Developmental changes in cognitive control

Temporal dynamics of task performance across trial sequences

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General introduction

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KEY CONCEPTS AND SHORT THESIS OUTLINE

Introduction

For a long time, it was thought that humans were born as 'tabulae rasae' (i.e., blank slates), that completely filled up during the development through experiences. For example, James (1890) stated: *"The baby, assailed by eyes, ears, nose, skin, and entrails at once, feels it all as one great blooming, buzzing confusion."*, and Locke (1689) wrote already centuries before: "*All ideas come from sensation or reflection. Let us then suppose the mind to be, as we say, white paper, void of all characters, without any ideas."* It is clear that this picture is not entirely correct. Young children are, for example, fully capable detecting (ir)regularities in their environment. In this way, they are perfectly able to quickly learn routines or rules (e.g., Pascalis, de Haan, & Nelson, 2002; Piaget, 1954; Romberg & Saffran, 2010; Zelazo, Frye, & Rapus, 1996). Rita Vuyk, the first full professor of developmental psychology at the University of Amsterdam (1960-1978), concluded already in her 1945 dissertation on analogy formation and induction in five- and six year old children that, *"…the mental organization of man is already fully existent, if not completely developed, in the small child"* (Vuyk, 1945; p. 126). However, on the other hand, anyone who has interacted with (young) children knows that adults are far better in flexibly and dynamically monitoring and controlling their actions and goals, and reflecting on their own thoughts compared to children. Munakata, Snyder, and Chatham (2012) pose: *"Infants and children show striking limitations in their abilities to break out of habitual ways of thinking and behaving."* (p. 1). But how develops a child, initially thinking and behaving routinely in habitual ways, to an adult who flexibly controls thoughts and behavior, and is, consequently, able to decide to pay attention to something, make plans or derogate from it, create a strategy, solve problems, or adjust their behavior after making an error? Obviously, an enormous leap has to be made. How do these underlying fundamental control processes develop from childhood to adulthood? Clarifying these developmental changes is the main focus of this thesis.

This chapter is a general introduction addressing the key topics covered in this thesis. The concept of cognitive control and the developmental changes therein will be explained in more detail first. Following a short thesis outline, the three main topics (including the questions addressed in this thesis) that are central to the four empirical chapters will be introduced; i.e., sequential effects, performance monitoring and adjustment, and conflict monitoring and adaptation. The chapter concludes with a short summary and a list of references of the studies presented in this thesis.

Cognitive control

Acting effectively in non-routine situations to achieve our behavioral goals, by monitoring and adjusting our performance, is a hallmark for intelligent behavior, is essential for success in life, and keeps us standing in a complex dynamically changing environment. This goal-directed behavior refers to the ability to flexibly control and orchestrate thoughts and actions in accord with internally represented behavioral goals (e.g., Koechlin & Summerfield, 2007; Miller & Cohen, 2001; Petersen & Posner, 2012; Stuss & Alexander, 2000; Zelazo, Muller, Frye, & Marcovitch, 2003). The umbrella term for these cognitive processes is called 'cognitive control'. Cognitive control refers to processes that are important in non-routinized, complicated or novel situations, requiring sustained conscious attention and effort, planning and strategic thinking, feedback evaluation, and flexible adjustment of behaviour in order to change quickly and flexibly to the demands of the novel environment (Miller & Cohen, 2001; Zelazo et al., 2003).

The literature on cognitive control distinguishes between two main components: regulatory (or executive) and evaluative control (see Botvinick, Braver, Barch, Carter, & Cohen, 2001; Botvinick, Cohen, & Carter, 2004; Botvinick & Cohen, 2014; Kerns et al., 2004; MacDonald, Cohen, Stenger, & Carter, 2000; Perlstein, Larson, Dotson, & Kelly, 2006). *Regulatory control* refers to the ability of the cognitive system to configure itself to perform specific tasks through adjustments of perceptual selection, biasing of response selection, and the maintenance of contextual information over temporally extended periods. In other words, regulatory control is responsible for the activation and implementation of mechanisms subserving coordination and goal-directed behaviors. Regulatory control is thought to rely crucially on sub-regions of the prefrontal and orbitofrontal cortex. *Evaluative control*, on the other hand, refers to the ability of the cognitive system to monitor the internal and external environment for signals that indicate the demand for increased regulatory control. This type of control predominantly involves the medial frontal cortex (e.g., anterior cingulate cortex, ACC) (e.g., Egner, 2011; Egner & Hirsch, 2005; Kerns et al., 2004; Mac Donald et al., 2000; Ridderinkhof, van den Wildenberg, Segalowitz, & Carter, 2004).

Braver and colleagues (e.g., Braver, 2012; Braver, Paxton, Locke, & Barch, 2009) proposed the dual-mechanisms of control (DMC) framework, distinguishing between *proactive* and *reactive* control. Proactive control reflects the active maintenance of task goals, i.e., a top-down process that relies upon the anticipation and prevention of interference before it occurs, and is associated with sustained anticipatory activation of the lateral prefrontal cortex (Amodio, 2010; Braver, 2012). Reactive control, on the other hand, relies upon the detection and resolution of interference after its onset and reflects bottom-up reactivation of task goals through brief spreading activation of lateral prefrontal cortex and other brain regions (Botvinick et al., 2001; Botvinick & Cohen, 2014; Braver, 2012). The continuous performance task (AX-CPT) is a popular paradigm for examining changes in the use of proactive and reactive control. In this task certain probe trials (termed BX) evoke dominant, but inappropriate response tendencies that may require *reactive control* to over-ride. In contrast, preceding contextual cues produce expectancies regarding the upcoming probes that can be used for *proactive control*. Proactive control is beneficial for BX probes, but is actually detrimental to performance on another probe type (AY), because on these the cue-triggered expectancy is invalid (Braver, 2012).

The specific tradeoff between proactive and reactive control is thought to depend on situational factors (e.g., task manipulations of expected interference or working memory load) or inter-individual differences (e.g., individuals differing in reward or threat sensitivity performing tasks favoring proactive control by, respectively, reward or punishment) (Braver, 2012). For example, task-switching paradigms typically require participants to rapidly switch between task-sets and must internally represent and update task-set information. Therefore, such tasks require *mainly* proactive control. Tasks that provoke inhibition of responses (e.g., the stop-signal paradigm or the Go/Nogo task) or tasks constructed to elicit conflict, i.e. interference control processes (e.g., Eriksen flanker paradigm or the Simon task), rely heavily on (external) cues, and thus require a high degree of reactive control.

Developmental changes in cognitive control

Studies designed to track the development of cognitive control across human lifespan have indicated that control processes develop gradually during childhood through adulthood (Anderson, 2002; Best & Miller, 2010; Chevalier & Blaye, 2008; Cragg & Chevalier, 2012; Dempster, 1992; Huizinga, Dolan, & van der Molen, 2006; Huizinga & van der Molen, 2011; Kharitonova & Munakata, 2011; Munakata et al., 2012; Stuss, 1992; Tamnes et al., 2010; van der Molen & Ridderinkhof, 1998; Welsh, 2002; Zelazo et al., 2003). This developmental course has been suggested to depend on the maturation of the neural networks (i.e., prefrontal, medial frontal and orbitalfrontal cortices) implicated in cognitive control (see Muller & Kerns, 2015). Age-related improvement has been observed on tasks that require the flexible adjustment of task sets, including the Wisconsin Card Sorting Task (e.g., Chelune & Baer, 1986; Crone, Ridderinkhof, Worm, Somsen & van der Molen, 2004; Heaton, Chelune, Talley, Kray, & Curtis, 1993; Paniak, Miller, Murphy, Patterson, & Keizer, 1996; Rossellini & Ardela, 1993), inhibition and interference tasks (Cragg & Nation, 2008; Diamond, Kirkham, & Amso, 2002; Garon, Bryson, & Smith, 2008; Ridderinkhof & van der Molen, 1995), and dimensional shift tasks and task-switch studies (Cepeda, Kramer & Gonzalez de Sather, 2001; Huizinga & van der Molen, 2007; Zelazo, Craik, & Booth, 2004; but see Aron, Monsell, Sahakian, & Robbins, 2004; Crone et al., 2004; Kray, Eber, & Lindenberger, 2004).

