptation* (Chapter 5). The results of the empirical chapters are reviewed below and an attempts is made to relate the results to the DMC framework.

EXPERIMENTAL RESULTS AND CONCLUSIONS

Developmental change in sequential effects on speeded performance

In broad outline, sequential effects are dependencies emerging from past local history of preceding trials, measured within a block of a standard (two-) choice reaction time task (for reviews, see Kirby, 1980; Luce, 1986). The most thoroughly studied sequential effects are those related to the *immediately* preceding trial. These effects are referred to as the first-order sequential effects. Higher-order sequential effects refer to the impact of *sequences* of preceding trials on the current trial (for reviews, see Kirby, 1980; Luce, 1986; see also Soetens et al., 1985). Sequential effects in two-choice tasks are traditionally explained by two distinct mechanisms, i.e., automatic facilitation (indicated by a first-order repetition effect and higher-order benefit-only pattern) and subjective expectancy (indicated by a first-order alternation effect and higher-order cost-benefit pattern) (e.g., Bertelson, 1961; Rapoport & Budescu, 1997; Soetens et al., 1985; Wagenaar, 1972). These mechanisms appear to be manifestations of processes underlying cognitive flexibility, which is a key aspect of cognitive control. Children's responses to sequential dependencies in "simple" choice RT tasks provide important insights into the changes that may occur in the flexibility and control of their cognitive systems (e.g., Zelazo et al., 2003).

Chapter 2 and 3 together contain four experiments that aimed to investigate systematically the developmental trends in basic processing mechanisms underlying sequential effects in serial reaction time (RT) tasks. The first experiment of Chapter 2 was aimed at assessing developmental trends in the strength of automatic facilitation and subjective expectancy (7-25 yrs). Participants performed a serial RT task with response to stimulus intervals (RSI) of 50 and 500 ms in which they made a binary response to stimuli appearing left or right from a fixation line. The second experiment was aimed to further assess the automatic facilitation hypothesis of the developmental decrease in the first-order repetition effect (e.g., Kerr et al., 1982) and higher-order benefit-only pattern, assuming a central locus of the age-related change in automatic facilitation. Participants performed the exact same task as in the first experiment, but were randomly assigned to a compatible or incompatible task condition. The primary goal of the experiments presented in Chapter 3, was to assess how developmental change (5-25 yrs) in automatic facilitation and subjective expectancy evolve, when experimental manipulations provide more room for subjective expectancy, either by manipulating RSI (the first experiment) or by allowing participants more practice (the second experiment).

The results of the experiments of the first study (Chapter 2) replicated the findings reported previously in the adult literature on sequential effects. For the short RSI, adults demonstrated the typical patterns associated with automatic facilitation; i.e., a repetition effect and the benefit-only pattern. This pattern of results have, typically, been explained by 'residual processing traces left by previous S-R cycles', that have not been faded out yet with 50 ms RSI and accumulate over trials (e.g., Bertelson, 1961). For the long RSI, adults showed the usual alternation effect (i.e., gambler's fallacy; expecting more alternations than repetitions in a series of events) and the cost-benefit pattern that is suggestive of subjective expectancy, explained by participants' expectation that sequences will continue with repetitions or alternations (Soetens, 1998). Finally, consistent with the previous literature (e.g., Soetens et al., 1985; Soetens, 1998), S-R compatibility manipulation altered the effects of automatic facilitation, but subjective expectancy was not altered by the changing S-R mappings. At first sight, higher task demands on the response choice stage increases the beneficial effect of residual processing traces.

Concerning the developmental effects, the current findings were consistent with previous observations that children show a stronger repetition effect (Fairweather, 1978; Kerr et al., 1980, 1982), or show a repetition effect where adults demonstrate an alternation effect. In addition, the results were also in line with a preliminary study showing a more prominent benefit-only pattern in children compared to adults (Soetens & Hueting, 1992). Together, the results seemed to indicate that the strength of automatic facilitation decreases with advancing age. However, this result had to be qualified in view of the data that emerged from the S-R compatibility manipulation. That is, children compared to adults, showed a stronger increase of the higher-order benefit-only pattern for incompatible relative to compatible responses, whereas this pattern was absent for the first-order repetition effect. In line with previous findings (e.g., Melis et al., 2002; Soetens et al., 1985; Vervaeck & Boer, 1980), two separate mechanisms were proposed. It was assumed that the first-order repetition effect is mediated by a kind of low-level rapidly decaying mechanism (e.g., Soetens et al., 1985; see also Cho et al., 2002), whereas the higher-order benefit-only pattern is thought to arise from a high-level response monitoring mechanism (e.g., Gehring & Fencsik, 2001; Kirby, 1980; Soetens, 1998; Soetens & Notebaert, 2005).

With a long RSI children showed a more pronounced cost-benefit pattern than adults suggesting, at face value, an age-related decrease in subjective expectancy. This finding was contrary to expectations (see Soetens & Hueting, 1992), and difficult to reconcile with the current observation of a first-order repetition effect where adults showed an alternation effect with long RSI. The latter pattern suggests a developmental increase in subjective expectancy, not an age-related decrease. In order to provide a unified account of the pattern of findings associated with long RSI, it was assumed that two dissociable mechanisms rather than a single one mediate subjective expectancy. In line with suggestions made in the sequential effects literature, it was assumed that first-order effects arise from the tendency to predict alternations over repetitions (i.e., the gambler's fallacy), whereas the higher-order effects arise from the tendency to expect runs (repetitions or alternations) to continue. When expectation is violated the predicted response should be inhibited and the alternate response activated. These processes are assumed to be more time consuming in children than adults (e.g., van den Wildenberg & van der Molen, 2004; Band et al., 2000).

Interestingly, it should be noted here, that Gao et al. (2009) identified separable sources of sequential effects in two-choice reaction time tasks by using connectionist modeling. They separated three processes or sources; i.e., a low-order *post-response residual decision unit activity* explaining the first-order repetition effect (*not* the higher-order benefit-only pattern), a *conflict-induced bias* (i.e., strategic priming mediated by conflict monitoring; higher proportion of alternations in the sequence produce more conflict) producing the higher-order benefit-only pattern, and a top-down *expectation bias* that, together with the decaying conflict-induced bias, produces the higher-order cost-benefit pattern in long RSIs. It should be noted, however, that there is evidence suggesting that alternation advantages could also result from a sensory based process (e.g., Fecteau, Au, Armstrong, & Munoz, 2004), or due to an inhibition-of-return phenomenon (e.g., Lupianez, Klein, & Bartolomeo, 2006; Klein, 2000; Fecteau & Munoz, 2003), or the involvement of automatic patterns detector mechanisms (Tubau & López-Moliner, 2009; Huettel, Mack, McCarthy, 2002), rather than being mediated by top-down control or a strategically informed expectancies. Concerning the low-order process, Gao et al. (2009) argued that neural findings provide support for the notion of (the decay in) residual activity. It has been observed, for example, that neurons accumulating evidence for a decision to be made, experience rapid decay following that decision (e.g., Roitman & Shadlen, 2002). Moreover, Gao et al. (2009) argued that their notion of top-down biasing is consistent with the cognitive neuroscience literature showing that conflict monitoring is associated with the anterior cingulated cortex (Botvinick et al., 2001; Ridderinkhof et al., 2004) and repetition/alternation memories (producing an expectation bias) with the prefrontal cortex (e.g., Baldo & Dronkers, 2006; Barbey et al., 2011).

The three separate sources of sequential effects suggested by Gao et al. (2009) provide an elegant framework for our results. First, it could be that the stronger first-order repetition effects and higher-order benefit-only patterns as a result of incompatible S-R translations (i.e., higher task demands on response choice processes), are caused by a post-response residual activity that becomes more beneficial, together with conflict-induced biases becoming stronger. Second, with advancing age the beneficial effects of post-response residual activity decreases and conflict-induced biases become weaker (see Gao et al., 2009). Together this may result in the observed weaker repetition effects and benefit-only patterns observed for adults. Finally, the relatively stronger higher-order benefit-only pattern for children compared to adults with higher task demands (i.e., for non-routine S-R translations) could imply that, for incompatible responses, the conflict-induced bias is stronger for children compared to adults. Interestingly, developmental studies have Eshel indeed indicated that conflict monitoring mediated by the anterior cingulated cortex is slow to mature (e.g., Eshel et al., 2007; and see Chapter

4 and Section 6.3) and that prefrontal cortex mechanisms mediating on-line memory show a protracted developmental course (e.g., Huizinga, Dolan & van der Molen, 2006).

In two regards the results from this study are somewhat difficult to reconcile with the Gao et al. framework. First, the Gao et al. framework cannot explain the additive pattern of effects found between S-R compatibility and age on first-order effects. The post-response residual activity source is basically identical to the S-R traces notion proposed by Bertelson (1961) (see also Gao et al., 2009, p. 2421). As already indicated above, the active S-R traces are especially beneficial when S-R translation is difficult (e.g., in children compared to adults) or non-routine (e.g., in tasks with complex S-R mappings). Thus, in contrast to the additive effect that was found in the present study, the Gao et al. (2009) framework predicts an interaction between S-R compatibility and age on the first-order repetition effect, identical to the higher-order benefit-only pattern. Secondly, the results concerning the long RSI conditions (stronger higher-order cost-benefit patterns for children compared to adults) suggest that with advancing age, expectation biases decrease whereas response conflict-induced bias increases. This is difficult to bring into line with our findings associated with short RSI conditions, suggesting a stronger conflict-induced bias in children compared to adults (and hence a decrease in developmental perspective). We continue to believe that the stronger cost-benefit pattern in children probably arises from a less efficient inhibition of the predicted response together with a greater difficulty in activating the alternate response.

