Developmental changes in cognitive control

Temporal dynamics of task performance across trial sequences

Smulders, S.F.A.

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Developmental studies of cognitive control indicated that control processes develop gradually during childhood through adulthood. The focus of this thesis is on developmental change in performance adjustments across trial sequences in relatively simple reaction time tasks. The results yielded robust developmental trends across an age range between 5 and 25 years. Collectively, however, the results question the idea that developmental change in trial-to-trial performance adaptation is guided by maturational changes in top-down cognitive control.
DEVELOPMENTAL CHANGES IN COGNITIVE CONTROL

TEMPORAL DYNAMICS OF TASK PERFORMANCE ACROSS TRIAL SEQUENCES

Silvan F.A. Smulders
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DEVELOPMENTAL CHANGES IN COGNITIVE CONTROL

TEMPORAL DYNAMICS OF TASK PERFORMANCE ACROSS TRIAL SEQUENCES

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aan de Universiteit van Amsterdam
op gezag van de Rector Magnificus
prof. dr. ir. K.I.J. Maex
ten overstaan van een door het College voor Promoties ingestelde
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Faculteit der Maatschappij- en Gedragswetenschappen (FMG)
aan mijn ouders

voor Teun, Job en Annelies
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General introduction
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.
Chapter 1

**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 temporarily 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; MacDonald 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 pre-
frontal 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-à-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, Abrahame, 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.”
Chapter 1

(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. 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).

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.

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. 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,

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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).
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.
Chapter 1

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., Eppingher, 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 systematically 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

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\(^5\) 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 incongruent 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,
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 an 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-stimulus (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
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., 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)


Sequential effects on speeded information processing: a developmental study
ABSTRACT

Two experiments were performed to assess age-related changes in sequential effects on choice reaction time (RT). Sequential effects portray the influence of previous trials on the RT to the current stimulus. In Experiment 1, three age groups (7-9, 10-12, and 18-25 yrs) performed a spatially compatible choice task, with response-to-stimulus intervals (RSI) of 50 and 500 ms varied between trial blocks. In Experiment 2, three age groups (7-9, 15-16, and 18-25 yrs) performed the task with spatial S-R mappings (compatible versus incompatible) varied between participants. For adults, the experiments yielded a pattern of sequential effects suggestive of ‘automatic facilitation’ (i.e., a first-order repetition effect and a higher order benefit-only pattern for short RSIs) and ‘subjective expectancy’ (i.e., a first-order alternation effect and a higher order cost-benefit pattern for long RSIs). Automatic facilitation was more pronounced for incompatible relative to compatible responses. Both experiments showed the anticipated decrease in automatic facilitation with advancing age. Finally, the first-order alternation effect showed the predicted age-related increase, but the cost-benefit pattern revealed an opposite trend, suggesting that the first-order and higher order indexes of subjective expectancy may relate to dissociable mechanisms.
INTRODUCTION

The latency of human responding in choice reaction time (RT) tasks has long served as an important source of data regarding the mechanisms underlying human cognitive performance (Luce, 1986; Woodworth, 1938). More specifically, such data laid the foundations for theories regarding the mechanisms implicated in the selection of responses and response adjustments when adequate performance fails (Allport, 1987; Botvinick et al., 2001; Laming, 1979; Mayr, 2004; Wickelgren, 1977). For example, participants responded with more caution on the current trial when they selected the wrong response or failed to refrain from responding on the immediately preceding trial (Rabbitt, 1966, 1967; Rabbitt & Philips, 1967). Such adjustments in performance suggest the operation of a mechanism responsible for response monitoring and response amendment when performance goes astray. Such a mechanism is typically conceptualized within the broader framework of executive control vis-à-vis prefrontal cortex functioning (Carter et al., 1998; Mayr, 2004; Norman & Shallice, 1986).

Recent studies examining developmental change in executive function using tasks requiring the flexible adjustment of task sets (from conventional Winsconsin Card Sorting Task [WCST] to experimental task-switching paradigms) converge on the conclusion that cognitive flexibility improves during childhood (Dempster, 1992; Stuss, 1992; van der Molen & Ridderinkhof, 1998; Welsh, 2002; Zelazo et al., 2003). The aim of this study was to examine developmental change in cognitive flexibility by looking at the dependency between trials in a standard choice RT task (e.g., Hyman, 1953; for reviews Kirby, 1980; Luce, 1986). In this way we suggest an alternative avenue for examining cognitive flexibility. More specifically, we focus on the underlying processing mechanisms. These processes are rather understudied in the developmental literature, and could be a compelling framework for future research concerning cognitive flexibility. First, we briefly review what is known about it based on tasks that require switching of task sets.

Children make substantial performance gains on the WCST, which requires matching of geometrical shapes on a target card to four standard tasks. The matching rule is not provided but is inferred from performance feedback. After a series of correct matches, the rule is changed without warning and the new matching rule must be found using the feedback provided by the experimenter. Developmental studies using the WCST to assess executive function show that, as children grow older, they find significantly more matching rules and show a reduced tendency to make perseveration errors following a rule change (e.g., Chelune & Baer, 1986; Heaton et al., 1993; Paniak et al., 1996; Rossellini & Ardila, 1993). Recently, Crone and colleagues examined developmental change in the performance on an experimental analogue of the WCST (Crone et al., 2004). Participants
were required to respond to the spatial position of one of four stimuli mapped onto the index and middle fingers of the left and right hands. There were three different mapping rules: compatible mapping for both hands, incompatible mapping within hands, and incompatible mapping between hands. Following Barcelo and Knight (2002), Crone and colleagues (2004) focussed on two types of errors: perseveration errors and distraction errors. Perseveration errors were defined as a failure to switch to a new mapping rule following the first negative feedback, and distraction errors were defined as an inappropriate switch to another mapping rule. Similar to the results obtained previously using the conventional WCST, Crone and colleagues observed a significant age-related decrease in perseveration errors during childhood, and an analogous trend was observed for distraction errors. This pattern of results was interpreted to suggest that children's ability to switch between task sets in response to negative performance feedback (indexed by the decrease in perseveration errors) and their ability to maintain a task set across a series of trials (indexed by the decrease in distraction errors) improves rapidly during childhood.