Recently, Munakata et al. (2012) suggested three key transitions in development toward more flexible behaviour, incorporating the two main processes of the MDC framework. Children would first develop an increasing ability to overcome habits by engaging cognitive control in response to environmental signals (developing reactive control). Then, children shift to recruiting cognitive control proactively, in preparation for needing it. The transition from reactive to proactive control has been observed in AX-CPT tasks. It has been shown that eight-year-olds show a higher degree of proactive maintenance of stimuli for preparing their responses compared to three-year-olds. Instead, the latter group of children appears to rely on reactive control even in situations where proactive control would seem to be more efficient. Moreover, in cases in which lack of preparation benefits performance, three-year-olds show relatively less difficulty than eight-year olds (Chatham, Frank, & Munakata, 2009). This suggests a developmental gradient in maintaining task goals allowing to focus attention and process future critical events appropriately (Blackwell & Munakata, 2014; Chatham et al., 2009; Chevalier, James, Wiebe, Nelson, & Espy, 2014; Vallesi & Shallice, 2007). Recent evidence, however, indicates that young children might be capable of proactive control, but only when reactive control is made more difficult. This may imply that meta-cognitive processes are important with regard to the engagement of proactive control (see Chevalier, Martis, Curran, & Munakata, 2015). Finally, during the later stages of the development in cognitive control, children are increasingly able to determine which type of cognitive control will result in better performance at the lowest costs, hence becoming more self-directed. These transitions can be understood in terms of the development of increasingly active and abstract goal representations in the prefrontal cortex (e.g., Munakata et al., 2012).

Short thesis outline

This thesis further explores developmental changes in cognitive control on task performance. More specifically, this thesis examines developmental change in reactive and proactive control processes (DMC framework; Braver, 2012) involved in adjusting performance based on detection and resolution of recently incurred actions or interference because of conflicting stimulus inputs (see e.g., Jacoby, Kelley, & McElree, 1999; Purmann, Badde, & Wendt, 2009; Ridderinkhof, 2002).[1] Hence, the focus is on the

1 It should be noted, however, that proactive and reactive control cannot be easily separated from each other within a task or measure. To cite Braver (2012): "*Given that no task or measure is "process pure", it would be of considerable interest to find multiple behavioral indices to establish that these indices tap into shared and dissociable variance components associated with proactive and reactive control*." This thesis, however, uses the

temporal dynamics of task performance across trial sequences rather than on average performance across trial blocks. Three types of trial-by-trial effects are central in this thesis: *sequential effects* (Chapter 2 and 3), effects related to *performance monitoring and adjustment* (Chapter 4), and those related to *conflict monitoring* and *adaptation* (Chapter 5). Before discussing these effects in greater detail in the following sections, a brief overview first.

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 (Hyman, 1953; 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 Gao, Wong-Lin, Holmes, Simen, & Cohen, 2009; Kirby, 1980; Luce, 1986; see also Soetens, Boer, & Hueting, 1985). These effects are traditionally explained by two distinct mechanisms, i.e., automatic facilitation and subjective expectancy (e.g., Bertelson, 1961; Rapoport & Budescu, 1997; Soetens et al., 1985; Wagenaar, 1972), that appear to be manifestations of processes underlying cognitive flexibility, which is a key aspect of cognitive control - to recognize the new act and focus accordingly. Both proactive and reactive control processes play a key role in sequential effects. Proactive control because sequential effects are based on predictions on previous trial runs (possibly related to subjective expectancy), reactive control because response-monitoring provide a matching process between the given response vis-á-vis the intended response (possibly related to automatic facilitation). Importantly, earlier studies have demonstrated, although somewhat tentatively, that automatic facilitation and subjective expectancy follow different developmental trajectories (Fairweather, 1978; Kerr, 1979; Soetens & Hueting, 1992). Children's response to sequential dependencies on these "relatively simple" choice RT tasks may thus provide important insights into the changes that may occur in the balance between proactive and reactive control processes (e.g., Zelazo et al., 2003). This thesis will further examine the developmental changes in the basic processing mechanisms underlying sequential effects.

Secondly, an important aspect of cognitive control is the ability to detect errors and adjust performance to prevent further errors. In a choice RT task, to optimize performance, a balance between speed and error is essential. In adapting that balance, by

DMC framework for the analysis of trial-to-trial sequences, and, importantly, to establish predictions with respect to the developmental changes in cognitive control. The balance between the two control modes will be indicated in the subsequent sections when necessary.

tracking or monitoring the performance, trial-by-trial speeding towards an error occurs. Subsequently, the post-error response is slower than the average correct response (i.e., post-error slowing, known as PES). The Rabbitt effect refers to the seminal work of Rabbitt (e.g., Rabbitt, 1966, 1968; Rabbitt & Vyas, 1970), who suggested that errors are not random events but, typically, represent attempts to assess optimal performance limits in response to the instruction to perform as quickly and accurately as possible. In addition, mapping these outcomes on the DMC framework by Braver (2012), post-error processing could be reactive in the sense that it occurs locally in response to the error, and proactive in the sense that it is set in a top-down manner as a function of the control demands that characterize the overall (block/experiment-wide) context (see Regev & Meiran, 2014). A review of the literature on the developmental changes in PES revealed a heterogeneous pattern of findings, showing both developmental *change* and *invariance* (e.g., Brewer & Smith, 1989; Fairweather, 1978; Gupta, Kar, & Srinivasan, 2009; Jones, Rothbart, & Posner, 2003; van de Laar, van den Wildenberg, van Boxtel, van der Molen, 2011). This thesis will review the extant literature on post-error slowing in children and will assess developmental change in the performance adjustments following an error.

Finally, detecting conflict in performance or the environment, and, subsequently, adjusting behavior, is essential for cognitive control (see Larson, Clayson, & Clawson, 2014). Hence, this conflict monitoring process refers to the process of monitoring performance for simultaneously competing response options (Botvinick et al., 2001, 2004). If conflict is not detected adequately and subsequent adjustments in behavior are not implemented, goal-directed behavior will falter. Again, trial-to-trial effects are important and can be linked to the dual mechanisms of the control framework. For example, performance adjustment on trials subsequent to a (non-) conflict trial (i.e., slow responses after conflict trials compared to non-conflict trials; and faster responses on conflict trials that are preceded by conflict trials compared to non-conflict trials) provides a window on the operation of proactive control. However, people tend to respond also much slower to a conflict trial itself as compared to a non-conflict trial, that could be related to reactive control (i.e., bottom-up reactivation of task goals) (see Mansfield, van Boxtel, & van der Molen, 2012). Previous findings indicated that children are less proficient in conflict monitoring (evaluative control) and less able to recruit adjustment mechanisms in dealing with conflict proactively (e.g., Waxer & Morton, 2011). However, the developmental trend depends heavily upon the specific instantiation of conflict (i.e., the task manipulations) (see Ambrosi, Lemaire, & Blaye, 2016; Braem, Abrahamse, Duthoo, & Notebaert, 2014; Wilk & Morton, 2012). This thesis aims to obtain robust developmental trends in conflict adaptation across tasks differing in the type of conflict they elicit.

SEQUENTIAL EFFECTS

Introduction

It is well-known that the performance on a specific trial, as indexed by response time (RT), is sensitive not just to the current stimulus of experimental condition, but also to its immediate past history of events (for reviews, see Gao et al., 2009; Kirby, 1980; Luce, 1986; see also Bertelson, 1961, 1963; Hyman, 1953; Jones, Cho, Nystrom, Cohen, & Braver., 2002; Jones, Curran, Mozer, & Wilder, 2013; Kornblum, 1973; Soetens et al., 1985). Although the importance of these so-called '*sequential effects*' has been pointed out in many studies (even though they not specified why), most of them simply neglect them, *probably* because they can only be observed through special data analysis (see Podlesek, 2010). Moreover, for a long time there were a lot of uncertainties about these effects.[2] Indeed, Luce (1986) already showed than sequential effects are clearly observable effects, but the results from several studies are somewhat difficult to reconcile. The effects are still complex in nature, sometimes inconsistent (probably because of different task characteristics), but should, perhaps for that very reason, not be minimized. After all, our actions unfold within the context of other actions. Sequential effects can uncover the patterns underlying cognitive flexibility in adjusting from one trial to the next. In this way, sequential effects reflect trial-by-trial patterns that can reveal processes underlying stimulus-response tracking and may reflect optimal adaptation to a dynamic environment. Recently, sequential effects have also been linked to specific brain areas and processes (e.g., ERP studies: Jentzsch & Sommer, 2001, 2002; Sommer, Leuthold, & Soetens, 1999; brain-imaging studies: Huettel, Song, MacCarthy, 2005). In the following sections, the effects will be discussed in more detail.