The basic patterns of sequential effects, observed in the second study (Chapter 3), were similar to the results reported previously. In line with Fairweather (1978) and Kerr (1979), we observed an age-related decrease in the first-order repetition effect and, consistent with our previous study (Smulders et al., 2005; see Chapter 2), we obtained a decrease in the higher-order benefit-only pattern with advancing age. Overall, these findings indicate that the beneficial effect of automatic facilitation decreases when children are growing older. With a lengthening of RSI, the first-order repetition effect changed towards a first-order alternation effect, and the higher-order benefit-only pattern into a cost-benefit pattern. This is consistent with previous findings (e.g., Kirby, 1980; Smulders et al., 2005; Soetens et al., 1985). When RSI was lengthened from 50 to 1000 ms, we observed a decrease in the repetition effect for all participants, but an alternation effect only emerged for the older age groups (10-12 yrs and older) at the longest RSI, not for the two youngest child groups (5-6 and 7-9 yrs). Additionally, the lengthening of RSI resulted in an orderly change from a benefit-only pattern to a cost-benefit pattern. The transition phase towards a cost-benefit pattern was somewhere in between the 150-500 ms RSI range, with the exact transition depending on the participant's age (i.e., 150 ms for adults, 200 ms 10-17 yrs, and 500 ms for 5-9 yrs). The findings are important, indicating that sequential effects in children (even the youngest) are not mediated by a lower-order automatic facilitation mechanism only, but under appropriate conditions (i.e., lengthening RSI), also by subjective expectancy. The current findings may suggest that subjective expectancy is already in place in young children but easily overshadowed by automatic facilitation.

Interestingly, Sommer et al. (1999) already found, that cost-benefit pattern amplitudes are always active, unaffected by RSI, when looking at event-related potentials (ERP). They suggested that the expectancy-like mechanism influences performance only when RSI is long. It may be interesting to find out whether also young children produce the expectancy pattern in ERP with short RSIs. Another interesting aspect of the current data refers to the difference in the timing of the transition from first-order repetition- to alternation effect vs. the transition from a benefit-only to a cost-benefit pattern. This timing difference may suggest that first-order and higher-order sequential effects follow different developmental trajectories. We will address this issue later.

The results from the second experiment were only partly consistent with our expectation that the impact of automatic facilitation would decrease with practice. Practice is supposed to reduce the time needed for central processing due to a strengthening of S-R pathways, especially in children (e.g., Logan, 1990; Welford, 1980). However, the first-order effects were not altered by practice while practice had a considerable beneficial effect on overall reaction time; i.e., participants responded faster with more practice. Practice did reduce the higher-order benefit-only pattern (i.e., only in the last session), but this effect did not interact with advancing age. The cost-benefit pattern systematically decreased with practice but again the decline did not vary between age groups. Practice strengthens central S-R links thereby reducing automatic facilitation and, according to Soetens et al. (1985), with extended practice participants begin to realize that trial runs are random rather than having an intelligible structure and, thus, subjective expectancy will gradually decrease. The absence of age differences of the practice-related decrease in the cost-benefit pattern suggests that even young children are keeping a record of trial sequences; suggestive of at least a rudimentary monitoring ability.

Finally, in returning to the issue of the timing of transitions in sequential effects, we argued that the framework developed by Gao et al. (2009) might provide a unified account of the present data. The sources underlying sequential effects (i.e., two top-down biases concerning conflict monitoring vs. expectancy, and a residual decision unit activity) could explain the differences in RSI transition values for first-order and higher-order indices (see also Soetens & Notebaert, 2005). First, the results that emerged from the present study showed that the transition of the first-order effect occurred at longer RSIs compared to the transition of the higher-order effect (see also Cho et al., 2002). Within this context, the current observation showing an age-related delay in the RSI transition value of the first-order effect could be interpreted to suggest that in young children the decision mechanism is less efficient, implying longer-lasting residual activity and, thus, repetition effects that continue to persist for longer RSIs. The age-related change in the RSI transition value associated with higher-order sequential effects seems to indicate a more rapid decay of the inhibition bias exercised by the top-down monitoring mechanism. Finally, the simulation studies by Gao et al. (2009) demonstrated that practice has a twofold effect on the choice-reaction process; i.e., one effect consists of speeding up non-decision (i.e., sensorimotor) processes and the other effect consists of speeding up *all* processing components in the network (rather than adjusting their relative strengths). The former effect is manifested in an overall shortening in RT and a differential RSI effect on mean RT. In this regard, our findings are consistent with the outcomes of the Gao et al. (2009) simulations. In addition, the current findings showed that the practice benefit was more pronounced for adults than children, suggesting practice affects sensorimotor processing to a greater extent in adults than children. The current observation that practice failed to substantially change sequential effects suggests that, with the amount of practice used in the present study, and the within-subjects manipulation of RSI, practice did not exert a significant effect on the speed of the decision and top-down biasing mechanisms.

To sum up, four experiments were conducted to assess age-related changes in sequential effects on choice RT. The experiments yielded patterns of sequential effects suggestive of automatic facilitation (with short RSIs) and subjective expectancy (with long RSIs). The results clearly showed that the strength of both automatic facilitation and subjective expectancy decreases with advancing age. With incompatible stimulus-response trials automatic facilitation, not subjective expectancy, increased in strength. Only the higher-order benefit-only pattern, not the cost-benefit pattern, increased more in children compared to adults. Lengthening RSI (50-1000 ms) resulted in an orderly change from automatic facilitation to subjective expectancy. Importantly, the exact point of transition depends on the participant's age (i.e., adults to show subjective expectancy with shorter RSIs). With practice, first-order effects were not affected but both higher-order patterns decreased in strength. Importantly, practice failed to influence age-related changes.

Based on the current results, and in line with suggestions in the sequential-effects literature, a multi-facetted pattern consisting of developmental change in bottom-up and top-down influences on the choice reaction process was proposed. It was assumed that the first-order repetition effect is mediated by a kind of low-level mechanism (residual processing traces) that is rapid to decay (but stronger in children than in adults), whereas the higher-order benefit-only pattern is thought to arise from a high-level response monitoring mechanism (which is supposed to be more efficient in adults). It was also assumed that subjective expectancy is mediated by two dissociable mechanisms rather than a single mechanism. The first-order repetition effect arises from the tendency to predict alternations over repetitions (i.e., the gambler's fallacy, which is assumed to be less strong in children), whereas the higher-order cost-benefit pattern arises from the tendency to expect runs to continue, which is less pronounced in children). When expectation is violated, the predicted response should be inhibited and the alternate response activated; processes that are assumed to be more time consuming in children.

A developmental study of post-error slowing

An important aspect of cognitive control is the ability to detect errors and adjust performance to prevent further errors. The tracking or monitoring of speeded performance results in a trial-by-trial speeding towards an error and a post-error correct response that is slower than the average correct response (i.e., post-error slowing, known as PES). Rabbitt and colleagues suggested that errors are not random events but, typically, represent attempts to attain optimal performance limits in response to the instruction to perform as quickly and accurately as possible (e.g., Rabbitt, 1966; Rabbitt, 1968; Rabbitt & Vyas, 1970). PES is associated with an increased response caution and, to a lesser extent, a change in response bias (Dutilh et al., 2012). That is, individuals tend to accumulate more information before initiating a decision (i.e., changing their response thresholds adaptively; becoming slightly less cautious after a correct response, and more cautious after an error). The change in response bias implies that errors facilitate response alternations and hinder response repetitions. A review on developmental changes in PES suggested a heterogeneous pattern of findings (see Chapter 4). Both developmental change and invariance has been found (e.g., Brewer & Smith, 1989; Fairweather, 1978; Gupta et al., 2009; Jones et al., 2003; van der Laar et al., 2011).

In Chapter 4 a study was presented that contains two experiments designed to systematically assess the developmental change in PES from childhood into adulthood (5-25 yrs). A standard choice RT task was used in both experiments (similar to tasks used in the sequential effects studies and similar to the tasks used in adult studies of PES). In the first experiment, we manipulated only RSI (from 50 ms to 1000 ms), in the second experiment we increased the number of observations (multiple experimental sessions) but reduced the number of RSIs (RSI was 50 ms or 500 ms).

The experiments yielded a consistent pattern of results consisting of a relatively fast error followed by post-error slowing (PES). Moreover, the results were in accord with previous reports showing that PES is most pronounced when RSIs are short (e.g., Jentzsch & Dudschig, 2009; Danielmeier & Ullsperger, 2011). With regard to our developmental perspective, both experiments yielded a decrease in PES with advancing age (i.e., children slow down to a greater degree than adults after making an error). Moreover, the results of the second experiment indicated that this trend was disproportional and, thus, could not be interpreted in terms of developmental change in the speed of responding *per se*. Furthermore, we anticipated that the RSI effect on PES (i.e., PES is more prominent in short RSIs) would be more pronounced for children compared to young adults. However, both experiments showed that this was not the case. On the account that children are more sensitive to interference (e.g., van der Molen, 2000), it was anticipated that they would exhibit disproportional slowing at short RSIs relative to young adults. These expectations were not borne out by the current data.