The observed developmental change in WCST error pattern is consistent with recent response latency data obtained using the task-switching paradigm. Within that paradigm, participants are usually instructed to switch between two simple tasks, A and B. In Task A, for instance, they are instructed to respond to the color (e.g., red versus blue) while ignoring stimulus shape (e.g., square versus circle). The instruction is opposite in Task B, where participants are required to respond to stimulus shape while ignoring the color of the stimuli. The tasks are presented in mixed blocks of trials, and the usual finding is that responses are slower on switch trials (A\textsuperscript{B} or B\textsuperscript{A}) than on repeat trials (A\textsuperscript{A} or B\textsuperscript{B}) (Monsell, 2003). Only few studies examined developmental change in the ability to switch between different task sets, but the findings so far seem to indicate that the ability to switch between tasks improves during childhood (Cepeda et al., 2001; Huizinga & van der Molen, 2004; Zelazo et al., 2004; but see Kray et al., 2004). These findings have been taken in terms of mechanisms that fall under the umbrella of executive control because it is assumed that task switching relies on the processes of preparation and inhibition of inappropriate task sets (e.g., Rogers & Monsell, 1995). Such processes are supported, in large part, by prefrontal regions of the brain (e.g., Aron et al., 2004; Brass & von Cramon, 2004; Kimberg, Aguirre, & D’Esposito, 2000).

In the current study, developmental change in cognitive flexibility was examined by taking advantage of recurrent observations that the performance on the current trial, within a block of a standard choice RT task, depends on the past history of trials (e.g., Hyman, 1953; for reviews, see Kirby, 1980; Luce, 1986). That is, when trials repeat (i.e., the stimulus and response of the current trial and of the immediately preceding trial are
Sequential effects on speeded information processing

the same), the speed of responding is faster than when they alternate (i.e., the stimulus and response of the current trial and of the immediately preceding trial are different). The beneficial effect of trial repetition may change into an alternation effect when the interval between trials is lengthened beyond 500 ms. In that case, responses are faster when trials alternate than when they repeat. The beneficial effect of trial repetitions has been attributed to an “automatic facilitation” due to residual processing traces left by previous (S-R) cycles (e.g., Bertelson, 1961). In contrast, the mechanism operating in trial blocks using long intervals giving rise to the alternation effect is assumed to reflect “subjective expectancy”. The latter interpretation assumes that 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). When expectancy is confirmed (i.e., an alternation occurs), response speed is fast; conversely, when expectancy is disconfirmed (i.e., a repetition occurs), response speed is slow.

THE CURRENT STUDY

Only few studies have examined developmental change in sequential effects, and the results that emerged from those studies revealed an age-related decrease in the repetition effect, suggesting that the beneficial effect of automatic facilitation becomes less powerful with advancing age (e.g., Fairweather, 1978; Kerr, 1979; Soetens & Hueting, 1992). The primary goal of the current study was to further assess developmental change in the basic processing mechanisms underlying sequential effects in serial RT tasks. Children’s response to sequential dependencies in this simple choice RT tasks may provide important insights into the changes that may occur in the flexibility and control of their cognitive systems (e.g., Zelazo et al., 2003).

In an early study, Fairweather (1978) observed that the size of the repetition effect was smaller in 11-year-olds compared to 6-year-olds. Likewise, in a series of studies, Kerr and colleagues consistently found a smaller repetition effect in adults than in 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 (Kerr, 1979; Kerr et al., 1980, 1982). Consistent with the theoretical framework devel-

1 Actually, a third type of sequential effect has been observed in addition to automatic facilitation and subjective expectancy. This sequential effect refers to residual fluctuations in the speed of responding that have been coined 1/f noise. This type of correlated noise has been encountered in a variety of experimental paradigms and has been observed to explain a considerable portion of the variance. Correlated noise is taken to be a signature of dynamic complexity, and its presence in psychological data has been associated with the dynamics of memory representation (cf. Gilden, 2001). To the best of our knowledge, 1/f noise has not been examined in developmental studies.
oped in adult studies (e.g., Kirby, 1980), 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 cor-
rect response that is particularly slow in children relative to adults (cf. Kerr et al., 1982).