First-order and higher-order sequential effects

In two-choice reaction time tasks, two kind of sequential effects have been distinguished, related to *repetitions* and *alternations* in a run of trials. *First-order* effects refer to the effect of the first previous trial on the speed of responding to the current trial. *Higher-order* effects refer to changes in the speed of responding to the current trial due to a sequence of previous trials. The literature on sequential effects established distinct patterns depending on the response-to-stimulus interval (RSI) between trials

2 Interestingly, R. Duncan Luce (1986) provided, in his authoritative volume about response times and their role in understanding the mind's structure, a footnote to a fairly extensive section on sequential effects, in which he described that Donald Laming, providing comments on his manuscript, indicated that *"the section should be dropped entirely, because there would exist too little consensus about the empirical facts"* concerning sequential effects. Luce felt that, *"in spite of its complexity and inconsistencies, the literature is simply too important to ignore."* Soetens (1990), in his doctoral thesis, concluded that *"any model that ignores sequential effects is incomplete, and likely is wrong as well."*

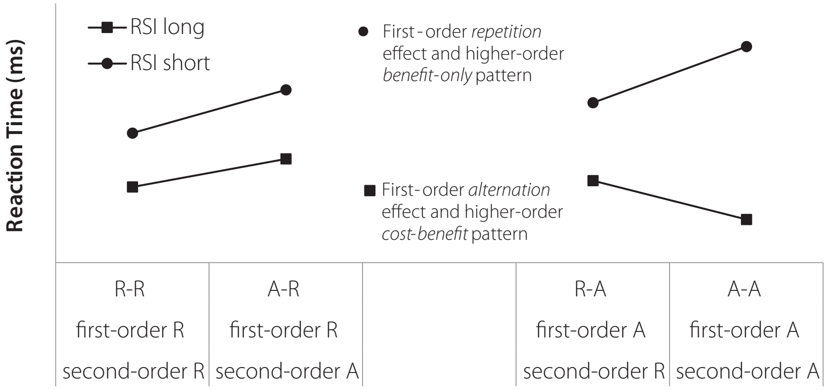

Figure 1. Graphical representation of first- and second-order sequential effects depending on response-to-stimulus interval (RSI) for a hypothetical spatially compatible two-choice RT task.
Note. R, repetition trial; A, alternation trial. The R-R, R-A, A-R, and A-A codes represent the complete sequence consisting of the first- and second-order conditions under which the current RT resorts.

(Luce, 1986; see also Cho et al., 2002; Jentzch & Sommer, 2002; Perruchet, Cleeremans, & Destrebecqz, 2006; Soetens et al., 1985; Tubau & Lopez-Moliner, 2009).

In Figure 1, a graphical representation is shown with regard to both the first-order and higher-order sequential effects for a hypothetical short and long RSI condition.[3] The presented patterns associated with the specific RSI conditions are valid for relatively simple spatial compatible two-choice RT tasks.

Short RSIs and interpretations

When trials are presented in quick succession (i.e., 50-100 ms RSI), the first-order effect consists of a repetition benefit (i.e., faster responding when successive trials require the same response; first-order repetitions are responded faster on average than first-order alternations) (see Figure 1). The higher-order effect consists of a benefit-only pattern (i.e., some higher-order trial sequences are always beneficial to the speed of responding on the current trial, no matter which response has to be executed; second-order repetitions are responded faster on average than second-order alternations) (see Figure 1).

3 Some studies (e.g., Remington, 1969; Soetens et al., 1984, 1985, and see Jones et al., 2013) take into account all possible sequences of four preceding stimuli (i.e., fourth-order effects). However, the typical patterns of sequential effects can be found and studied clearly (with increased statistical power) with two preceding trials (i.e., a sequence of three consecutive trials resulting in second-order effects). Because of this, and due to the fact that not the specific underlying structures of sequential effects are central in this thesis, but the developmental gradient is, this thesis will only adhere to second-order sequential effects with respect to the higher-order patterns.

The repetition effect and the benefit-only pattern have been attributed both to an *"automatic facilitation"* process. The first-order effects are due to residual processing traces left by previous stimulus-response (S-R) cycles (e.g., Bertelson, 1961). On repetitions, the residual trace somehow facilitates the processing of the stimulus whereas on alternations there is little gain or perhaps some interference due to the residual trace. The higher-order benefit-only pattern is due to an accumulation of residual processing traces that will not decay when RSIs are short (Soetens, Deboeck, & Hueting, 1984; Soetens et al., 1985; for a review Kirby, 1980). However, the higher-order benefit-only (or higher-order repetition effect) has also been considered as a manifestation of a high level response-monitoring activity, dissociating the first- and higher-order patterns into two separate mechanisms. During the monitoring process the actual response executed on a particular trial is compared to the one required on that trial in order to ensure the desired performance level. The notion of response monitoring received considerable support from recent brain potential and brain imaging studies of error detection and feedback processing studies (e.g., Carter et al., 1998; Gehring & Fencsik, 2001). In tasks with short RSIs, response monitoring may continue for some time after the arrival of the stimulus on the next trial resulting in a delay in responding. Obviously, the need for response monitoring decreases with trial repetitions, resulting in the benefit-only pattern observed for short RSIs.

Long RSIs and interpretations

When trials are presented using a long RSI (i.e., 250-500 ms and beyond), the first-order effect consists of an alternation benefit (i.e., first-order alternations are responded faster on average than first-order repetitions), whereas the higher-order effect displays a cost-benefit pattern (i.e., the speed of responding after some sequences on the current trial is fast for one particular stimulus, but slow for the alternative; for first-order repetitions the second-order alternation is responded slower than second-order repetitions, whereas for first-order alternations this pattern is reversed).

The first-order alternation effect has been taken as a manifestation of *"subjective expectancy"*; i.e., individuals tend to expect more alternations than repetitions in a series of events - a phenomenon that is known as the "gambler's fallacy" (Rapoport & Budescu, 1997; Wagenaar, 1972). The higher-order cost-benefit pattern is interpreted along similar lines (e.g., Soetens, 1998). The more participants expect a particular stimulus on the basis of the preceding higher-order sequence, the faster the response will be if that stimulus is presented. This is the benefit. On the other hand, when the alternative stimulus is presented the response will be slower, because expectancy for this stimulus has gradually decreased. This is the cost. In this sense, individuals expect a continuation of runs of alternations or repetitions. Response speed increases with longer trial runs and decreases when runs are interrupted (Soetens, 1998; for a review Kirby, 1980). This pattern has been suggested to reflect a conflict monitoring process between expected and actual stimuli (see Jones et al., 2002; see however Jones et al., 2013, p. 657).

Other factors affecting sequential effects

It should be noted that RSI is not the sole factor influencing the patterns of sequential effects. For example, several studies showed that the repetition effect grows stronger with increasing number of alternatives (e.g., four-choice or eight-choice instead of two-choice) (Hale, 1969; Hyman, 1953; Rabbitt, 1968; Remington, 1969, 1971). This effect is largely due to longer RTs to nonrepeated stimuli as compared to repeated stimuli (Kornblum, 1969). In a similar vein, the probability of stimuli (a priori stimulus probability) and of repetitions/alternations (transitional probability) has been suggested as an important factor influencing the sequential effects patterns. For example, the repetition effect is enhanced relative to the random condition when the proportion of repetitions is 75%, while there is a small alternation effect when the proportion of alternations is 75% (Bertelson, 1961; Kornblum, 1967; Moss, Engel, & Faberman 1967; see also Jones et al., 2013; and Wilder, Jones, Ahmed, Curran, and Mozer (2013) about this issue concerning positive and negative autocorrelations).

Stimulus-response (S-R) compatibility is another factor strongly affecting the patterns of sequential effects. S-R compatibility is the natural tendency of subjects to relate specific stimuli and responses or to favour specific relationships (e.g., left stimulus /left response, versus right stimulus/left response). Although all responses are somewhat slower under incompatible conditions (i.e., the reverse mapping) (for a review see Hommel & Prinz, 1997), responses to alternations are particularly affected, resulting in stronger repetition effects (Bertelson, 1963; Keele, 1969; Rabbitt & Philips, 1967; Schvaneveldt & Chase, 1969). Moreover, compatibility interacts strongly with RSI. Several studies demonstrated a prolonged influence of automatic facilitation and a postponement of subjective expectancy in incompatible conditions (Bertelson, 1963; Kornblum, 1973; Soetens et al., 1985; Soetens, 1998). This effect is in accordance with Kirby's (1980) conclusion, from a review of sequential effects in standard choice reaction tasks, stating that automatic facilitation pertains primarily to central processes involved in S-R translation rather than peripheral stimulus identification and response execution processes (Kirby, 1980; p. 164). Interpreting the S-R compatibility in terms of response choice is generally recognized (e.g., Kornblum, Hasbroucq, & Osman, 1990; Sanders, 1990).