The pattern of results suggested that, at least, two mechanisms are involved in PES; one operating at short RSIs that is age invariant and another that is sensitive to development and is RSI invariant. The notion of two distinct mechanisms operating within different timeframes has been proposed previously by Jentzsch and Dudschig (2009). A tentative interpretation of the current findings assumes that PES is a joint function of orienting *and* response caution at short RSIs while it results from response caution only at longer RSIs. Notebaert et al. (2009) proposed the orienting account of PES based on results suggesting that slowing is a function of the frequency of the preceding response rather than its accuracy. Orienting facilitates attention to the surprising event and is associated with a temporary de-activation of the motor system (Lynn, 1966; Sokolov, 1963; see also Ursin, 2005). There is no reason to believe that hard-wired orienting is subject to age-related change (e.g., Mento & Tarantino, 2015). Orienting is short-lived and dissipates over time. When RSI is long, the 'emergency brake' following an error (or infrequent event) is released prior to the occurrence of the new stimulus. PES on those trials is then due to increased response caution.

Yet two issues need to be addressed, i.e., the heterogeneous pattern of findings reported previously in studies exploring PES in children (see review in Chapter 4), and the apparent dissociation between implicit vs. explicit error detection (e.g., Ullsperger et al., 2014). Two factors could have contributed to the heterogeneous pattern of findings reported earlier. Although there are a few exceptions (e.g., Gupta et al., 2009; Jones et al., 2003), most studies, using various types of conflict tasks in contrast to relatively standard choice reaction tasks, found that PES was age-invariant. Possibly, errors are less easily detected in conflict paradigms, thereby obscuring developmental changes in PES. Alternatively, it could be that participants, when confronted with such a paradigm, are overall more cautious (e.g., see van der Laar et al., 2011). The change in the macro speed-accuracy tradeoff associated with conflict might obscure developmental changes in micro-speed accuracy tradeoff associated with performance monitoring (but see Schachar et al., 2004). The limited amount of observations could have also prevented the detection of developmental change in PES. For example, Berwid et al. (2014) reported stability of PES rather than developmental change based on an average of 40 trials of which 13% were errors. Our study underlines the importance of a sufficient number of observations; i.e., a disproportional developmental trend in PES and a substantial reduction in PES with lengthening RSI (50 vs 500 ms) was demonstrated when we increased the number of trials in our second experiment.

Concerning the second issue, most studies observed that the ERN (i.e., a negative brain potential associated with error detection), but not PES, discriminated between age groups (see table in Chapter 4). This suggests that the mechanism thought to generate the ERN is not a prerequisite for PES to occur (e.g., Stemmer et al., 2004; Nieuwenhuis et al., 2001). This pattern of findings has been interpreted to suggest a dissociation between implicit and explicit error detection (Ullsperger et al., 2014). It has been suggested that implicit error detection, indexed by the ERN, matures at a slower rate compared to explicit error detection, indexed by the an error-related positivity (Pe) (Wiersema et al., 2007). Accordingly, adults may rely on automatic error detection without the need for explicit monitoring while young children have to rely on conscious and fallible error monitoring (Lyons & Zelazo, 2011). With advancing age, children rely increasingly on implicit monitoring that is both less taxing and more accurate. It is then assumed that PES decreases with advancing age as a result of this change from explicit error monitoring to implicit monitoring, freeing-up resources for more efficient performance adjustments.

In conclusion, this study showed a decrease in PES with advancing age. This observation indicates that young children are perfectly able to detect errors and adjust performance accordingly. The speed of PES recovery, indexed by the speed of responding on the two trials following the first post-error trial, did not differ between age groups. This finding suggests that when children encounter an error they have difficulty in regulating their speed of responding only on the immediately subsequent trial. This finding is worthy of further investigation because it would be expected that the less efficient performance adjustments in young children would be manifested also in the speed of performance on the subsequent post-error trials.

A developmental study of trial-to-trial conflict adaptation

Detecting conflict and adjusting behavior is essential for cognitive control (see Larson et al., 2104). Conflict monitoring refers to the process of checking performance for simultaneously competing response options (Botvinick et al., 2001, 2004). Many studies have shown that, when competition or conflict arises between behavioural choices, performance is adversely affected in terms of speed and accuracy. The detrimental effect of conflict is referred to as *conflict cost* (i.e., response speed increases and accuracy decreases on *in*congruent/conflict vs. congruent/non-conflict trials). Importantly, conflict costs are not just limited to the *current* trial. They also affect performance on the subsequent trial. Typically, conflict costs are reduced on trials immediately following a conflict trial. This patterns has been observed on a range of conflict tasks, and has been coined the *conflict adaptation effect* or the *Gratton effect* (Duthoo et al., 2014; Gratton et al., 1992; Kerns et al., 2004; Kunde, 2003; Kunde & Wuhr, 2006; Notebaert et al., 2001). It has been suggested that conflict adaptation is due to participants utilizing previous conflict information to optimize current conflict resolution (Botvinkick et al., 2001; Braver, 2012; Braver et al., 2009; Egner, 2014). Within the developmental literature, conflict adaptation is considered to be a manifestation of top-down (proactive) cognitive control and, given the protracted developmental course of brain mechanisms implicated in proactive control processes, it has been assumed that with advancing age children are better able to deal with conflict when it arises and more efficient in preparing for future conflict (e.g., Iani et al., 2014). Several studies observed conflict adaptation in young children (e.g., Ambrosi et al., 2016; Stins et al., 2007) suggesting that they are already able to effectively respond to conflict and to implement performance adjustments in order to handle future conflict. However, developmental studies examining the advance of cognitive control yielded inconsistent findings—ranging from an age-related decrease in the size of the conflict adaptation effect (van de Laar et al., 2011) to its absence in young children (Waxer & Morton, 2011).

Chapter 5 presented a study that systematically assessed developmental change in conflict adaptation (7-25 yrs). We used different conflict tasks (a Simon task, an SRC task, and a Choice-reaction/NoGo task) as the specific implementation of conflict adaptation may depend on the specific conflict elicited by the task (e.g., Braem et al., 2014; Egner, 2008) and, thus, may contribute to the inconsistencies observed in the developmental literature. The leading hypothesis of the study was that the size of the conflict adaptation effect would change with advancing age consistent with the idea that brain mechanisms involved in conflict adaptation are slow to mature. Furthermore, it was assumed that all three experiments would generate a developmental trend, although the pattern of conflict adaptation may differ across experiments depending upon the specific conflict elicited. Comparability across experiments was ensured by using a similar task format—left- vs right-pointing arrows in different colors. In all three experiments, it was examined whether repetition-priming may contribute to the observed developmental trends. This was done because it has been argued that conflict adaptation might result from a repetition of stimulus and response features across trials (e.g., Hommel et al., 2004; Mayr et al., 2003). Finally, RSI was manipulated in all three experiments (50 vs. 500 ms, in separate trial blocks). Previously, it had been observed that conflict adaptation was absent for a 50 ms RSI and this finding was taken to suggest that the implementation of the performance adjustments to conflict adaptation requires some time to be implemented (Notebaert et al., 2006).

The results from the first experiment yielded pronounced Simon congruency effects; i.e., RTs on congruent trials were responded faster than on incongruent trials (e.g., Vu & Proctor, 2004). Moreover, this effect decreased in magnitude with advancing age, which is consistent with previous results (e.g., Araujo et al., 2015; Davidson et al., 2006; Gathercole et al., 2014; Jerger, 1999; but see Band et al., 2000). In addition, the current results showed that the Simon effect was considerable reduced on trials following an incongruent trial relative to a congruent trial (e.g., Soetens et al., 2010; Sturmer et al., 2002; Duthoo et al., 2014, for a review). This sequential modulation pattern (i.e., conflict adaptation) was more pronounced in children compared to adults, although statistical analysis revealed that the apparent developmental trend was not disproportional. This supports the notion that conflict adaptation is present in children performing on a Simon task (e.g., Ambrosi et al., 2016; Iani et al., 2014). The sequential modulation pattern was different between short vs. long RSI trials. For both RSIs, there was a robust Simon effect on trials preceded by a congruent trial. For the long RSI, the Simon effect was considerably reduced on trials preceded by an incongruent trial, whereas the Simon effect on trials following an incongruent trial was basically annihilated when RSI was short. This pattern was observed for all three age groups. The dual-route model, proposed by Kornblum et al. (1990), was suggested to provide a possible interpretation of the apparent annihilation of the conflict adaptation effect in the 50 ms RSI condition. Most likely, participants tend to inhibit the fast, automatic route with incongruent trials that persists into the next trial when RSI is very short. Accordingly, stimulus processing follows the slow, controlled route on all trials, incongruent and congruent, thereby annihilating the Simon effect.