More recently, 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. Higher order effects refer to changes in the speed of
responding on the current trial due to a sequence of previous trials (for reviews, see
Luce, 1986; Soetens, 1998). Like first-order effects, higher order sequential effects are
critically dependent on the time interval between successive trials. For short RSIs, the
typical result is a “benefit-only” pattern. That is, 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. This pattern is assumed to provide a higher order index
of automatic facilitation that, although residual processing traces are thought to decay
rapidly, may accumulate over time when RSIs are short (Soetens et al., 1984), producing
the benefit-only pattern. For long RSIs, in contrast, the usual finding is a “cost-benefit”
pattern, reflecting that the speed of responding is fast on the current trial for some
sequences but is slow for other sequences. The cost-benefit pattern is interpreted to
provide a higher order index of subjective expectancy, assuming that individuals expect
a continuation of runs of alternations or repetitions—the longer the run, the faster the
responses and the slower the responses when runs are interrupted (Soetens, 1998). The
pattern has also been found in functional magnetic resonance imaging (fMRI) studies
as a gradual change of activity in the anterior cingulate cortex and is assumed to reflect
conflict monitoring between expected and actual stimuli (Jones et al., 2002).

The adult pattern of results that emerged from the Soetens and Hueting (1992) 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- to 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 a higher order cost-benefit pattern for the 500 ms RSI that seemed to be less
pronounced in children than in adults. These preliminary findings were interpreted as
suggesting that automatic facilitation is stronger in children, whereas children’s subjec-
tive expectancy is weaker than that in adults. The current study presents the results
of two experiments designed to submit this hypothesis to a more stringent test by including more age groups, with each group consisting of a larger number of participants. The first experiment aimed at replicating the pattern of developmental change in first-order and higher order sequential effects observed previously by Soetens and Hueting (1992). The second experiment was designed to further assess the automatic facilitation hypothesis of the developmental decrease in the first-order repetition (Kerr et al., 1982) and higher order benefit-only pattern (Soetens & Hueting, 1992).

**EXPERIMENT 1**

The goal of Experiment 1 was to assess developmental trends in the strength of automatic facilitation and subjective expectancy. Three age groups participated in the experiment: a group of young adults (18-25 years), and two groups of children (7-9 years and 10-12 years). The participants performed a standard choice RT task with RSIs of 50 and 500 ms, similar to the task used by Soetens and Hueting (1992). Based on the pertinent literature just reviewed, we predicted that adults would show a first-order repetition effect and a higher order benefit-only pattern when the RSI is short, whereas they would show a first-order alternation effect and a cost-benefit pattern when the RSI is long (e.g., Soetens, 1990). Children were anticipated to show a stronger first-order repetition effect (Fairweather, 1978; Kerr et al., 1982) and a less pronounced first-order alternation effect (Soetens & Hueting, 1992). This pattern of results is indicative of a developmental decrease in the strength of the automatic facilitation mechanism and an increase in the strength of subjective expectancy mechanism. Accordingly, the higher order benefit-only pattern should decrease with advancing age, whereas the higher order cost-benefit pattern should reveal a developmental increase. In the current study, the analysis of higher order effects was restricted to second-order effects to increase the power of statistical tests.

**METHOD**

**Participants**

Participants were recruited from three age groups; one group consisted of 25 children between 7 and 9 years of age ($M = 8.2$ years, 7 girls and 18 boys), a second group consisted of 31 children between 10 and 12 years of age ($M = 11.5$ years, 15 girls and 16 boys), and a third group consisted of 35 adults between the ages of 18 and 25 years of age ($M = 20.0$ years, 32 females and 3 men). Preliminary analysis of the results using gender as a covariate indicated that gender did not systematically alter the sequential effects that emerged from this and the second experiment. Children were selected with the help of their teachers for average or above average school performance. They...
were reported to be healthy and participated with permission of their primary caregivers. The adults were recruited by flyers posted on the university campus and received credit points for their services. They reported to be healthy and not on medication.

**Apparatus and stimuli**

The experiment was run on 12- and 15-in. screen computers and laptops. A vertical black line was presented through the center of the screen against a white background. The stimuli were red circles with a diameter of 2 cm, presented 5 cm to the left or right of the vertical line. Participants responded to the stimuli by pressing the “z” key with their left index finger or pressing the right “/” key with their right index finger. These keys are on left and right of the bottom row of a ‘qwerty’ keyboard.

**Design and procedure**

Participants performed a serial RT task in which they made a binary response to stimuli that appeared to the left or right of the fixation line. Speed and accuracy of responding were recorded by the computer to the nearest millisecond. RT was recorded as the time between stimulus onset and the moment that one of the response keys was switched. Switching ended stimulus exposure and started RSI, which was fixed either at 50 or 500 ms. Error corrections were not allowed.

An experimental session consisted of 12 experimental blocks: six short RSI blocks (50 ms) and six long RSI blocks (500 ms). Each RSI condition started with a 50-trial practice block, followed by the six experimental blocks of 100 stimuli of the same RSI. Between blocks, there was a 30-s rest period. The first five trials in each experimental block were practice trials and were eliminated from statistical analyses. The order of RSI conditions was counterbalanced within each age group. Participants received an on-screen instruction before starting the experiment. Participants were instructed to respond as quickly and accurately as possible. Special care was taken to ensure that children understood the task instructions.