Finally, practice also interacts differently with automatic facilitation and subjective expectancy. It is assumed that practice reduces the time needed for central processing due to a strengthening of S-R pathways (e.g., Logan, 1990; Welford, 1980). It should be noted, however, that the pertinent literature is inconsistent in this regard. There is indeed evidence that automatic facilitation can be overruled by training (Kirby, 1980; Soetens et al., 1985; Vervaeck & Boer, 1980). Soetens et al. (1985), for example, observed that extended practice reduced both first-order repetition and alternation effects. However, Suzuki and Goolsby (2003), focusing on first-order effects, observed that changes were minimal even after long-term practice extending to several months. They concluded from their findings that practice and first-order sequential effects affect the choice reaction process via different mechanisms.

Developmental changes in sequential effects

Although Wickens (1974) pointed to sequential effects as an important avenue for examining developmental change in the speed of information processing, these phenomena received surprisingly little attention in the experimental child psychology literature since the publication of his influential review paper. In the context of cognitive control processes it is also very interesting and important to study the developmental changes in sequential effects in more detail. Predictions based on previous trial runs could easily be associated with proactive control, whereas response-monitoring with reactive control (comparing the given response with the intended response). Actually, only a few studies examined developmental change in sequential effects, but were confined to the analysis of the first-order (repetition) effects (e.g., Fairweather, 1978; Kerr, 1979). Soetens and Hueting reported in 1992 for the first time some preliminary findings with respect to developmental changes in higher-order sequential effects.

Fairweather (1978) observed that the size of the repetition effect was smaller in 11-year olds compared to 6-year olds, and likewise, in a series of studies, Kerr and colleagues (Kerr, 1979; Kerr, Blanchard, Miller, 1980; Kerr, Davidson, Nelson, & Haley, 1982) found consistently smaller repetition effects in adults compared to children. Moreover, with a lengthening of the response-to-stimulus interval (RSI) from 250 to 750 ms, the repetition effect changed into an alternation effect in adults, but not in children. Consistent with the theoretical framework developed in adult studies, Kerr and colleagues interpreted the age-related decrease in the repetition effect in terms of automatic facilitation. More specifically, these authors suggested that repetitions reduce the time needed for selecting the correct response that is particularly slow in children relative to adults (cf. Kerr et al. 1982). In providing an explanation for the developmental decrease in automatic facilitation, Kerr and co-workers submitted the *automatic facilitation hypothesis,* stating that the stronger repetition effect they observed for children is due to their protracted central processing times (Kerr et al., 1982). More specifically, they assumed a short-cutting of central processing on repetition trials that is more beneficial in children than adults due to longer central processing times in the former relative to the latter.

Although it seems difficult to distinguish between 'trace' vs. 'bypassing' interpretations (cf. Luce, 1986), the important point here is that Kerr et al. (1982) assume a central locus of the age-related change in automatic facilitation.

Soetens and Hueting (1992) reported preliminary findings that emerged from an experiment designed to assess developmental change in both first-order and higher-order sequential effects. The adult pattern of results that emerged from this study replicated previous findings in showing a first-order repetition effect and a higher-order benefit-only pattern associated with a 50 ms RSI together with a first-order alternation effect and a higher-order cost-benefit pattern for a 500 ms RSI. The results obtained for a small group (n=10) of 10-12 year olds deviated from the adult findings by showing (a) a stronger first-order repetition effect for the short RSI and (b) the absence of a first-order alternation effect for the long RSI. These results are consistent with the age-related decrease in the size of the repetition effect reported previously by Fairweather (1978) and Kerr (1979) (see also Kerr et al., 1980, 1982). In addition, Soetens and Hueting (1992) observed higher-order benefit-only patterns for the short RSI, whereas no age-related differences were found. They observed a cost-benefit pattern for the 500 ms RSI that seemed less pronounced in children compared to adults. These preliminary findings were interpreted as suggesting that automatic facilitation is stronger in children (as detected by the first-order effects), while children's subjective expectancy is weaker compared to adult. In general, the sequential patterns support a differential evolution of automatic facilitation and subjective expectancy with age. Previously, Fairweather (1978) concluded already that 'any theory for the development of perceptual motor skill based on gross RT is thus inadequate since it will apply to only a restricted part of overall performance' (p. 416).

Questions addressed in this thesis

The primary goal of the studies concerning sequential effects in this thesis was to further assess developmental change in the basic processing mechanisms underlying sequential effects in serial reaction time (RT) tasks. In this way, we try to examine the developmental changes in reactive and proactive cognitive control. The first experiment of the first study (see Chapter 2) was aimed at replicating the pattern of developmental change in first-order and higher-order sequential effects observed previously by Soetens and Hueting (1992). A developmental decrease in the strength of automatic facilitation and an increase in the strength of subjective expectancy was predicted on the basis of their results.

The second experiment was aimed to further assess the *automatic facilitation hypothesis* of the developmental decrease in the first-order repetition (e.g., Kerr et al., 1982) and higher-order benefit-only pattern (Soetens & Hueting, 1992). Kerr et al. (1982) assumed a central locus of the age-related change in automatic facilitation; i.e., because children experience longer central processing times, their shortcutting of central processing on repetition trials are more beneficial for them than adults. Assuming that automatic facilitation affect response choice rather than stimulus identification or response execution (Kirby, 1980), and interpreting S-R compatibility in terms of response choice (e.g., Kornblum, 1973), it was predicted that the effects of age and an S-R compatibility manipulation should interact in their contribution to automatic facilitation.

The main goal of the second study on sequential effects (Chapter 3) was to assess how developmental change in automatic facilitation and subjective expectancy evolve, when experimental manipulations aim at providing more room for subjective expectancy, either by lengthening RSI (the first experiment) or by allowing participants more practice (the second experiment). Soetens et al. (1985) observed a transition zone from automatic facilitation to subjective expectancy around 100-250 ms RSI for adult participants. Based on our findings (the first study), we anticipated for children a transition zone around 500 ms RSI or beyond. We anticipated a shift from a benefit-only pattern, associated with a short RSI, towards a cost-benefit pattern associated with a long RSI. Moreover, we expected a stronger benefit-only pattern for children, spanning over a wider RSI range, and conversely, a weaker cost-benefit pattern for children, appearing for longer RSIs. In contrast, if the cost-benefit pattern would be more pronounced in children relative to adults, as was the case in our first study, then we conclude that first-order and higher-order effects are mediated by separate mechanisms rather than a single subjective-expectancy mechanism.

In the second experiment, we investigated the influence of practice. It was assumed that practice reduces the time needed for central processing due to a strengthening of S-R pathways (e.g., Logan, 1990; Welford, 1980). Consequently, we expected practice to reduce the strength of automatic facilitation, especially in children. Accordingly, it was anticipated that the practice-related decrease in automatic facilitation provides more room for subjective expectancy to occur in children. This hypothesis is based on the notion that automatic facilitation and subjective expectancy compete for expression. Short RSIs and task difficulty favor automatic facilitation whereas long RSIs and practice allow subjective expectancy to manifest itself more easily.

PERFORMANCE MONITORING AND ADJUSTMENT

Introduction

As already indicated above, the ability to adjust performance to a dynamically changing environment is a hallmark of intelligent behavior. However, before we can *adjust* our performance, we have to monitor our actions. A key aspect in performance monitoring is the ability to detect errors and become aware of them (internal feedback) and learn from explicit external feedback.[4] A large body of research examined the electrocortical concomitants of error processing (e.g., Overbeek, Nieuwenhuis, & Ridderinkhof, 2005). These studies showed that error detection is associated with a negative brain potential, coined the Ne (Falkenstein, Hohnsbein, Hoormann, & Blanke, 1995) or ERN (Gehring, Goss, Coles, Meyer, & Donchin, 1993), followed by a positive brain potential, Pe, which has been associated with error awareness (Nieuwenhuis, Ridderinkhof, Blom, Band, & Kok, 2001). Recent neurocognitive models of performance monitoring agree on the idea that the mediofrontal cortex, especially the anterior cingulated cortex (ACC) plays an important role during performance monitoring (e.g., Ridderinkhof et al., 2004; Ullsperger, Danielmeier, Joacham, 2014). However, there are still a lot of differences with regard to their assumptions about its specific function. For example, Holroyd and Coles (2002), in their reinforcement-learning model, assume that committed errors (or unexpected negative feedback), signal the need to change our behavior and thus modify our actions based on experience, i.e., undesirable outcomes. However, Alexander and Brown (2010, 2011) proposed that the key function of the ACC is to code the *unexpectedness* of events, not specifically *negative* results. And according to the conflict monitoring theory (Botvinick et al., 2001, 2004), the role of the ACC is to detect conflict or competition between an executed incorrect response and activation of the correct response due to ongoing stimulus evaluation. Either way, when monitoring our actions (evaluative control), we focus to optimize our performance (reactive control) based on the monitoring outcome. With other words, remedial action is required after error detection to prevent further errors.