The results that emerged from Experiment 2 were consistent with the literature in showing that mixing compatibility resulted in the overall elimination of the SRC effect (e.g., van Duren & Sanders, 1992). This effect was the similar across age groups. More specifically, the results showed that, consistent with previous studies (e.g., Jennings et al., 2002; Mansfield et al., 2012; but see de Jong, 1995), the typical SRC effect (i.e., slower responses on incompatible relative to compatible trials) seen on trials following a compatible trial turned into its opposite on trials following an incompatible trial. It has been suggested that the reversal of the SRC effect on trials following an incompatible trial results from a preparatory bias for the incompatible mapping (e.g., Jennings et al., 2002) that has been interpreted in terms of proactive control; that is, a willful strategy facilitating incompatible mappings (Mansfield et al., 2012). Importantly, on the hypothesis that young children are less able or inclined to adopt a proactive strategy in handling cognitive conflict (e.g., Chevalier et al., 2014; Munakata et al., 2012), we anticipated that pattern of trial-to-trial modulation of SRC on the speed of responding would less manifest in children than adults. The results were opposite to our expectations. If anything, trial-to-trial modulation was stronger, not weaker, in children although it should be noted that the differences between age groups lost significance when controlling for basic response speed. The current failure to obtain a disproportional developmental trend in the pattern of sequential SRC effects on the speed of responding may present a challenge to notions that proactive control is a key factor in producing this pattern. A second challenge is presented by the current observation that this pattern is less rather than more manifest for the longest RSI. In order to provide an account for the current findings reference has been made to the task-switching literature (for a review Vandierendonck et al., 2010). In this literature, comparisons are made between trial sequences repeating a task and trial sequences involving a change from one task to another. Typically, task transitions involve a cost that is usually greater for the strongest task (e.g., over-learned or well-practiced tasks; e.g., Allport et al., 1994) and costs decrease with increasing RSIs in the absence of foreknowledge (e.g., Sohn & Anderson, 2001). Accordingly, the current data pattern (i.e., stronger mixing costs for compatible relative to incompatible trials and a reduction of mixing costs for the longer RSI) is highly similar to the findings reported in the task-switching literature. Herein, it has been proposed that the task set of the previous trial carries over into the current trial and may facilitate or hinder the implementation of the task set that is required on this trial (e.g., Rogers & Monsell, 1995; for a review Grange & Houghton, 2014).

Consistent with previous studies, the third experiment showed responses that were slower on Choice-reaction trials preceded by NoGo relative to Choice-reaction trials (e.g., Gade & Kock, 2005; Jamadar et al., 2010; Rieger et al., 2003; Verbruggen & Logan, 2008). Importantly, the developmental findings were similar to the pattern obtained in previous studies (Huizinga & van der Molen, 2011; van der Laar et al., 2011). That is, the trial sequence effect decreased with advancing age. However, in contrast to the previous findings, the developmental trend did not survive when controlling for age-group differences in basic respond speed. The current pattern of age-related change in sequential effects was interpreted in terms of conflict adjustment. That is, the readiness to respond decreases following the encounter of a Nogo trial (see Jamadar et al., 2010), resulting in an increase in response thresholds. The more pronounced delay in the speed of responding observed in children was explained by assuming that adults are better able to fine-tune their response thresholds (cf. Huizinga et al., 2011; p. 499). It must be noted, however, that we proposed there is a legitimate argument to suggest that the results from this experiment are possibly due to a design error (i.e., the interval between NoGo and Go trials was much longer, i.e., 3 s, than between successive Go trials). This could have resulted in slower and more variable responses for (young) children, because they are less able to maintain optimal levels of preparation. We suggested, in contrast, that this is nevertheless quite unlikely given the current RSI findings and the results reported by others about the inter-trial effects that hardly differ between children and adults (see e.g., Mento & Tarantino, 2015; see also Adams et al., 2011; Mento & Vallesi, 2016; Näätänen et al., 1974; Vallesi & Shallice, 2007). Attributing the delay in responding on a choice-reaction trial preceded by a NoGo trial to reduced response readiness associated with a longer wait is, therefore, not very likely.

The current study yielded evidence for developmental change in the sequential modulation of conflict effects on three tasks; a Simon task, a mixed SRC task and a hybrid Choice-reaction/NoGo task. In broad outline, the current pattern of results contributes to an emerging literature demonstrating that sequential modulation of conflict effects can be observed already in young children (e.g., Ambrosi et al., 2016; Iani et al., 2014; Larson et al., 2012; Nieuwenhuis et al., 2006; Stins et al., 2007; Wilk & Morton, 2012; but see Waxer & Morton, 2011). The observation of conflict-modulation in young children does not seem to square with interpretations of conflict adaptation in terms of top-down control (e.g., Gratton et al., 1992; Botvinick et al., 2001). Developmental cognitive neuroscience amassed evidence to suggest that both the anterior cingulate cortex (ACC) and prefrontal cortex (PFC), involved in reducing conflict and improving performance, follow a protracted maturational course (for a review Crone & Steinbeis, 2017). Collectively, the literature suggests that manifestations of conflict adaptation that have been observed in young children are not likely to originate from top-down cognitive control strategies. In this regard, the suggestion, put forward by Ambrosi et al. (2016), that even 5-to-7 year olds are able to coordinate reactive and proactive control strategies does not seem to be very plausible. The present findings showed a developmental decrease in the trial-by-trial modulation of the Simon effect, a more pronounced reversal of the SRC effect following an incompatible trial for younger children and a downward age-related reduction in the speed of responding following a NoGo trial. Importantly, none of these age-related trends survived when controlling for age-group differences in basic speed. The current downward trend in the conflict-adaptation effect is most readily explained by assuming that contextual cues associated with the probability of conflict may automatically retrieve from memory the control settings that are compatible with the current task demands (e.g., Crump & Logan, 2010). It should be noted that this view does preclude but goes beyond simple associative notions of trial-by-trial conflict adaptation (e.g., Egner, 2014). Indeed, the current results revealed that response priming altered the sequential effects, in particular on the SRC task. Importantly, however, such priming effects did not interact with age. Furthermore, results indicated that sequential modulation was present even for trial sequences that did not involve response repetitions. Collectively, the sequential modulation patterns observed in the current study indicate that conflict adaptation observed for the current tasks is not just a manifestation of associative mechanisms (see also Ullsperger et al., 2005).

In closing, the current age-related downward trend in conflict adaptation is difficult to reconcile with developmental changes in strategic top-down cognitive control. On the other hand, the current findings cannot be explained by resorting to simple associative views of trial-to-trial conflict adaptation. The current interpretation opted for the middle ground proposed by Egner (2014) assuming that, once the task set involved in the resolution of conflict has been established, it can be automatically triggered and implemented by the appropriate contextual information (see also Egner, 2008; Hubbard et al., 2016). The finding that the age-related downward trend in the size of the conflict adaptation effect did not survive when controlling for age-group differences basic response speed may then suggest that, when the appropriate control settings have been retrieved from memory, the implementation and workings of the mechanisms needed to resolve conflict become more efficient with advancing age. In this regard, developmental change in those mechanisms follows the general path of the information processing system towards greater efficiency (e.g., Cerella & Hale, 1994).

TRIAL-TO-TRIAL EFFECTS WITHIN THE DUAL MECHANISMS OF CONTROL FRAMEWORK

How do the trial-to-trial effects examined in this thesis relate to the dual-mechanisms model of control (DMC) (Braver, 2012)? Within this framework, cognitive control is assumed to consist of two separable regulatory mechanisms; that is, reactive and proactive control. Reactive control refers to resolving conflict *after* its onset, reflecting a bottom-up mechanism. Proactive control refers to a top-down process that relies upon the anticipation of conflict *before* it occurs (Braver, 2012). It has been suggested that, initially, young children opt for reactive control (e.g., Blackwell & Munakata, 2014; Chatman et al., 2009; Chevalier et al., 2015; Munakata et al., 2012; Vallesi & Shallice, 2007). They have to resort to reactive control because the cognitive systems implicated in proactive control are still immature. Alternatively, they opt for reactive control because it is less demanding compared to the costs involved in proactive control. It should be noted, however, that Braver (2012) already indicated that it is difficult to disentangle reactive and proactive control because tasks or measures are not 'process pure'; that is, they are not linked to reactive or proactive control in a one-to-one fashion. Moreover, other interpretations of trial-to-trial effects are quite conceivable. These issues will be further elaborated in the sections below.

Sequential effects

We examined developmental change in first- and higher-order sequential effects on speeded responses. The first-order results revealed a decrease of the repetition effect with advancing age and a developmental transition towards an alternation effect when lengthening RSI from 500 to 1000 ms. The repetition effect was more pronounced for incompatible than compatible stimulus-response mappings. Finally, extensive practice failed to alter the first-order repetition effects. We interpreted the repetition benefit in terms of residual processing traces that remain active during the current trial, thereby facilitating speeded responses (e.g., Soetens et al., 1985; see also Cho et al., 2002). The stronger repetition effects for young children were then explained by assuming that residual processing traces remain longer active in young relative to older children. With a lengthening of RSI active stimulus-response links will decay and the repetition effect will turn into an alternation affect; at least for older children and adults. The alternation effect was interpreted in terms subjective expectancy (i.e., the gambler's fallacy; Rapoport & Budescu, 1997; Wagenaar, 1972). Responses on the current trial will be fast when expectancy is confirmed but they will be slow when the current trial violates anticipation.