**Coding and selection of trial sequences**

A computer program searched through the list of trials, and at each trial, T<sub>n</sub> (n ranges from 6 to 100), the program determined for trials T<sub>n</sub>, T<sub>n-1</sub>, and T<sub>n-2</sub> whether the response was correct or incorrect and whether it was left or right. For correct responses, the program then decided whether the responses on T<sub>n</sub> and T<sub>n-1</sub> were the same (i.e., left followed by left or right followed by right) or different (i.e., left followed by right or right followed by left). When the responses were the same, the program generated an R code for trial T<sub>n</sub> (with R standing for repetition). When the responses were different, the program generated an A code for trial T<sub>n</sub> (with A standing for alternation). The R
and A codes were used for the analysis of first-order effects. In addition, the program determined whether the responses on trials \( T_{n-1} \) and \( T_{n-2} \) were the same or different. When they were the same, the program generates an R code for trial \( T_n \) that is preceding the code based on the comparison of trials \( T_n \) and \( T_{n-1} \); that is, RR when the latter comparison yielded an R code (for same responses) and RA when the latter comparison yielded an A code. Similarly, when the responses on trials \( T_n \) and \( T_{n-1} \) were different, the program generated an A code for \( T_n \) preceding the code based on the comparison of the responses on trials \( T_n \) and \( T_{n-1} \). These latter R and A codes were used for the analysis of second-order effects. The RR, RA, AR and AA codes represent the complete sequence consisting of the first- and second-order conditions under which the current RT resorts. The trial coding procedure is illustrated in Table 1. Finally, it should be noted that when the response on trial \( T_n \) was incorrect, the program moved to trial \( T_{n+3} \) and the same procedure was repeated.

An illustration of how (correct) trials contribute to the analysis of first- and second-order effects is presented in Table 2. The first column of the table refers to trial number. Recall that the five trials at the beginning of the trial block served as warm-up and, thus, were excluded from analysis. The second column presents the response that was given on a particular trial (left, right, or error response). The third column presents the first-order sequence codes generated for each trial (R or A). The fourth column presents the second-order codes (R or A). The fifth column shows the combination of first- and second-order sequence (RR, AR, AA or RA). Following trial coding, median RTs were computed for the RR, AR, AA and RA sequences for short and long RSI blocks separately. The resulting RTs were then analyzed using analysis of variance (ANOVA) that included two sequence factors; first-order sequence and second-order sequence. The first-order sequence factor consists of two levels: repetitions (i.e., the average of the median RTs

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<th>Second-order coding ( (T_{n-2} &gt; T_{n-1}) )</th>
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Note. R, repetition; A, alternation; T, trial; and n, trial number.
of the RR and AR sequences) and alternations (i.e., the average of the median RTs of the RA and AA sequences). The second-order sequence factor also consists of two levels: repetition sequences (i.e., the average of the median RTs of the RA and RR sequences) and alternation sequences (i.e., the average of the median RTs of the AR and AA sequences). Thus, each RT is used only once in one of the four combinations of first- and second-order effects. The only dependency inherent to the coding procedure was that an R or A that is used for coding the first-order sequence of trial $T_n$ was also used as an

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Sequential effects on speeded information processing

R or A for coding the second-order sequence of trial $T_{n+1}$. Because the order of trials was random, unwanted dependencies between RT measurements did not occur.

RESULTS AND DISCUSSION

In the short (50 ms) RSI condition, error rates were 6.8 %, 5.6 % and 5.3 % for young children (7-9 years), older children (10-12 years), and young adults (18-25 years), respectively. The corresponding values were 6.5 %, 5.7 %, and 5.1 % in the long (500 ms) RSI condition. Error rates correlated positively with mean RTs excluding a trade-off between speed and accuracy. Because error rates were infrequent, no further analysis was conducted.

Each trial block contained on average of 46.1 first-order repetitions and an equal number of first-order alternations. Each trial block contained on average 23.1 RTs for each combination of first-order and second-order sequences. Median RTs were then calculated for each trial ending a sequence and for each RSI, participant, and age group separately. The results are presented in Table 3. The RTs were subjected to an ANOVA with age group as a between-subjects factor and with RSI, first-order sequences, and second-order sequences as within-subjects factors. The ANOVA yielded a highly significant main effect of age, $F(2, 88) = 35.85, p < .001$. Adults responded faster ($M = 349$ ms) than did both older ($M = 433$ ms) and young children ($M = 481$ ms). Follow-up tests indicated that each age group differed significantly from the other ($ps < .001$ between adults and the two child groups and $p < .016$ between the two child groups).

Responses were faster following a long RSI ($M = 395$ ms) than following a short RSI ($M = 447$ ms), $F(1, 88) = 77.10, p < .001$. The two remaining main effects also reached significance: first-order effects, $F(1, 88) = 33.71, p < .001$, and second-order effects, $F(1, 88) = 32.86, p < .001$.

The ANOVA yielded a significant four-way interaction among age group, RSI, first-order effects, and second-order effects, $F(2, 88) = 6.71, p < .002$. The sequential effects for each age group are plotted in Figure 1, with first-order effects shown in Figure 1 (a) and second-order effects shown in Figure 1 (b). In Figure 1 (a), it can be seen that the repetition effect decreases with age for the short RSI and that children show a repetition effect where adults demonstrate an alternation benefit for the long RSI. In Figure 1 (b), a developmental decrease can be observed in both the benefit-only pattern associated with the short RSI and the cost-benefit pattern associated with the long RSI. These visual impressions were statistically verified by subsequent analyses done separately for the short and long RSI.
The ANOVA done for the short RSI condition yielded a significant main effect of first-order repetition, $F(1, 88) = 33.01, p < .001$. As shown in Figure 1 (a), RTs for sequences ending with a repetition are shorter than those for sequences ending with an alternation. Subsequent analyses indicated that for all three age groups, responses were faster on repetitions than on alternations: adults, $F(1, 34) = 5.12, p < .03$, older children, $F(1, 30) = 13.15, p < .001$, and young children, $F(1, 24) = 12.83, p < .002$. But the first-order repetition effect was qualified by a significant interaction with age group, $F(2, 88) = 3.47, p < .036$. That is, the magnitude of the first-order repetition effect decreased with advancing age. More specifically, follow-up analyses indicated that the first-order repetition effect discriminated significantly between the child groups and adults: young children versus adults, $F(1, 58) = 6.07, p < .017$, and older children versus adults, $F(1, 64) = 6.05, p < .017$. The two child groups did not differ in this regard ($p > .88$).