Typically, responses following an error are slower and usually more accurate. This pattern has been observed in humans (Laming, 1979; Rabbitt & Rodgers, 1977), monkeys (Jedema et al., 2011) and rodents (Narayanan, Cavanagh, Frank, & Laubach, 2013). Rabbitt, in his seminal work on error processing (e.g., Rabbitt, 1966, 1968; Rabbitt & Vyas,

4 For optimal task performance it is necessary to be able to process *external* feedback and to change our behavior accordingly (e.g., a signal in an experiment or reaction from an individual). This thesis does not cover the effects of external feedback monitoring. For an extensive review on performance monitoring, including the developmental changes, see Ferdinand & Kray (2014).

1970), suggested that errors are not random events but, typically, represent attempts to assess optimal performance limits in response to the instruction to perform as quickly and accurately as possible. The tracking of performance may result in trial-by-trial speeding towards an error and a post-error response that is typically slower than the average correct response.

Interpretations of post-error slowing

Post-error slowing (PES), attracted various interpretations, aimed at answering the question *'why does one slow down after making an error?'* (see Dutilh et al., 2012). The notion of *'increased response caution'* is probably most prominent. Participants monitor their responses constantly to keep performance at an acceptable and relatively constant level of accuracy. They interpret an error as a sign for excessive increase in response criteria, reducing the probability of a second consecutive error, but also slowing response times. The idea is that people can adaptively change their response thresholds; i.e., becoming less cautious after a correct response, and more cautious after making an error (Botvinick et al., 2001; Brewer & Smith, 1989; Rabbitt & Rodger, 1977). As such, it is a direct measure of reactive cognitive control. A second explanation is that people become negatively biased against the response option that was just executed in error (e.g., Laming, 1968, 1979; Rabbitt & Rodgers, 1977). This bias should facilitate response alternations and hinder response repetitions. However, PES could also be the result of a distraction of attention (Notebaert et al., 2009). The occurrence of an error is an infrequent surprising event that distracts participants during the processing of the subsequent stimulus. Alternatively, it has been suggested that errors delay the start of the evidence accumulation process on the post-error trial. That is, people might need some time after an error to re-assess their own performance level and overcome disappointment (Rabbitt & Rodgers, 1977; see Danielmeier & Ullsperger, 2011; Ullsperger et al., 2014).

Dutilh et al. (2012) isolated and identified the psychological processes responsible for PES by using a drift diffusion model. In a very large lexical decision data set, they found that PES was associated with an increased response caution and, to a lesser extent, a change in response bias. They did not find any support for the perceptual distraction or time wasted on irrelevant processes. As such, this result supports a response-monitoring account of PES and is readily integrated with various models of cognitive control (e.g., Botvinick et al., 2001). For example, post-error processing could be reactive in the sense that it occurs locally in response to the error, and proactive in the sense that it is set in a top-down manner as a function of the control demands that characterize the wide (block/experiment-wide) context (see Regev & Meiran, 2014). In this sense, post-error slowing is particularly important to examine within a developmental perspective.

Developmental changes in post-error slowing

The developmental studies on performance monitoring using electrophysiological methods (i.e., ERN), point to some clear results. That is, a continuing maturation of the underlying monitoring system from early childhood through early adulthood as reflected by an increase of the ERN (e.g., Davies, Segalowitz, & Gavin, 2004; Hogan, Vargha-Khadem, Krikham, & Baldeweg, 2005; Kim, Iwaki, Imashioya, Uno, & Fujita, 2007; Ladouceur, Dahl, & Carter, 2007; Santesso, Segalowitz, & Schmidt, 2006; Wiersema, van der Meere, & Roeyers, 2007; for reviews Ferdinand & Kray, 2014; Tamnes, Walhovd, Torstveit, Sells, & Fjell, 2013). This developmental increase has been interpreted to reflect the maturation of brain mechanisms implicated in error-monitoring (i.e., the dorsal medial prefrontal cortex). The results for PES in these studies are somewhat contradicting. Some studies observed PES in children (e.g., Davies et al., 2004; Ladouceur et al., 2007), but failed to demonstrate a developmental change in PES (however see Santesso & Segalowitz, 2008). Other studies failed to demonstrate such slowing entirely (e.g., Eppinger, Mock, & Kray, 2009; van Meel, Heslenfeld, Rommelse, Oosterlaan, & Sergeant 2012). This observation suggested the idea that, initially, the mechanisms involved in error monitoring and performance adjustments are disconnected to become intertwined only later (cf. Lyons & Zelazo, 2011).

There are, however, performance studies that did show age-related changes in PES. For example, Fairweather (1978) was the first in examining developmental change in PES. He found, in a series of standard choice reaction tasks, a substantial decrease in PES with advancing age. He concluded that with increasing age the implementation of remedial action becomes more efficient, however, the basic mechanisms involved in error-monitoring and performance adjustment are in place already in young children. Brewer and Smith (1989) found also inaccurate error detection and inefficient performance adjustments in young children. Their findings indicated that children detect their errors but young children are less accurate. Moreover, response speeding towards errors and PES were found in children, although somewhat less pronounced. Their data demonstrated that the performance tracking mechanism is already present in young children. Using another task-paradigm (i.e., conflict task), Jones et al. (2003) and Schachar et al. (2004) reported a developmental *increase* in PES. However, van de Laar et al. (2011) observed *no age-related effect* on PES. Finally, Gupta et al. (2009) observed that PES *decreased* between 6 and 11 year olds, and interpreted this pattern in terms of orienting towards the error signal. Performance studies of PES in children that did not have a developmental focus, showed that PES was present in children between 8 to 11 years (O'Connel, Bellgrove, Dockree, & Robertson, 2004; Ornstein et al., 2009) or failed to observe PES in children aged between 7 to 16 years (Yordanova et al., 2011).

In sum, the performance studies investigating PES in children yielded a strong heterogeneous pattern of results (an increase, a decrease or age invariant). Similarly, the ERN studies produced a mixed pattern of PES results (not always present and, mostly, no developmental change in PES). So currently, given the paucity of developmental data, little definitive can be said about age-related change in post-error slowing.

Questions addressed in this thesis

This thesis presents one extensive study, including an overview of the developmental literature, that systematic assesses the developmental change in PES from childhood into adulthood. This was done by using a two-choice RT task, as this paradigm has generated previously stable post-error slowing patterns in adults (e.g., Laming, 1979). Examining developmental change in PES, Brewer and Smith (1989) used a four-choice task and observed that the influence of performance tracking was already visible in 5-year olds. We used a two-choice task to avoid potential confusion between responses, so as to reduce the demands on response monitoring (e.g., Fairweather, 1978). Fairweather (1978) reported a developmental decrease in PES using choice tasks involving two, four, or eight responses but the RSI in these tasks was relatively short (i.e., only 200 ms). When using short RSIs it is difficult to decide whether PES is due to interference caused by a corrective response or orientation reaction, to blocking associated with a response-monitoring process, increased response caution or a combination of these processes (e.g., Laming, 1979). Thus, we manipulated RSI from 50 to 1000 to assess whether the anticipated developmental change in PES is altered by RSI. It was predicted that PES would decrease with a lengthening of RSI (e.g., Dudschig & Jentzsch, 2009), and this trend should be more pronounced for young children compared to adults assuming that they experience more difficulty to resolve the interference of immediate reactions to the error. Two experiments were conducted to assess the robustness of the age-related change in PES. This assessment seems warranted in view of the heterogeneous pattern that emerged from the literature available to date.

Three age groups participated in the first experiment covering an age-range between 5 to 25 years. This range includes the ages examined by Davies et al. (2004) and Wiersema et al. (2007) who reported that developmental change in PES is absent. The age range is also similar to the one used by Brewer and Smith (1989) who observed that PES did occur in young children but, unfortunately, did not test whether it changed with advancing age. Fairweather (1978) performed such a test and reported a significant developmental decrease in PES over a limited age range (5 to 12 years). The current study will add to his findings by examining a wider age range and by assessing whether developmental change in PES is sensitive to the manipulation of RSI. Moreover, it will be tested whether the age-related differences in PES, if they occur, are disproportional and, thus, are not resulting from basic response speed differences between age groups.

It should be noted that most studies examining error processing in children used conflict tasks. These tasks generate much more errors than the standard compatible two-choice RT task. But the apparent disadvantage of a conflict task is that it is much more difficult for, especially young, children to discern between correct vs. erroneous responses. Obviously, this would reduce the possibility of post-error slowing in children. Actually, the use of the conflict tasks might contribute to the disparate pattern observed in the developmental literature. Second, we wanted to stay as close as possible to the tasks (highly compatible serial RT tasks) used in the seminal adult studies performed by, for example, Rabbitt and Laming (e.g., Rabbitt, 1966, 1968; Rabbitt & Vyas, 1970; Laming, 1979).