It seems that repetition effects operate outside the reach of the dual mechanisms model. Repetition effects refer to residual activity of processing traces leading to the response. In this regard, repetition effects are better explained in terms of low-level response priming rather than reactive or proactive control (e.g., Soetens et al., 1985). Repetition priming is dominant in young children and for short RSIs. When children are growing older and when RSI is lengthened the repetition effect changes into an alternation benefit. The alternation benefit is thought to arise from expectancies generated by trial history. In this regard, the alternation benefit could be considered a manifestation of proactive control, whereas the remedial action required when the current trial violates anticipation would be a manifestation of reactive control. We observed that, by the end of primary school, the repetition effect changes into an alternation effect. Accordingly, this observation may indicate that from this age on children are able to balance reactive and proactive control.

Turning to the higher-order patterns, we observed a decreasing benefit-only pattern with advancing age and with a lengthening of RSI. The developmental decrease in the benefit-only pattern was more pronounced for incompatible relative to compatible stimulus-response mappings. Furthermore, the developmental change in higher-order sequential effects was not influenced by extensive practice. In line with previous results (e.g., Kirby, 1980; Soetens, 1998), we suggested that the higher-order benefit-only pattern must be considered as a manifestation of response monitoring, comparing the actual response with the intended response. Response monitoring is time or capacity consuming, resulting in a response delay. With an increasing number of repetitions there is less need for monitoring and, thus, RT will shorten. The benefit-only pattern was more pronounced for incompatible relative to compatible responses. This observation is in line with notions assuming that with greater task complexity (i.e., incompatible stimulus response mappings) the need for monitoring increases and, thus, should result in a more pronounced benefit-only pattern (e.g., Soetens et al., 1985).

Within the context of the cognitive control literature, monitoring is considered an evaluative control mechanism (Botvinick et al., 2001). This type of performance monitoring is reactive in the sense that it operates ex post facto (e.g., Alexander & Brown, 2010). In this regard, the benefit-only pattern can be assumed to be a manifestation of reactive control. This observation is important, as it suggests that first-order and higher-order sequential effects associated with short RSIs are mediated by different processes rather than a single 'automatic facilitation' mechanism; the former is due to response priming while the latter relies on evaluative monitoring that is considered to be an instance of reactive control.

The cost-benefit pattern, associated with longer RSIs, was interpreted in terms of subjective expectancy (e.g., Soetens, 1998). Individuals expect a continuation of runs of alternations or repetitions. Responses are fast when this occurs but slow when expectation is violated, thus resulting in the typical cost-benefit pattern. Within the context of the dual mechanisms model, the subjective expectancies derived from trial sequences could be considered a manifestation of proactive control but the remedial action required when expectancy is violated would be a manifestation of reactive control. Hence, cost-benefit patterns result from balancing reactive (related to the costs) and proactive (related to the benefits) control.

The developmental findings yielded an age-related decrease in the benefit-only pattern at short RSIs. On the hypothesis that the benefit-only pattern results from response monitoring, the current findings suggest that this monitoring becomes more efficient when children are growing older. This interpretation is consistent with both behavioral and cognitive neuroscience studies examining developmental change in performance monitoring (e.g., Davies et al., 2004; Fernandez-Duque et al., 2000; Hogan et al., 2005; Kim et al., 2007; Ladouceur et al., 2007; Santesso et al., 2006; Wiersema et al., 2007; for reviews Ferdinand & Kray, 2014; Tamnes et al., 2013). Cognitive neuroscience studies indicated that response monitoring relies on the anterior cingulate cortex (e.g., Ridderinkhof et al., 2004; Ullsperger et al., 2014) and developmental neuroscience studies suggest that this structure exhibits a protracted maturational course (e.g., e.g., Eshel et al., 2007; Luna et al., 2015; for a review Crone & Steinbeis, 2017). Children showed more pronounced cost-benefit patterns. More specifically, we observed that, for long RSIs, young children showed larger costs and benefits than older children and adults (Smulders et al., 2005; Figure 1b and 2b). At face value, this observation seems to suggest that proactive control in children is more efficient in young than adults. Obviously, such an interpretation runs counter accepted notions of developmental change in cognitive control. Before accepting this interpretation, we should examine the robustness of the developmental change in cost-benefit patterns in future research. In addition, we should consider alternative interpretations of sequential effects.

Traditionally, sequential effects have been interpreted in terms of two mechanisms; automatic facilitation and subjective expectancy (e.g., Bertelson, 1961; Luce, 1986; Rapoport & Budescu, 1997; Soetens et al., 1985; Wagenaar, 1972). Automatic facilitation refers to a low-level mechanism by which a previous encounter with a stimulus facilitates the processing of the current stimulus. This mechanism is predominant at short RSIs consistent with the decay of processing traces at longer RSIs. Subjective expectancy refers to a higher-level strategic mechanism setting up expectations for repetitions or alternations. This mechanism may require a minimum time to establish and thus is most prominent for longer RSIs.

Several authors examined automatic facilitation and subjective expectancy using the leaky accumulator model proposed by Usher and McClelland (2001). This model involves leaky, stochastic, nonlinear accumulation of activation in two mutually inhibitory decision units. Cho et al. (2002) added a component to this model that is relevant for the current discussion. This component performs stimulus-history dependent biasing. That is, the component responds to repetitions or alternations and primes the decision units accordingly. Their model successfully captured various sequential effects patterns reported in the literature but it should be noted that their data-sets were all concerned with long RSIs. Gao et al. (2009) extended the work of Cho et al. (2002). Their variety of the leaky accumulator model incorporates three biasing mechanisms influencing the decision units; i.e., residual activity from the immediately preceding trial, expectation-based top-down bias, and bias due to conflict monitoring. The study of these separate biasing mechanisms revealed that first-order repetition effects are mediated by residual activity in the decision units while the higher-order benefit-only pattern results from strategic priming mediated by conflict monitoring. The higher-order cost-benefit patterns associated with long RSIs were seen to result from expectation-related biases that increase during RSI while response-conflict bias decays, thereby producing the transition from benefit-only to cost-benefit pattern with a lengthening of RSI.

Two studies adopted a different approach in examining sequential effects. Jones et al. (2013) examined sequential effects by using a model assuming that response base rate and stimulus repetition rate are both learned simultaneously incrementally. Current updates are then generating expectancies for each oncoming trial such that responding is faster when the actual outcome provided a closer match. This model provided an adequate explanation for sequential effects obtained using long RSIs but failed to address sequential effects associated with short RSIs. This observation led Jones et al. (2013) to conclude expectancy is not involved in sequential effects with short RSIs (p. 657). Gökaydin et al. (2016) examined the latent variables underlying sequential effects in a dataset obtained from 158 individuals performing different experiments. Principal component analysis yielded four components after rotation. One component, accounting for most of the variance, was related to individual mean RT and the three other components were associated with sequential effects. The two major components appeared across the longer RSIs (>250 ms); one associated with stimulus and the other with response processing. In this regard, the PCA findings reported by Gökaydin et al. (2016) are consistent with the results obtained by Jones et al. (2013) who related the incremental learning of base rate with response processing whereas the learning of repetition rate would be rooted in stimulus processing. Another similarity across studies is that results are associated with long not short RSIs.

Finally, Meyniel, Maheu, and DeHaene (2016) applied a model to the study of sequential effects that they coined the "local transition probability model". This model goes beyond the incremental learning model used by Jones et al. (2013). The crucial difference is in what is learned. Meyniel et al. (2016) obtained evidence to suggest that sequential effects are better explained in terms of learning local transition probabilities compared to absolute frequencies of events and/or transition of events. In their model "transition probability" refers to the probability of an event given the identity of the preceding event. The learning is local, or dynamic in that the transition probabilities may change over time. Meyniel at al. (2016) re-examined the cost-benefit pattern reported by Cho et al. (2002) and observed that their model and models based on leaky accumulation provided a good fit of the general pattern of these data but only their model, and not the leaky accumulation models, was able to capture local deviations of the cost-benefit pattern. For example, the Cho et al. (2002) data showed relatively fast responses for RAAR sequences relative ARAR. The difference between these two sequences is that in the former sequence a repetition has already been encountered previously whereas it is not in the latter sequence. Thus, expectancies are less violated for RAAR compared to ARAR sequences. This result is important in demonstrating that sequential effects arise from learned statistical expectations associated with local transition probabilities.

The results from brain imaging research focusing on sequential effect may add to the conclusions that can be derived from the simulation studies. The study reported by Jones et al. (2002) provides a convenient bridge between the simulation and brain imaging studies. These authors extended the leaky accumulator model used by Cho et al. (2002) to incorporate mechanisms for conflict detection and control adjustment. Conflict detection was associated with the decision units of the model and control adjustment was realized via a strategic priming unit influencing response decision and execution. Basically, the role of conflict detection was to increase control by decreasing strategic priming in response to conflict. The extended model provided a good fit to the behavioral cost-benefit pattern revealed by RT. The model correctly predicted the increase in neural activation in the anterior cingulate cortex in response to violations of expectancies associated with repetition or alternation sequences of increasing length (ending with an alternation or repetition, respectively). These findings were interpreted to suggest that sequential-related conflict signals generated by the anterior cingulate cortex are used for the trial-by-trial adjustments of the speed of performance. Similar results have been reported by Huettel et al. (2002) who observed a lengthening of RT associated with pattern violations; the more so the longer the sequence. The hemodynamic response corresponded closely to performance; an increase in amplitude to sequence violations that was more pronounced for longer sequences. Both repetition and alternation violations evoked activation in regions of the prefrontal cortex, including the anterior cingulate cortex. These findings were interpreted to suggest that the prefrontal cortex is involved in the construction of predictive mental models that become stronger with consistent information so that violations evoke more brain activation to strong relative to weak models.