The second-order effect revealed the typical benefit-only pattern and was highly significant, $F(1, 88) = 140.92, p < .001$. As anticipated, the magnitude of the second-order effect decreased with advancing age, $F(2, 88) = 3.99, p < .022$. Follow-up analyses revealed that the benefit-only pattern discriminated between the youngest children and adults, $F(1, 58) = 6.43, p < .014$. The adults did not differ from the older children ($p > .29$), and the two child groups did not differ from each other ($p > .14$).

| Table 3. Mean RTs and standard deviations (in milliseconds) for each transition sequence (first-order and higher order) and RSI condition observed for each age group in Experiment 1. |
|---------------------------------|---------------------------------|---------------------------------|
|                                | 7-9 years                       | 10-12 years                     | 18-25 years                     |
|                                | M      | SD    | M      | SD    | M      | SD    |
| 50 ms RSI                       |        |       |        |       |        |       |
| RR                              | 446    | 85    | 429    | 85    | 348    | 85    |
| AR                              | 501    | 88    | 455    | 88    | 384    | 88    |
| RA                              | 502    | 76    | 472    | 76    | 370    | 76    |
| AA                              | 545    | 85    | 518    | 85    | 392    | 85    |
| First-order Repetition          | 473    | 85    | 442    | 85    | 366    | 80    |
| First-order Alternation         | 523    | 77    | 495    | 77    | 381    | 73    |
| 500 ms RSI                      |        |       |        |       |        |       |
| RR                              | 426    | 67    | 371    | 67    | 313    | 67    |
| AR                              | 460    | 65    | 403    | 65    | 341    | 65    |
| RA                              | 522    | 65    | 443    | 65    | 341    | 65    |
| AA                              | 445    | 69    | 376    | 69    | 303    | 69    |
| First-order Repetition          | 443    | 64    | 387    | 64    | 327    | 60    |
| First-order Alternation         | 483    | 64    | 410    | 65    | 322    | 61    |

Note. R, repetition; A, alternation.

50-ms RSI

The ANOVA done for the short RSI condition yielded a significant main effect of first-order repetition, $F(1, 88) = 33.01, p < .001$. As shown in Figure 1 (a), RTs for sequences ending with a repetition are shorter than those for sequences ending with an alternation. Subsequent analyses indicated that for all three age groups, responses were faster on repetitions than on alternations: adults, $F(1, 34) = 5.12, p < .03$, older children, $F(1, 30) = 13.15, p < .001$, and young children, $F(1, 24) = 12.83, p < .002$. But the first-order repetition effect was qualified by a significant interaction with age group, $F(2, 88) = 3.47, p < .036$. That is, the magnitude of the first-order repetition effect decreased with advancing age. More specifically, follow-up analyses indicated that the first-order repetition effect discriminated significantly between the child groups and adults: young children versus adults, $F(1, 58) = 6.07, p < .017$, and older children versus adults, $F(1, 64) = 6.05, p < .017$. The two child groups did not differ in this regard ($p > .88$).

The second-order effect revealed the typical benefit-only pattern and was highly significant, $F(1, 88) = 140.92, p < .001$. As anticipated, the magnitude of the second-order effect decreased with advancing age, $F(2, 88) = 3.99, p < .022$. Follow-up analyses revealed that the benefit-only pattern discriminated between the youngest children and adults, $F(1, 58) = 6.43, p < .014$. The adults did not differ from the older children ($p > .29$), and the two child groups did not differ from each other ($p > .14$).
In sum, the current findings yielded the typical pattern of automatic facilitation reported previously by studies of sequential effects (e.g., Kirby, 1980; Luce, 1986). Automatic facilitation is indexed by a first-order repetition effect and a second-order benefit-only effect. Most importantly, the current findings agree with the preliminary
results reported by Soetens and Hueting (1992) by showing an age-related decrease in automatic facilitation. More specifically, the age-related decrease in the first-order repetition effect is in line with the findings of previous developmental studies of first-order sequential effects (Fairweather, 1978; Kerr, 1979). The results that emerged from the current experiment add to this literature by showing a developmental trend in the second-order index of automatic facilitation.

**500-ms RSI**

The ANOVA performed on the data obtained using the long RSI showed a significant interaction between the first-order effect and age group, $F(2, 88) = 7.56, p < .001$. Subsequent analyses yielded a significant first-order repetition effect (see Figure 1 (a)) for both the young children and older children, $F(1, 24) = 16.81, p < .001$, and $F(1, 30) = 4.91, p < .034$, respectively. Both the young children and older children differed from adults, $F(1, 58) = 20.89, p < .001$, and $F(1, 64) = 6.60, p < .013$, respectively. The two child groups did not differ from each other ($p > .25$). Contrary to expectations, the first-order effect did not reach significance for adults ($p > .28$). We return to this issue later.