CONFLICT MONITORING AND ADAPTATION

Introduction

Dealing flexibly with conflict situations is a crucial aspect of cognitive control and, thus, an essential dimension in dynamically changing environments. Critical to cognitive control is the idea that conflict is detected (evaluative control) and, subsequently, signals for increased implementation of control (reactively and proactively). Botvinick et al. (2001, 2004), in their influential conflict monitoring theory, put forward the general mechanisms behind conflict monitoring and adaptation. They indicated that there is an ACC (anterior cingulate cortex)-mediated conflict monitoring mechanism that monitors information processing, makes an assessment of current demands, and signals for increased recruitment of control (in the dorsolateral and ventrolateral prefrontal cortex) when information processing demand exceed the current level of control.[5]

Conflict effects and interpretations

Conflict specifically refers to the simultaneous activation of competing stimulus or response options (Botvinick et al., 2001), and is typically studied with congruency tasks, where participants respond on the basis of relevant stimulus features while ignoring irrelevant stimulus features. Many studies have shown that when such competition or conflict arises between behavioural choices, performance is adversely affected in terms

5 See Larson et al. (2014) for an extensive review about conflict-related ERPs, including ERN, flanker N2, Stroop N450, conflict slow potential, negative slow wave, and an analysis of how these ERPs inform the conflict monitoring theory. See, however, Mansouri, Tanaka, and Buckley (2009) who proposed challenging revisions of the Botvinick et al. model concerning the neural architecture.

of speed and accuracy, and is referred to as *conflict cost* (i.e., response speed increases and accuracy decreases for *in*congruent vs. congruent trials). Importantly, the behavioural effects of conflict are not just limited to the *current* trial. They also affect performance in the subsequent trial, in which they are manifested as a behavioural improvement if the subject is faced with conflict again. For instance, RTs in conflict trials that are immediately preceded by another conflict trial are shorter than those in conflict trials that are immediately preceded by no-conflict trials. This facilitative effect of previously experienced conflict has been demonstrated in a range of different tasks, and has been coined the *conflict adaptation effect* or the *Gratton effect* (Duthoo, Abrahamse, Braem, Boehler, & Notebaert, 2014; Gratton, Coles, & Donchin, 1992; Kerns et al., 2004; Kunde, 2003; Kunde & Wuhr, 2006; Notebaert, Soetens & Melis, 2001; Schmidt, Notebaert, & van den Bussche, 2015). Although this effect attracted various interpretations (Egner, 2007, 2014; Braem et al., 2014 for a review), the one that is most compatible with the cognitive control framework proposed by Braver and colleagues (2009, 2011) suggests that participants utilize previous conflict information to optimize current conflict resolution (Botvinick et al., 2001). That is, individuals are inclined to expect that (non-) conflict will repeat on the upcoming trial (e.g., Gratton et al., 1992). When they expect a conflict trial to repeat they will up-regulate cognitive control facilitating the processing of relevant stimulus features and activation of the appropriate response thereby reducing the performance decrement associated with conflict trials. In contrast, when they expect a non-conflict trial to repeat they will down-regulate cognitive control allowing the processing of irrelevant stimulus features and reducing the threshold for activating the competing, incorrect response.

Neurocognitive studies provided convincing support for the view as described above (e.g., Kerns et al., 2004; for a review Larson et al., 2014). In general, increased neural processing (required for incongruent stimuli relative to congruent stimuli), is thought to be mediated by ongoing response conflict monitoring systems arising from the anterior cingulate cortex (ACC). It is suggested that the ACC detects conflict, subsequently signaling frontal areas, such as the dorsolateral prefrontal cortex (DLPFC) and ventrolateral prefrontal cortex (VLPFC), to allocate and regulate cognitive control processes (Botvinick et al., 2001; Egner & Hirsch, 2005; Kerns et al., 2004). Efficient cognitive control takes advantage of this added neural capacity to maximize responses to subsequent trials, resulting in conflict adaptation. That is, ACC, DLPFC, and VLPFC resources remain active long enough to enhance processing for several subsequent trials (Clayson & Larson, 2011; Durston et al., 2003), such that ACC activation during high-conflict trials predicts prefrontal cortex activation during the succeeding trial (Kerns et al., 2004). Therefore, consecutive incongruent trials require reduced neural processing compared to a congruent trial followed by an incongruent trial (Gratton, et al., 1992; Kerns et al., 2004; Ullsperger, Bylsma, & Botvinick, 2005). This is marked behaviorally by reduced response times (RTs) and electrophysiologically by an attenuated neural response for incongruent compared to congruent trials (i.e., conflict adaptation). Additionally, consecutive congruent trials result in faster RTs than an incongruent trial followed by a congruent trial due to task-switching effects between response strategies (Gratton et al., 1992; Egner & Hirsch, 2005).

Conflict tasks

Tasks eliciting conflict provide the opportunity to study control processes. More specifically, performance on post-conflict trials, relative to post-nonconflict trials (e.g., conflict adaptation effect), provides a window on the operation of proactive control mechanisms. Slower responses on conflict trials compared to non-conflict trials gives a picture of reactive control processes (conflict costs). For example, in the well-studied *Stroop task*, in incongruent (high-conflict) conditions, when the color's name differs from the ink color, subjects are less accurate and slower than in congruent (low-conflict) conditions, in which the color name matches the ink color, or in neutral conditions, in which the word is not color-related (Stroop, 1935; MacLeod, 1991; MacLeod & MacDonald, 2000). This task has also demonstrated considerable conflict adaptation effects (e.g., Egner & Hirsch, 2005; Egner, Delano, & Hirsch, 2007; Kan et al., 2013; Kerns et al., 2004; Notebaert, Gevers, Verbruggen, & Liefooghe, 2006; Spapé & Hommel, 2008, for a auditory Stroop task; Wendt, Kluwe, & Peters, 2006; Wuhr, Duthoo, & Notebaert, 2014).

Conflict can also be induced in *Go-NoGo paradigms*, in which subjects are required to respond to 'go' defined stimuli/stimulus sets but have to withhold responses to 'nogo' defined presented stimuli/stimulus sets (see Donders, 1865; Donkers & van Boxtel, 2004). Adult findings derived from a variety of Go-NoGo tasks showed that the speed of responding is delayed considerably on Go trials following a NoGo trial relative to a Go trial (e.g., Hoffmann, Kiesel, & Sebald, 2003; Kleinsorge & Gajewski, 2004; Rieger & Gauggel, 1999; Rieger, Gauggel, & Burmeister, 2003; Schuch & Koch, 2003). Adopting the proactive control framework (Botvinick et al., 2001; Braver, 2012), this slowing of response speed on post-conflict Go trials would be explained by assuming that the conflict induced on the preceding NoGo trial up-regulates control mechanisms reducing the risk of a commission error by raising response thresholds. In this regard, the slowing on post-conflict trial in the Go-NoGo paradigm seems similar to the post-error slowing on standard choice reaction time (RT) tasks (e.g., Dutilh et al., 2012; Smulders, Soetens, & van der Molen, 2016).

In another common conflict task, the so-called *Simon task*, conflict arises from the mismatch between the spatial location of a stimulus and the required response; i.e., between responses to the task-irrelevant stimulus source vs. the task-relevant stimulus content on incongruent trials whereas stimulus source and response location correspond on congruent trials (e.g., Simon & Rudell, 1967). Numerous studies indicated that the task-irrelevant spatial information associated with the stimulus has a relatively small but robust effect on the speed of responding—the speed of responding is delayed on incongruent relative to congruent trials (review in Lu & Proctor, 1995). This delay has been attributed to the need to suppress the pre-potent response towards the stimulus source (e.g., Eimer, 1999; Miles & Proctor, 2012). Conflict adaptation effects are also clearly present in the Simon task; i.e., conflict effects diminishes when trials are preceded by conflict (incongruent) trials (Notebaert et al., 2001; Ullsperger et al., 2005; Wuhr & Ansorge, 2005; but see Spapé & Hommel, 2014).