In broad outline, it seems that the sequential effects pattern observed in young children, i.e., a strong first-order repetition effect and a higher-order benefit only pattern, is beyond the dual-mechanisms model of control proposed by Braver and colleagues (2009, 2012). Moreover, this pattern is not easily explained by referring to the simulation and brain imaging studies reviewed above. Most of these studies are concerned with sequential effects associated with longer RSIs that are characterized by a first-order alternation benefit and a higher-order cost-benefit pattern. Jentzsch and Sommer

(2002), in providing a unified account of their performance and brain potential data that emerged from a series of experiments designed to identify the processing loci of sequential effects, referred to Kahneman and Tversky (1982) who suggested that there might be two types of expectancy; one passive and the other active. The passive type of expectancy resembles priming in that it is automatic and effortless. Passive expectancy yields a benefit when confirmed but there are no costs involved when passive expectancy is disconfirmed. Accordingly, it seems that sequential effects in young children originate primarily from passive expectancy. In contrast, active expectancy is thought to be conscious and effortful. It will produce a benefit when outcome is consistent with expectations but a cost for unanticipated events. The sequential effects obtained for young adults when RSIs are relatively long might thus be dominated by active expectancy. Within this framework, it could be predicted that there is a shift from passive to active expectancy when children are getting older. This shift is manifested in a transition from a first-order repetition to an alternation effect and from a higher-order benefit only to a cost-benefit pattern. This scheme is admittedly crude and the precise conceptualization of active expectancy could be nuanced in view of the simulation studies reviewed above. But at this stage, this scheme seems to do a better job in providing an account of our developmental results than the dual-mechanisms model of control.

Post-error slowing (PES)

Within the context of the dual-mechanisms model of cognitive control (Braver, 2012), there is reason to believe that PES reflects reactive control because it occurs locally in response to the error. Indeed, the conflict monitoring theory (Botvinick et al., 2001; Yeung, Botvinick, & Cohen, 2004) stresses the role of increased *reactive* control in post-error processing. That is, slower post-error performance reflects reactive implementation of cognitive control, elicited by the detection of conflict. Specifically, error trials entail response conflict between co-activated representations of the correct (i.e., needed response) and erroneous responses (i.e., given response). A system responsible for detecting conflicts in information processing then leads to a relatively more conservative and controlled behavior on subsequent trials.

There is also evidence to suggest that proactive control is involved in PES. This evidence comes from studies showing that manipulations focusing on top-down control affect PES size (e.g., Jentzsch & Leuthold, 2006; Lorist, Boksem, & Ridderinkhof, 2005; Regev & Meiran, 2014; Schroder, Moran, Infantolino, & Moser, 2013; Smith & Brewer, 1995; Steinhauser & Kiesel, 2011). This observation indicates that PES is influenced by the control demands of the experimental context of a given trial. PES is obviously a response to a special event (error) mediated by reactive control but this response is modulated by proactive control that is instigated by the experiment-wide conditions rather than local trial factors. The balancing of reactive and proactive control as manifested by PES can be likened to the dichotomy of cognitive control proposed by Ridderinkhof et al. (2010). These authors distinguished between on-line action control and anticipatory action regulation. The former is involved in the suppression of unwanted responses in favor of the execution of desired responses. In this regard, on-line action control is similar to the Braver et al. (2009, 2012) notion of reactive control. The latter refers to those processes that strengthen on-line action control or reduce to need for such control. Accordingly, anticipatory action regulation bears a strong resemblance with the proactive control conceptualization entertained by Braver et al. (2009, 2012).

We reviewed developmental studies examining age-related changes in error processing. This review revealed that most studies were concerned with brain potentials associated with error processing; most notably, the error-related negativity (ERN). The ERN has been suggested to index conflict monitoring; i.e., the conflict between the activation of the desired, correct vs. the unwanted, incorrect response. Developmental ERN studies suggested that ERN amplitude increases with advancing age into adulthood (for reviews Crone, 2014; Ferdinand & Kray, 2014; Tamnes et al., 2013). The ERN is thought to originate from the anterior cingulate cortex, which is part of the neurocognitive control system (.g., Luna et al., 2015). Given that this system is immature in young children one would indeed predict that they exhibit smaller ERN amplitudes but also that their performance is characterized by less PES or even its absence. Surprisingly, only few studies reported the predicted increase in PES (Jones et al., 2003; Santesso & Segalowitz, 2008) and, disappointedly, most studies did not evaluate developmental change (see Chapter 4).

Prompted by the absence of a solid evaluation of age-related change in PES we designed two experiments using a standard choice reaction task similar to those employed in the seminal studies of PES by Rabbitt (Rabbitt, 1966, 1968; Rabbitt & Vyas, 1970) and Laming (1979). Both experiments revealed an age-related decrease in PES, consistent with an early developmental study reported by Fairweather (1978) who interpreted his findings in terms of interference. More specifically, he suggested that PES results from the interference of error correction processes following the error trial and the selection of the appropriate response on the post-error trial. Young children would be more sensitive to such interference relative to older participants. Consequently, they will exhibit a more pronounced PES. This interpretation might apply to results obtained by short RSIs (Fairweather used an RSI of 200 ms) but is seems less likely that PES associated with longer RSIs (>500 ms) are due to the interference of post-error correction. Our results, obtained using a range of RSIs (from 50 ms to 1000ms) yielded an interesting pattern. We observed additive effects of RSI and Age group on PES. This pattern led us to conclude that two mechanisms are in effect; one operating at short RSIs that is insensitive to the influence of advancing age and the other that is sensitive to the influence of advancing age but not to RSI. Consistent with the ideas of Jentzsch and Dudschig (2009) we speculated that our findings point to two distinct mechanisms. PES at short RSIs might be due to the orienting reaction to errors (Notebaert et al., 2009) or an attentional bottleneck evoked by error detection (Buzzell, Beautty, Paquette, Roberts, & McDonald, 2017) while the age-related change in PES results from the increasing ability to exercise response caution (e.g., Dutilh et al., 2012; Laming, 1979).

Our results revealed an age-related decrease in PES. Two conclusions, albeit negative, can be derived from this finding. First, in between-group comparisons, PES magnitude cannot be taken to index the ability in cognitive control (i.e., larger PES ≠ more effective cognitive control; in contrast to Jones et al., 2003). Secondly, PES presence in young children demonstrates that, somehow, they detect their errors and respond accordingly. Consequently, the smaller or absence of the ERN in young children cannot be taken to suggest that monitoring mechanisms do not operate or operate less effectively (e.g. Velanova, Sheeler, & Luna, 2008). Possibly, children and older participants engage different mechanisms in performance monitoring. Alternatively, the orientation of the neuro-electric source of the ERN might differ between age groups. Be that as it may, the conclusion of Velanova and colleagues (2008) that a smaller ERN in young children would indicate that they receive less signaling for error correction and, thus, would be a source underlying their immature performance levels is not supported by the current data. Our PES results indicate that children do detect their errors. Incidentally, in the Velanova et al. (2008) study, allowing error correction on anti-saccade trials, there was no difference in the proportion of corrected errors between age groups). Our PES results seem to indicate that major source of age-related change refers to post-error performance adjustments rather than error detection.

How do our developmental PES findings square with the dual-mechanisms model of cognitive control? When presenting the standard choice-reaction task to our participants they were instructed to respond as quickly and accurately as possible. Thus, they were required to balance the speed and accuracy of their responses. Overall, young children responded somewhat more erroneously than the older participants but their performance was clearly within acceptable limits. Young children are able to balance speed and accuracy. The setting of the speed-accuracy tradeoff is typically considered a manifestation of top-down proactive control involving a complex network of dorsolateral and premotor areas of the prefrontal cortex, parietal cortex and basal ganglia (Bogacz, Wagenmakers, Forstmann, & Nieuwenhuis, 2010; Forstmann et al., 2010; Lo, Schroder, Moran, Durbin, & Moser, 2015; Vallesi, McIntosh, Crescentini, & Stuss, 2012; van Veen et al., 2008). Accordingly, young children seem already equipped with the ability to proactively control their performance as indicated by the balancing of speed and accuracy.

When setting the balance between speed and accuracy, performance must be monitored continuously to maintain speed while avoiding unacceptable error rates. Performance tracking must be considered another aspect of proactive control (e.g., Brown, 2013). This tracking requires the evaluation of actual outcome, in terms of speed and accuracy, against the desired outcome derived from the setting of the speed-accuracy tradeoff. Our PES findings leave no doubt that, when involved in the task, young children are able to monitor their performance. There is ample evidence to suggest that this performance monitoring involves dorsal and posterior regions of the medial frontal cortex (for a review Ridderinkhof et al., 2004). Future research should address the question why performance reveals that young children are able to monitor their performance while the neural manifestation of such monitoring (viz., the ERN) is greatly reduced or even lacking (for reviews Crone, 2014; Ferdinand & Kray, 2014; Tamnes et al., 2013).