The ANOVA revealed also a significant first-order by second-order interaction, $F(1, 88) = 266.14, p < .001$. The first-order by second-order interaction was altered by age group, $F(2, 88) = 6.00, p < .004$. Both young children and older children differed from adults, $F(1, 58) = 10.23, p < .002$, and $F(1, 64) = 8.69, p < .004$, respectively. The two child groups did not differ from each other ($p > .46$).

In sum, it was anticipated that adults would show a first-order alternation effect and a second-order cost-benefit pattern. Consistent with previous reports (e.g., Melis, Soetens, & van der Molen, 2002; Soetens, 1998; Soetens et al., 1985), the current findings yielded the second-order cost-benefit pattern, but the anticipated first-order alternation effect was not significant. In addition, based on the preliminary study reported by Soetens and Hueting (1992), it was anticipated that the cost-benefit pattern would become more prominent with advancing age. In contrast to this prediction, however, the cost-benefit pattern was more pronounced for the child groups relative to the adult participants.

Design differences may have contributed to the apparent divergence between the current findings and the results reported previously by Soetens and colleagues. In the experiments reported by Soetens and colleagues, RSI was a between-subjects manipulation (e.g., Soetens et al., 1985; Soetens & Hueting, 1992), whereas in the current experiments, RSI was a within-subjects manipulation. To assess the potential effect of this design difference, the overall ANOVA was repeated with RSI order (i.e., 50-ms RSI
Sequential effects on speeded information processing

first and 500-ms RSI second versus 500-ms RSI first and 50-ms RSI second) as a between-subjects factor. The only significant interaction that included RSI order was among RSI order, first-order effect, RSI, and age group, $F(2, 85) = 3.77, p < .027$. Follow-up analyses indicated that RSI order changed the pattern of effects obtained for the long RSI but not for the short RSI, $F(2, 85) = 3.30, p < .042$. The interaction between RSI order and first-order effect was significant only for the long RSI, $F(1, 33) = 9.27, p < .027$. When the long RSI condition preceded the short RSI condition, adults demonstrated a significant first-order alternation effect, $F(1, 16) = 9.04, p < .008$, that was absent when RSI order was reversed. In conclusion, the results that emerged from the first experiment were in accord with expectations except for the age-related decrease in the second-order cost-benefit pattern. One of the goals of the second experiment was to assess the reliability of this age-related difference.

**EXPERIMENT 2**

The primary goal of Experiment 2 was to further assess the developmental change in automatic facilitation by manipulating central processing time. The results of Experiment 1 indicated that the strength of automatic facilitation decreased with advancing age. The predominant interpretation of automatic facilitation is that the effect consists of some sort of residual trace that is left by previous 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. Studies examining the locus of automatic facilitation in the chain of the reaction process suggest that repetition effects occur at virtually all processing stages—from stimulus identification to response programming (Rabbitt & Vyas, 1973). Simulations showing that automatic facilitation affects all processing stages indiscriminately are consistent with the experimental findings (Soetens et al., 1984). More recent evidence indicates that automatic facilitation exerts its strongest effect on the processing stage that is most time consuming for a particular task (Soetens, 1998). This observation is consistent with Kirby’s (1980) conclusion from a review of sequential effects in standard choice reaction tasks, that automatic facilitation pertains primarily to central processes involved in S-R translation rather than peripheral stimulus identification and response execution processes. Indeed, several studies complicating the response choice process by manipulating S-R compatibility yielded stronger facilitation effects on incompatible trials relative to compatible trials (e.g., Soetens, 1998; Soetens et al., 1985).

In providing an explanation for the developmental decrease in automatic facilitation, Kerr et al. (1982) submitted the hypothesis that the stronger repetition effect that they observed for children was due to the children’s protracted central processing times.
More specifically, these authors assumed that short-cutting of central processing on repetition trials is more beneficial in children than in adults due to longer central processing times in children. Although it seems difficult to distinguish between “trace” and “bypassing” interpretations (cf. Luce, 1986), the important point here is that Kerr and colleagues assumed a central locus of the age-related change in automatic facilitation. When it is further assumed that, in standard choice reaction tasks, automatic facilitation affects response choice rather than stimulus identification or response execution (Kirby, 1980), it can be predicted that the effects of age and manipulations of response choice should interact in their contribution to automatic facilitation.

This prediction was tested in Experiment 2 by manipulating spatial S-R compatibility. The time needed to respond to a spatially incompatible stimulus (e.g., a right-hand response to a stimulus left from central fixation) is typically longer than the time required to respond to a spatially compatible response (e.g., a right-hand response to a stimulus right of central fixation) (for a review, see Hommel & Prinz, 1997). Most investigators agree in interpreting the S-R compatibility in terms of response choice (e.g., Kornblum et al., 1990; Sanders, 1990). The results emerging from the spatial S-R compatibility manipulation in Experiment 2 should reveal a developmental decrease in automatic facilitation that is more pronounced for spatial incompatible S-R mappings than for spatial compatible S-R mappings. A secondary goal of Experiment 2 was to assess the reliability of the age-related decrease in the cost-benefit pattern that, unexpectedly, was observed in Experiment 1. As in Experiment 1, three age groups participated in Experiment 2. The youngest group and adults had approximately the same age as in Experiment 1 - 8 years and between 18 and 25 years, respectively. But the intermediate group in Experiment 2 was older than in Experiment 1 - 15 years versus 12 years. This was done, deliberately to obtain one more data point along the age span.