The *stimulus-response compatibility (SRC) task* involves making a compatible response to one set of stimuli (compatible trials) whereas another set of stimuli requires an incompatible response (incompatible trials) (e.g., van Duren & Sanders, 1988; Mansfield et al., 2012; Stoffels, 1996). For example, participants are asked to respond to the direction of a central arrow stimulus that is presented in two different colors. One color instructs participants to make a spatially compatible response (i.e., a left-hand response to a left-pointing arrow and a right-hand response to a right-pointing arrow) whereas the other color of the arrows instructs participants to make a spatially incompatible response to the direction of the arrow (i.e., a left-pointing arrow requires a right-hand response and a right-pointing arrow requires a left-hand response). The mixing of compatible and incompatible trials has been observed to annihilate the response speed advantage of compatible over incompatible trials when presented in blocked trials (e.g., Christensen, Ivkovich, & Drake, 2001; De Jong, 1995; Heister & Schroeder-Heister, 1994; Proctor & Vu, 2002; Shaffer, 1965; Stoffels, 1996; van Duren & Sanders, 1988; Vu & Proctor, 2004). That is, compatibility mixing reduces the speed of responding on compatible trials relative to blocked presentation whereas presentation mode has less effect on the speed of responding on incompatible trials. This pattern of results has been taken to suggest that compatibility mixing is associated with a strategic bias towards incompatibility resulting in an active suppression of the compatible mapping rule thereby reducing the SRC effect on the speed of responding (e.g., De Jong, Liang, & Lauber 1994). In this regard, the slowing of response speed on compatible trials in mixed SRC blocks can be considered an instance of proactive cognitive control. Here, it should be pointed that a mixed-blocked SRC task is essentially identical to a task-switching paradigm in which participants are required to switch back and forth between two or more choice-RT tasks afforded by the same class of stimuli (for a review see Monsell, 2003). Here, both bottom-up (stimulus driven) processes and top-down control processes contribute to task switching (e.g., Ruthruff, Remington, & Johnston, 2001; for a review see Grange & Houghton, 2014).

Developmental changes in conflict costs

Results from research examining developmental changes on conflict tasks show a highly variable pattern in terms of conflict-costs and conflict adaptation. To draw a clear picture of the findings, developmental changes on cost effects will be discussed first before elaborating on developmental changes in conflict adaptation. For example, Go-NoGo tasks have been widely used to examine age-related changes in the ability to inhibit pre-potent responses (e.g., Brocki & Bohlin, 2004; Casey et al., 1997; Cragg & Nation, 2008; Durston et al., 2002; Garon et al., 2008; Hammerer, Li, Muller, & Lindenberger, 2010; Huizinga & van der Molen, 2011; Johnstone et al., 2007; Jonkman, Lansbergen, & Stauder., 2003; Levin et al., 1991; Luria, 1961; Span, Ridderinkhof, & van der Molen, 2004). The results of most studies employing the Go-NoGo task converge on the conclusion that the ability to inhibit a pre-potent response develops rapidly during childhood and reaches mature levels when children enter the adolescent period (van der Molen, 2000).

Jerger, Pearson, and Spence (1999) reported a developmental decrease of the Simon congruency effect using an auditory variety of the Simon task (e.g., responding to the speaker's gender while ignoring the speaker's location). Band, van der Molen, Overtoom and Verbaten (2000) used an inter-modal Simon task requiring participants to respond to a visual stimulus while ignoring the location of a task-irrelevant auditory stimulus that was presented at different intervals following the onset of the visual stimulus. The only developmental difference was a larger Simon congruency effect for auditory accessories presented at longer intervals. Finally, Davidson, Amso, Anderson and Diamond (2006) presented age groups with visual implementations of a visual Simon task differing in the type of visual stimulus (e.g., pictures, arrows, dots). They observed a developmental decrease in the Simon congruency effect for one task (presenting pictures) but not others (presenting arrows).

Developmental studies examining spatial SRC effects are few and far between. Early studies by Clark (1982) and Lávadas (1990) showed a developmental decrease in the SRC effect on the speed of responding. Van den Wildenberg and van der Molen (2004) reported a similar pattern that was interpreted to suggest that children experience greater difficulty than adults in inhibiting the over-learned directional response to the stimulus. Other studies, however, reported developmental stability rather than age-related change in the SRC effect. Wright and Diamond (2014) examined SRC effects across a limited age range (from 6 to 10 years) and observed that for all ages the speed of responding was considerably faster on compatible relative to incompatible trials. A developmental trend was not reported, however. Casey, Tottenham and Fossella (2002) observed that the cost of an incompatible mapping relative to a compatible one did not differ between a child group (7 to 11 years) and a group of young adults. Similarly, Dornier and Meaney (2003) reported a pronounced SRC effect that did not change across age. At this point, it is difficult to provide a ready interpretation of the apparent inconsistencies in the data-patterns reported by the studies reviewed above.

Developmental changes in conflict adaptation

Surprisingly, there is only a handful studies available about conflict adaptation in children, and even less about developmental changes herein. Collectively, these studies yielded the anticipated pattern of findings based on the adult literature, however, only few obtained a robust developmental trend.

For example, Larson, Clawson, Clayson, and South (2012), using a *Stroop color-naming task*, obtained a sizable conflict adaptation effect, but this effect did not differentiate between children and young adults. Huizinga and van der Molen (2011), however, used a hybrid choice *Go-NoGo paradigm* in which participants were required to respond in a binary choice to a stimulus depending on its shape or to refrain from responding depending upon its color. Response speed was considerably slower on choice trials following a NoGo trial relative to a Go trial (i.e., 122 ms) and this effect was much larger in children compared to adults. This developmental change was interpreted in terms of more caution exercised on post-conflict trials resulting in a higher setting of response thresholds.

Van de Laar et al. (2011) reported somewhat similar results employing *stop-signal task* in which a color change of the choice stimulus communicates to the participant that the response to the stimulus should be inhibited. The speed of responding was slower on trials with a stop-signal compared to non-signal trials and this effect decreased with advancing age into young adulthood. However, this developmental trend was not significant when corrected for group differences in the basic speed of responding.

Iani, Stella, and Rubichi (2014) used a *Simon task* and observed that conflict adaptation was present already in 6- to 8-year old children. That is, the Simon effect was 85 ms following a congruent (non-conflict) trial and only 23 ms following an incongruent (conflict) trial. Iani, Rubichi, Gherri, and Nicoletti (2009) used the same task in an adult study and observed conflict adaptation values that were much smaller; 59 ms and -4 ms, respectively. Although indirect, the results of Iani and colleagues suggest that conflict adaptation in a Simon paradigm is sensitive to developmental change. Also Stins, Polderman, Boomsma, and de Geus (2007) observed that conflict adaptation was present (in 12-year-olds) on both the Simon task and the Eriksen flanker task. But the adaptation effect was considerably more pronounced for the Simon task relative to the Eriksen flanker task (respectively, 63 ms vs. 38 ms). In a similar study by Ambrosi et al. (2016), studying a group of 5- to 6-year –olds, a sizable conflict-adaptation effect for the Simon and Stroop tasks (respectively, 114 ms and 156 ms) was demonstrated, whereas the effect was considerably less pronounced for the Eriksen flanker task (53 ms). Ambrosi et al. (2016) drew attention to the apparent discrepancy between age-related changes in conflict adaptation and response inhibition: young children seem already achieve conflict adaptation whereas their ability to inhibit responses is still immature. Their results showed also that, although conflict adaptation occurs on all three tasks, the size of the effect differed across tasks suggesting specificity in the conflict elicited by each of the tasks.

Waxer and Morton (2011) examined conflict adaptation using a *compatibility task*. Different age groups (children, adolescents and young adults) were required to sort stimuli that varied in shape and color. Half of the stimuli were congruent (i.e., shape/color of the stimulus matched) and half of the stimuli were incongruent (i.e., shape/color of the stimulus did not match and, thus, these stimuli provided a source of conflict). Their results showed that adults and adolescents, but not children, were faster on incongruent trials preceded by incongruent relative to congruent trials. Further, only adults, not adolescents and children, were faster on congruent trials preceded by another congruent trial relative to an incongruent trial. Importantly, this pattern survived when correcting for group differences in basic speed. Waxer and Morton (2011) interpreted their pattern of results in terms of proactive control. That is, they assumed that the conflict elicited on an incongruent trial results in the strengthening of attention-guiding rules biasing the processing of stimuli on the subsequent incongruent trial towards task-relevant features of the stimulus thereby reducing conflict effects on performance. The developmental trend is then explained by assuming that the mechanisms implicated in the detection of conflict and the recruitment and maintenance of attention-guiding rules are under-developed in young children (Waxer & Morton, 2011; p. 1653); i.e., adults and adolescents were assumed to use prior conflict to prepare them for potential conflict on the subsequent trial (proactive control) whereas children respond to conflict as it occurs (reactive control).

Finally, to date there is only one developmental study in which SRC was manipulated between and within trial blocks (Crone et al., 2004). This study examined age-related change in the flexible use of SRC mappings in three different age groups; 8-year-olds, 11-year-olds and young adults. The results revealed that SRC mixing annihilated the SRC effect observed for pure blocks but only when responses across trials alternated, not when responses were repeated. Importantly, the interaction between trial block (pure vs. mixed) and SRC mapping (compatible vs. incompatible) did not vary across age groups.