Upon the detection of an error, one must take the necessary precautions for avoiding an error in the future. The actions taken to avoid another error can be considered another instance of proactive control in the sense that these actions must be implemented before the occurrence of the next trial. The typical outcome of these actions is a more accurate but slower response on the next trial. Our results showed a more pronounced PES compared to the older age groups. This finding was taken to suggest that the efficacy of the precautionary actions is less in young children relative to the older participants. Diffusion modeling of PES indicated that following an error participants exercise greater caution as evidenced by a heightening of response thresholds (e.g., Luce, 1986; Ratcliff & Koon, 2008). Our current prediction is that young children have difficulty in the precise setting of the response thresholds following an error. A combined approach of diffusion modeling and neuroimaging might be adopted to assess this prediction (Bogacz et al., 2010; Forstmann, Ratcliff, & Wagenmakers, 2016; van Maanen et al., 2011).

Conflict adaptation

The ability to detect and resolve conflict is a hallmark of flexible cognitive control (Miller & Cohen, 2001). Within the context of the dual-mechanisms model of cognitive control (Braver, 2012) it is assumed that different contexts evoke different types of control. For example, contexts characterized by frequent conflict typically elicit a future-oriented of proactive type of control ensuring an efficient resolution of conflict when it occurs. In contrast, context marked by an infrequent occurrence of conflict elicit a reactive type of control resolving conflict on the moment as it occurs (e.g., Gratton et al., 1992).

It has been suggested that proactive control follows a protracted maturational course (e.g., Church, Bunge, Petersen, & Schlagger, 2017; Doebel et al., 2017; Morton & Munakata, 2009; Munakata, 1998). Waxer and Morton (2011) examined the suggestion of a late occurrence of proactive control by comparing responses on conflict trials preceded by another conflict trial vs. responses on conflict trials preceded by a non-conflict trial. In adult and adolescent participants, the delay in the speed of responding on a conflict trial was considerably less when this trial was preceded by another conflict trial relative to the speed of responding on a conflict trial preceded by a non-conflict trial. This pattern was interpreted to suggest that conflict elicits proactive control aimed at reducing the detrimental effects of future conflict. Consistent with the notion of a protracted maturational course of proactive control, Waxer and Morton (2011) observed that in young children the adverse effects of conflict were not dampened when this conflict occurred just following another conflict trial. This absence was interpreted to suggest that, in contrast to adults and adolescents, young children rely on reactive control and try to resolve conflict ex post.

In a previous study, van de Laar et al. (2011) obtained evidence that is inconsistent with the interpretation of Waxer and Morton (2011) and that seems to challenge the idea that the ability of proactive control does not emerge until late childhood (e.g., Church et al., 2017). Van de Laar et al. (2011) examined developmental change in cognitive control using a stop-signal task. They observed that the speed of responding on standard choice trials was considerably reduced when stop-signal trials were inserted in the series of standard choice trials relative to a series without stop-signal trials. This delay is typically interpreted in terms of proactive strategy adjustments (e.g., Verbruggen & Logan, 2009). Importantly, the results showed that all age groups, including young children, exhibited performance adjustments. If anything, the slowing was more pronounced in young children relative to the adult participants. Van de Laar et al. (2011) concluded that even young children exercise proactive control in view of future conflict.

In the current thesis, developmental change in conflict adaptation was examined by presenting age groups with different conflict tasks. The use of different conflict tasks was prompted by recurrent observations that conflict adjustments are influenced by task context (e.g., Egner, 2008; Braem et al., 2014). The results revealed pronounced conflict modulation on all three tasks that were used—a Simon task, an S-R compatibility task and a hybrid Choice reaction/Go-NoGo task. The Simon effect was reduced substantially following an incongruent trial relative to a congruent trial. The S-R compatibility effect tended to reverse following an incompatible trial relative to a compatible trial and responses on Choice reaction trials were considerably delayed following a NoGo trial relative to another Choice reaction trials. Importantly, the magnitude of conflict adaptation decreased with advancing age although the developmental trends did not survive when controlling statistically for age group differences in basic speed. Given that the observed conflict adaptation provides an instance of proactive control, these findings present a serious challenge to the notion that proactive control develops relatively late. One interpretation would be that even young children are able to exercise proactive control in a timely and efficient fashion. Previously, Wilk and Morton (2012) obtained similar findings using a congruency task and observed conflict reduction following an incongruent trial across age from 9 to 32 years. Interestingly, despite comparable performance the neural activation associated with conflict resolution differed between young children and the older participants. These findings led Wilk and Morton (2012) to suggest that young children and older participants may use different strategies in resolving conflict although they did not exclude the possibility that the age-related differences in neural activation are associated with changes in neural network connectivity or brain hardware. Yet another possibility would be that the resolution of conflict on the congruency task is realized in ways beyond the proactive-reactive domain.

The results that emerged from the three tasks used in the current thesis showed that all age groups responded similarly to the different varieties of conflict. All age groups showed a robust congruency effect on the Simon task, the reversal of the compatibility effect on the mixed SRC task, and a sizeable proportion of commission errors on hybrid Choice reaction/Go-NoGo task. Although there were age-group differences in each of these patterns they were not dramatic or suggestive of age-related changes in the strategies entertained when confronting with conflict. In addition, all age groups exhibited conflict adaptation and its size did not differentiate between age groups when controlling for basic speed. We proposed that our results are most readily explained when it is assumed that the control settings that are used by the system to effectively deal with conflict when it is encountered are carried over to the next trial when the demands of this trial are similar to the previous one (e.g., Crump & Logan, 2010). In this regard, there does not need to be a qualitative difference between age groups. Older age groups might simply be more efficient than young children in implementing the required control procedures.

CONCLUSION

The present thesis contains four empirical studies designed to examine age-related changes in trial-by-trial effects on the speed of performance. More specifically, this thesis is concerned with the study of developmental change in sequential effects (Chapters 2 and 3), post-error slowing (Chapter 4) and conflict adaptation (Chapter 5). These issues were addressed by using varieties of standard choice reaction tasks to enable appropriate comparisons with the adult literature. In addition, the results that emerged from these studies were interpreted vis-a-vis a common framework of cognitive control that has been adopted in the developmental literature; i.e., the dual-mechanisms of control model proposed by Braver and colleagues (2009, 2012; Chatman et al., 2009; Munakata et al., 2012).

The results presented in Chapters 2 and 3 contribute to the relatively scant developmental literature on sequential effects (Fairweather, 1978; Kerr, 1979; Soetens & Hueting, 1992). This literature was primarily concerned with first-order sequential effects and indicated that young children's performance is dominated by a repetition benefit (e.g., Fairweather, 1978; Kerr, 1979; Kerr et al., 1980, 1982). This observation was replicated by the present findings. In line with Soetens and Hueting (1992), we included analyses of higher-order effects. These analyses revealed a benefit-only pattern that was stronger when incompatible reactions were required relative to compatible responses. Consistent with expectations, the strength of the benefit-only pattern decreased with advancing age but, inconsistent with expectations based on previous findings (Kirby, 1980; Soetens et al., 1985; Vervaeck & Boer, 1980; but see Suzuki & Goolsby, 2003), this pattern was not influenced by extensive practice. Interestingly, the benefit-only pattern continued to *dominate* the performance pattern in young children across RSIs of varying lengths whereas, consistent with previous findings (e.g., Soetens et al., 1985), the adult benefit-only pattern changed into a cost-benefit pattern with a lengthening of RSI. We considered but rejected the idea of interpreting our findings in terms of the dual-mechanisms of control model. First, the repetition benefit is typically interpreted in terms of associative priming (Bertselson, 1961; Soetens et al., 1984, 1985; for a review Kirby, 1980). Associative priming is clearly outside the scope of the dual-mechanisms of control model. Secondly, the complex pattern of results that resulted from the higher-order analyses of sequential effects seemed difficult to reconcile with the notions of reactive and proactive control. The benefit-only pattern seen for short RSIs could be interpreted in terms of response monitoring (i.e., comparing the actual response with the intended response; e.g., Gehring & Fencsik, 2001; Kirby, 1980; Soetens, 1998; Soetens & Notebaert, 2005). In this regard, the benefit-only pattern could be taken as a manifestation of reactive control and its age-related decrease might suggest greater efficiency when children are growing older. The cost-benefit pattern associated with longer RSIs could be associated with expectancy (Soetens, 1998; for a review Kirby, 1980) and thus, be considered a manifestation of pro-active control. But then it is difficult to explain why young children exhibit a stronger cost-benefit pattern compared to older participants. Consequently, we rejected the idea of interpreting the sequential-effects patterns in terms of reactive and proactive control and resorted to simulation studies of sequential effects in order to obtain an appropriate account of our developmental findings. Our review of this literature converged on the conclusion that most interpretations are concerned with sequential-effects patterns associated with long RSIs whereas the patterns associated with young children are typical for short RSIs. Finally, we followed Jentzsch and Sommer (2002) who referred to the expectancy notions proposed by Kahneman and Tversky (1982). Accordingly, the sequential-effect patterns associated with short RSIs and young children are assumed to result from passive expectancy that is automatic and effortless while the sequential-effects patterns associated with long RSIs and older participants are supposed to be due to active expectancy that is consciousness and effortful. Obviously, the interpretation of sequential-effects in terms of the Kahneman-Tversky scheme is utterly abstract and in need of further investigation.