**METHOD**

**Participants**

Participants were recruited from three age groups: 32 young adults between the ages of 18 and 25 year of age ($M = 22.2$ years, 21 women and 11 men), 29 high-school students 15 or 16 years of age ($M = 15.3$ years, 13 girls and 16 boys), and 21 children from primary school between 7 and 9 years of age ($M = 7.7$ years, 9 girls and 12 boys). Children and adolescents were selected with the help of their teachers for average or above average school performance. The children were reported to be healthy and participated with permission of their primary caregivers. The adults were recruited by flyers posted on the university campus and received credit points for their services. The adolescents and adults reported to be healthy and not on medication.
Apparatus and stimuli
The experiment was run on 12- and 15-in. screen computers. A vertical, black line was presented through the center of the screen against a white background. The stimuli, colored circles or triangles, were presented 5 cm to the left or right from the vertical line at a distance of 5 cm and measured 2 cm wide and high. Participants responded to the stimuli by pressing the “z” key with their left-index finger or pressing the “/” key with their right-index finger. These keys are located on the bottom row of a ‘qwerty’ keyboard.

Design and procedure
RT was recorded as the time between stimulus onset and the moment that one of the response keys was switched. The stimulus was response terminated. The response initiated the RSI, which was fixed either at 50 or 500 ms. Participants performed in both RSI conditions and were randomly assigned to the compatible task (i.e., the left stimulus mapped onto the left response and the right stimulus mapped onto the right response) or to the incompatible task (i.e., left stimulus mapped onto the right response or the right stimulus onto the left response).

An experimental session consisted of 20 experimental blocks (10 short RSI blocks and 10 long RSI blocks), each with 105 stimuli. The experimental session started with a 50 trial practice block with the long RSI. The first five trials in each experimental block were practice trials and were eliminated from statistical analyses. Between blocks, there was a 30-s rest period. A white screen and the upcoming vertical line initiated a new block. The order of short RSI blocks versus long RSI blocks was counterbalanced within each age group. Participants received an on-screen instruction before starting the experiment. They were asked to respond quickly and to avoid errors. All other experimental details were identical to Experiment 1.

RESULTS AND DISCUSSION
Error rate decreased with age (10.2, 10.1 and 7.1% for children, adolescents and young adults, respectively), \( F (2, 232) = 13.64, p < .001 \). Errors were less frequent in the compatible condition (8.2%) than in the incompatible condition (8.9%), \( F (2, 232) = 5.24, p < .006 \). In all conditions, error rate correlated positively with RT across sequences, indicating no trade-off between speed and accuracy. Sequences containing an error were eliminated from further statistical analyses.

Median RTs were calculated as in the first experiment, and the RTs for each combination of age group by RSI by task by sequence are presented in Table 4. The RTs were submit-
Chapter 2

Table 4. Mean RTs and standard deviations (in milliseconds) for each transition sequence (first-order and higher order), task and RSI condition observed for each age group in Experiment 2.

<table>
<thead>
<tr>
<th></th>
<th>7-9 years</th>
<th></th>
<th>15-16 years</th>
<th></th>
<th>18-25 years</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Compatible</td>
<td>Incompatible</td>
<td>Compatible</td>
<td>Incompatible</td>
<td>Compatible</td>
</tr>
<tr>
<td></td>
<td>M</td>
<td>SO</td>
<td>M</td>
<td>SO</td>
<td>M</td>
</tr>
<tr>
<td>50-ms RSI RR</td>
<td>417</td>
<td>56</td>
<td>404</td>
<td>61</td>
<td>324</td>
</tr>
<tr>
<td>RA</td>
<td>472</td>
<td>68</td>
<td>456</td>
<td>74</td>
<td>347</td>
</tr>
<tr>
<td>AA</td>
<td>526</td>
<td>76</td>
<td>578</td>
<td>83</td>
<td>365</td>
</tr>
<tr>
<td>First-order</td>
<td>582</td>
<td>109</td>
<td>679</td>
<td>118</td>
<td>412</td>
</tr>
<tr>
<td>Repetition</td>
<td>444</td>
<td>61</td>
<td>430</td>
<td>66</td>
<td>335</td>
</tr>
<tr>
<td>First-order</td>
<td>554</td>
<td>87</td>
<td>629</td>
<td>95</td>
<td>388</td>
</tr>
<tr>
<td>Alternation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>500-ms RSI RR</td>
<td>376</td>
<td>42</td>
<td>419</td>
<td>45</td>
<td>281</td>
</tr>
<tr>
<td>AR</td>
<td>444</td>
<td>54</td>
<td>471</td>
<td>59</td>
<td>305</td>
</tr>
<tr>
<td>RA</td>
<td>519</td>
<td>53</td>
<td>595</td>
<td>56</td>
<td>318</td>
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<tr>
<td>AA</td>
<td>436</td>
<td>69</td>
<td>561</td>
<td>75</td>
<td>273</td>
</tr>
<tr>
<td>First-order</td>
<td>410</td>
<td>46</td>
<td>445</td>
<td>50</td>
<td>293</td>
</tr>
<tr>
<td>Repetition</td>
<td>478</td>
<td>57</td>
<td>578</td>
<td>62</td>
<td>296</td>
</tr>
<tr>
<td>First-order</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alternation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note. R, repetition; A, alternation.

ted to an ANOVA with age group (3) and task (2) as between-subjects factors, and RSI (2), first-order sequence (2), and second-order sequence (2) as within-subjects factors. The ANOVA yielded a highly significant main effect of age group, $F(2, 76) = 132.41, p < .001$. RT decreased with advancing age: 496, 329, and 291 ms for children, adolescents, and young adults, respectively. Follow-up analysis indicated that adults and adolescents responded significantly faster than children ($p_s < .001$) and that adults responded faster than adolescents ($p < .006$). Participants responded faster when the stimulus required a compatible response ($M = 359$ ms) than when it required an incompatible response ($M = 385$ ms), $F(1, 76) = 6.82, p < .011$. Responses were faster following the long RSI than following the short RSI ($Ms = 352$ and 393 ms, respectively), $F(1, 76) = 61.25, p < .001$. Finally, both the first-order effect and the second-order effect reached significance, $F(1, 76) = 249.53, p < .001$, and $F(1, 76) = 80.10, p < .001$, respectively. All main effects were involved in a complex five-way interaction, $F(2, 76) = 4.37, p < .016$.