Questions addressed in this thesis

The primary goal of the current study was to examine the developmental change in the ability to adjust performance following a conflict trial (conflict adaptation). A secondary aim was to assess whether conflict adaptation follows different developmental trajectories depending on the type of conflict elicited by the tasks.

The conclusion that emerged from the above review of studies examining age-related changes in dealing with conflict (cost effects and conflict adaptation) strongly suggests that conflict adaptation is present in children, suggesting that the control mechanisms in conflict adaptation are already in place during childhood (but see Waxer & Morton, 2011). However, only few studies examined developmental change in conflict adaptation and the outcomes of those studies are inconsistent (see e.g., Huizinga & van der Molen, 2011; Larson et al., 2012; Waxer & Morton, 2011). Finally, the developmental trend depends upon the specific instantiation of conflict (e.g., Go-NoGo task, Simon task, Compatibility task, Stroop color-naming task, etc.) (see also Braem et al., 2014; Wilk & Morton, 2012, and recently Ambrosi et al., 2016). This observation is consistent with results reported in the adult literature suggesting that conflict adaptation is domain specific rather than domain general (for a review Braem et al., 2014). These conclusions prompted us to use various types of conflict tasks when evaluating developmental change in dealing with conflict— a version of a standard Simon task (Experiment 1), an SRC task (Experiment 2) and hybrid Choice-reaction (Go)/Nogo task (Experiment 3). The three different tasks contained identical stimuli, but different instructions. That is, participants (7 – 25 yrs) were asked to respond to colored left- or right-pointing arrows by depressing left- or right-hand response buttons depending upon the color and/or directional information provided by the arrows.

In view of the inconsistencies reported in the developmental literature, it would be difficult to formulate strong predictions regarding developmental change in conflict adaptation. One prediction can be derived from developmental notions suggesting that the efficiency of top-down (proactive) cognitive control increases with advancing age (e.g., Davidson et al., 2006; Luna, Padmanabhan, & O'Hearn, 2010; Munakata et al., 2012). On this hypothesis, it would be predicted that the conflict-adaptation effect should increase with advancing age, as suggested by the findings reported by Waxer and Morton (2011) (but see Huizinga & van der Molen, 2011). Another prediction can be derived from the literature suggesting the domain-specificity of conflict adaptation (e.g., Braem et al., 2014). This prediction states that the conflict adaptation effect will differ across tasks, as the conflicts elicited in the three tasks may be qualitatively different. Finally, given the hypothesis that conflict adaptation is a manifestation of top-down cognitive control (e.g., Kerns et al., 2004), performance adjustments may need some time to be implemented. Previously, Notebaert et al. (2006) observed that adaptation to Stroop conflict did not occur in adults when the response-to stimulues (RSI) was very short (i.e., 50 ms) while it was clearly visible when RSI was lengthened to 200 ms. In the current study, RSI was manipulated (in pure blocks) to be either 50 ms or 500 ms. Accordingly, it was predicted that age-related change in conflict adaptation would be visible only when RSI was long but not when it was short. When RSI is short neither adults nor children have sufficient time for the configuration of control measures required for performance adjustments.

SUMMARY

The present thesis comprises four empirical studies that aim to extend our understanding of the developmental pathway of cognitive control. More specifically, it examines the developmental changes in reactive and proactive cognitive control. These processes reflect those changes that occur within a trial or trial-by-trial. Hence, the pertinent research does not concern solely reaction time (RT) and related errors averaged over blocks of trials, but covers specifically trial-by-trial analyses subjacent to cognitive control; i.e., *sequential effects* (chapter 2 and 3), effects related to *performance monitoring and adjustment* (i.e., post-error slowing) (chapter 4), and those related to *conflict monitoring* and *adaptation* (chapter 5).

Children's response to sequential dependencies in "simple" choice RT tasks may provide important insights into the changes that may occur in the flexibility and control (reactively and proactively) of their cognitive systems (e.g., Zelazo et al., 2003). The primary goal of the studies concerning sequential effects (Chapter 2 and 3) was to further assess developmental change in the basic processing mechanisms underlying sequential effects in serial reaction time (RT) tasks. The first experiment of the first study (Chapter 2) was aimed at replicating the pattern of developmental change in first-order and higher-order sequential effects observed previously in a preliminary report by Soetens and Hueting (1992). 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 (Soetens & Hueting, 1992), assuming a central locus of the age-related change in automatic facilitation. The main goal of the second study (Chapter 3) on sequential effects was to assess how developmental change in automatic facilitation and subjective expectancy evolve, when experimental manipulations aim at providing more room for subjective expectancy, either by lengthening RSI (the first experiment) or by allowing participants more practice (the second experiment).

An important aspect of cognitive control is the ability to detect errors and adjust performance to prevent further errors. The tracking or monitoring of performance results in trial-by-trial speeding towards an error and a post-error response that is slower than the average correct response (i.e., post-error slowing, known as PES). Reviewing the literature on the developmental changes in PES, demonstrated a strong heterogeneous pattern of findings, showing both developmental change and invariance, which has differential implications for reactive and proactive control (e.g., Brewer & Smith, 1989; Fairweather, 1978; Gupta et al., 2009; Jones et al., 2003; van de Laar et al., 2011). This thesis presents one study (Chapter 4), including an extensive overview of the developmental literature, that systematic assesses the developmental change in PES from childhood into adulthood. This was done by using a standard choice RT task, as this paradigm has generated stable post-error slowing patterns in adults (e.g., Laming, 1979), and reduces the demands on response monitoring (e.g., Fairweather, 1978). We manipulated response-to-stimulus interval (RSI) from 50-1000 ms to differentiate between interference effects caused by corrective responses or orientation reactions, to blocking associated with a response-monitoring process, increased response caution or a combination of these processes (e.g., Laming, 1979). A second experiment was designed to test the robustness of the developmental trend in PES by increasing the observations.

Critical to cognitive control is the idea that conflict in performance or the environment is detected and subsequently signals for increased implementation of control (see Larson et al., 2014). Recent findings indicate that children are less proficient in conflict monitoring, and less able to recruit adjustment mechanisms in dealing with conflict (e.g., Waxer & Morton, 2011). However, the developmental trend depends heavily upon the specific instantiation of conflict (e.g., Go-NoGo task, Simon task, Compatibility task, Stroop color-naming task, etc.) (see also Braem et al., 2014; Wilk & Morton, 2012). The primary goal of the conflict study (Chapter 5) was to examine the developmental change in the ability to adjust performance following a conflict trial (conflict adaptation). A secondary aim was to assess whether conflict adaptation follows different developmental trajectories depending on the type of conflict elicited by the tasks. In separate experiments, we used three types of conflict tasks (with identical stimuli, but different instructions) when evaluating developmental change in conflict adaptation— a Simon task (Experiment 1), an SRC task (Experiment 2), and a Choice-reaction-NoGo task (Experiment 3). One aim of the first experiment was to obtain a solid pattern of developmental change in the Simon congruency effect. The major goal of this experiment was, however, to replicate the recurrent finding of conflict adaptation in the Simon task (for a review, Kerns, 2006) and to assess whether conflict adaptation would develop with advancing age. The goal of the second experiment was to examine developmental change in conflict adaptation using an SRC task with a mixed presentation of compatible and incompatible trials. In the third experiment we tried to replicate the age-related downward trend in conflict adaptation by Huizinga and van der Molen (2011). In addition, in each experiment the response-to-stimulus interval (RSI) was manipulated to accommodate proactive control mechanisms in long, whereas not in short RSIs.

Chapter 6 provides a general discussion based on the results of the empirical chapters. This chapter attempts to integrate results across studies and to derive some conclusions regarding the developmental changes in reactive and proactive control processes.

The four empirical chapters are published, or have been submitted to, international journals. They have been inserted in this thesis in their original submitted or accepted form. To acknowledge the important and necessary contributions of the co-authors, the following list of references is presented below.

- Smulders, S. F. A., Notebaert, W., Meijer, M., Crone, E. A., van der Molen, M. W., & Soetens, E. (2005). Sequential effects on speeded information processing: A developmental study. *Journal of Experimental Child Psychology, 90,* 208-234. **(Chapter 2)**

- Smulders, S. F. A., Soetens, E., & van der Molen, M. W. (*submitted*). Developmental change in sequential effects on speeded information processing is altered by response-to-stimulus interval but not practice. **(Chapter 3)**

- Smulders, S. F. A., Soetens, E., & van der Molen, M. W. (2016). What happens when children encounter an error? *Brain & Cognition, 104,* 34-47. **(Chapter 4)**

- Smulders, S. F. A., Soetens, E., & van der Molen, M. W. (*submitted*). How do children deal with conflict? A developmental study of trial-to-trial conflict adaptation. **(Chapter 5)**