Chapter 4 was concerned with the examination of developmental change in post-error slowing. The developmental literature is surprisingly silent on post-error slowing. Most developmental studies are concerned with the neural correlates of error monitoring (e.g., recent review of Downes, Bathelt, & de Haan, 2017). We reviewed the developmental literature for information on post-error slowing and observed that this scant literature yielded inconsistent findings. This prompted us to systematically assess age-related change in post-error slowing using a standard choice reaction task. Our analysis revealed a robust developmental pattern of post-error slowing; i.e., the magnitude of slowing decreases with advancing age. This finding indicates that young children do monitor their performance and respond accordingly when they committed an error.

Post-error slowing has been interpreted in terms of a dynamic interplay between proactive and reactive control. Ridderinkhof, Forstmann, Wylie, Burle, and van den Wildenberg (2010), for example, suggested that post-error slowing can be conceptualized as involving both proactive and reactive control. Proactive control would be engaged by task goal settings and is maintained for longer periods of time. Reactive control is involved in implementing remedial action upon the detection of an error. Both modes of cognitive control may interact in that proactive control may amplify the post-error performance adjustments. On the hypothesis that proactive control is immature in young children their pronounced post-error may relate to less proactive support of the implementation of remedial action. Although this interpretation cannot be excluded based on the current findings, we believe that the current interpretation of post-error slowing in terms of response caution is more straightforward. There is strong evidence to suggest that post-error slowing is associated with an increase in response caution (e.g., Botvinick et al., 2001; Brewer & Smith, 1989; Dutilh et al., 2012; Rabbitt & Rodger, 1977). Accordingly, the disproportional slowing observed for young children was explained by assuming that young children experience difficulty in fine-tuning their response thresholds. Obviously, this interpretation should be evaluated in future studies using diffusion modelling (e.g., Dutilh, Forstmann, Vandekerckhove, & Wagenmakers, 2013) and indices derived from premotor and motor systems (e.g., van de Laar et al., 2012).

Finally, the results presented in Chapter 5 were concerned with conflict adaptation. These findings demonstrated conflict adaptation in each of the age groups participating in the study and for each of the tasks that were used, although specific patterns differed across tasks. The predominant idea in the developmental literature is that conflict adaptation is a manifestation of top-down control that has a protracted developmental course (e.g., Ambrosi et al., 2016; Braem et al., 2014; Wilk & Morton, 2012). Accordingly, one would assume that young children do not exhibit conflict adaptation. But the current findings convincingly indicate that they do. Consequently, these findings present a challenge to the idea that conflict adaptation is realized via top-down cognitive control or, within the framework of the dual-mechanisms model of cognitive control (Braver, 2012), in terms of a flexible balancing of proactive and reactive control mechanisms. We argued that our findings can be accounted for in terms of episodic retrieval (for a review Egner, 2014). Within this context, conflict adaptation is assumed to result from memory-driven effects. Although this account does not exclude a potential role of proactive control (e.g., Egner, 2014; Spapé & Hommel, 2014; Verbruggen, Stevens, & Chambers, 2014; Verguts & Notebaert, 2009) its contribution was not or minimally manifested in the current data.

In conclusion, neurophysiological measures, such as event-related potentials (ERP) and functional magnetic resonance imaging (fMRI), as well as computational techniques may provide a solid basis in future research relating developmental changes in performance on tasks that aim to study the temporal dynamics across trial sequences. For example, simulation studies (e.g., Cho et al., 2002; Gökaydin et al., 2016; Jones et al., 2002; Jones et al., 2013, Meyniel et al., 2016; Yu & Cohen, 2009; Wilder, Jones, & Mozer, 2009) provide frameworks for assessing the relative contribution of the underlying mechanisms to the changes in sequential effects that can be observed with advancing age. Because most interpretations, based on these studies, are concerned with sequential-effects patterns associated with long RSIs, it would be particularly interesting to expand to shorter RSIs (see Gao et al., 2009), thus allowing to associate the typical sequential effects pattern in (young) children.

Furthermore, there is evidence from adult studies suggesting that subjective expectancy is always operative, also at short RSIs. For example, the 'break-through' phenomenon (i.e., shorter RTs for *A*AAA vs. *A*AAR sequences) shows that a critical number of alternations is required in short RSIs for an individual to detect a pattern and form an expectation for the upcoming trial (e.g., Soetens et al., 1984, 1985; Vervaek & Boer, 1980, Melis et al., 2002; Sommer et al., 1999, Exp. 2). Moreover, in several ERP-studies, clear P300-amplitude cost-benefit patterns in short and long RSIs conditions were found (i.e., covert signs of expectancy), despite evident differences in sequential effects observed in reaction time (Sommer et al., 1999; Jentzsch & Sommer, 2001). Sommer et al. (1999) suggested that signals related to expectancy integrate with 'possibly response-related' pathways at a late stage; if the RSI is too short this integration might not have time to occur, in which case reaction times would be fully determined by response-related effects. It would be of considerable interest to re-examine developmental change in the expectancy patterns using electrophysiological measures of expectancy (e.g., P300) to augment performance measures of sequential effects on speeded information processing. Here we could test the hypothesis that also children, like adults, demonstrate an expectancy-like mechanism independent of RSI. However, this should not be related to the presence of proactive control (see above for alternative accounts for our findings).

It would be of considerable interest to use a drift diffusion model (DDM; Ratcliff & Rouder, 1998, Ratcliff & Smith, 2004; Bogacz, Brown, Moehlis, Holmes, & Cohen, 2006) to investigate in more detail the developmental changes in human error dynamics. Previously, it has been successfully applied in PES research with young and older adults (Dutilh et al., 2013), in a study investigating the underlying processes of the developmental changes in task switching (Weeda, van der Molen, Barcelo, & Huizinga, 2014), and recently in task inhibition (Schuch & Konrad, 2017). Diffusion modeling of PES indicated that following an error participants exercise greater caution as evidenced by a heightening of response thresholds (e.g., Luce, 1986; Ratcliff & Koon, 2008). Our current prediction is that young children have difficulty in the precise setting of the response thresholds following an error. A diffusion modeling approach might be adopted to assess this prediction. Interestingly, Dutilh et al. (2013) indicated that PES originates from the interplay of different psychological processes whose contribution depends on both tasks settings and individual differences. That is, older adults became more cautious, process information less effectively, and spent more time on irrelevant processes, independent of the tasks used in this study. For young adults, however, the origin of PES depended on irrelevant processes in a random dot motion task, whereas PES was due to increased caution and decreased effectiveness in information processing in a lexical decision task. Finally, Goldfarb, Wong-Lin, Schwemmer, Leonard, and Holmes (2012) used a pure DDM to study both post-error slowing and sequential effects in serial two-alternative choice tasks. They presented a neurally plausible and conceptually straightforward account of sequential effects and post-error slowing by developing a simple repetition-based priming mechanism, coupled with an error-correction mechanism. It was suggested that an error-correction process, such as a simple adjustment of response thresholds after each trial, plays an instrumental role in sequential patterns in RT. These studies show that diffusion modeling of PES, and sequential effects, would be an interesting method to demount the underlying psychological processes in children.

Next, it would be particularly relevant using a functional magnetic resonance imaging (fMRI) technique in studying developmental changes in conflict resolution (see e.g., Egner, 2011; Kerns, 2006; Shin & Kim, 2015); in particularly, to zoom in on the results with regard to the age-related downward trend in conflict adaptation (see also Wilk & Morton, 2012). Interestingly, there is evidence that highlights the interplay between associative and controlled processing (e.g., Bunge, Burrows, & Wagner, 2004). Recently, the neural machinery mediating this interplay has been studies using fMRI (i.e., Chiu, Jian, & Egner, 2017). The results revealed the caudate nucleus as the key brain structure involved in selectively driving stimulus–control learning (see also Grahn, Parkinson, & Owen, 2009). These studies could be an interesting starting point for further assessing conflict adaptation effects in children, and test whether these originate from top-down cognitive control strategies or are indeed better accounted for in terms of memory-driven effect.

In closing, this thesis presented a trial-by-trial approach (i.e., sequential effects, post-error slowing, and conflict adaptation) in examining age-related change on the speed of performance. The results that emerged were interpreted vis-a-vis the dual-mechanisms of control model proposed by Braver (2012). In all three approaches investigated, we rejected the idea of interpreting the results in terms of reactive and proactive control and resorted to other accounts of our developmental findings; that is, sequential effects to processes that emerged in simulation studies and differences in passive vs. active expectancy, post-error slowing in terms of response caution, and conflict adaptation as a result from memory-driven effects. The results of the experiments in this thesis assume that the developmental changes in the temporal dynamics of task performance across trial sequences can be interpreted without using top-down control adjustments between trials (see also Verbruggen & McLaren, 2017; p. 52-53). Suggestions have been made for further research.