The first-order effects are plotted in Figure 2 (a), showing a developmental decrease in the first-order repetition effect associated with the short RSI. The developmental de-
Sequential effects on speeded information processing

**Figure 2 (a).** First-order sequential effects observed for each age group in both RSI and S-R compatibility conditions in Experiment 2. RT differences between first-order alternations and repetitions are plotted. A positive difference indicates a repetition effect; whereas a negative difference indicates an alternation effect. C denotes compatible S-R task; I, incompatible S-R task; and yrs, years.

**Figure 2 (b).** Second-order sequential effects for each age group, RSI condition, and task condition. RT differences between second-order AR versus RR and AA versus RA sequences are plotted. Two positive differences indicate a higher order benefit-only pattern, whereas a positive AR/RR difference and a negative AA/RA difference indicate a higher order cost-benefit pattern. C denotes compatible S-R task; I, incompatible S-R task; and yrs, years.
crease in the repetition effect is more pronounced when the task requires an incompatible response than when it requires a compatible response. In addition, it can be seen that S-R compatibility alters the first-order effect associated with the long RSI. In adults, the need to execute an incompatible response changes the alternation effect into a repetition effect, whereas in children, incompatibility induces a stronger repetition effect. The second-order effects are plotted in Figure 2 (b), showing a developmental decrease in the benefit-only pattern that seems more pronounced for the incompatible task than for the compatible task. S-R compatibility does not seem to systematically influence developmental change in the cost-benefit patterns. Subsequent analyses were done for short and long RSIs separately so as to break down the complex interaction.

50-ms RSI

The ANOVA for the short RSI condition yielded a significant first-order repetition effect, $F(1, 76) = 173.93, p < .001$, that was qualified by interactions with task, $F(1, 76) = 14.79, p < .001$, and age group, $F(2, 76) = 21.54, p < .001$. The repetition effect was more pronounced for incompatible responses than for compatible responses: 115 and 64 ms, respectively. Consistent with the results of the first experiment, the repetition effect decreased with advancing age: 154, 69, and 45 ms in children, adolescents, and adults, respectively. The repetition effect discriminated between children and adults, $F(1, 48) = 13.71, p < .001$, and between children and adolescents, $F(1, 51) = 30.70, p < .001$, but not between adolescents and adults ($p > .06$). Contrary to predictions, the effects of age group and task did not interact in their contribution to the size of the repetition effect, $F(2, 76) = 0.85, p = .43$.

There was a significant higher order interaction that included second-order sequence, age group, and task, $F(2, 76) = 5.01, p < .009$. The interaction between second-order sequence and task reached significance in each age group, $F(1, 19) = 6.76, p < .014$, $F(1, 27) = 5.37, p < .032$, and $F(1, 30) = 4.59, p < .041$, for children, adolescents and adults, respectively. In Figure 2 (b), it can be seen that all age groups showed the typical benefit-only pattern. As in the first experiment, this pattern was more pronounced in children than in adolescents, $F(1, 51) = 10.48, p < .002$, and in adults, $F(1, 48) = 4.70, p < .035$, respectively. Adolescents and adults did not differ in this respect ($p > .19$). Most importantly, this age-related trend is stronger for incompatible reactions than for compatible reactions, $F(2, 76) = 6.54, p < .002$.

In sum, the age-related pattern in first-order and second-order effects obtained using a short RSI are consistent with the results from Experiment 1—a developmental decrease
in the first-order repetition effect and second-order benefit-only pattern.\textsuperscript{2} Moreover, the results are also consistent with previous findings showing a stronger repetition effect and a more pronounced benefit-only pattern for incompatible S-R mapping than for compatible S-R mappings (Bertelson, 1963; Soetens et al., 1985). As predicted, the developmental decrease in the benefit-only pattern was more prominent on incompatible trials than on compatible trials, but contrary to expectations, the interaction between age group and task failed to reach significance for the first-order repetition effect.

\textbf{500-ms RSI}

The ANOVA done for the long RSI condition yielded a significant first-order repetition effect, $F(1, 76) = 121.61, p < .001$, but this effect was qualified by task, $F(1, 76) = 25.02, p < .001$, and age group, $F(2, 76) = 59.40, p < .001$, and the higher order interaction of these effects, $F(2, 76) = 3.44, p < .037$. Follow-up analyses indicated that the first-order repetition effect reached significance in children for compatible reactions, $F(1, 10) = 24.21, p < .001$, and reached significance in all three age groups for incompatible reactions: children, $F(1, 15) = 12.05, p < .003$, adolescents, $F(1, 14) = 8.78, p < .010$, and adults, $F(1, 9) = 79.20, p < .001$. The first-order repetition effect for children and adolescents were significantly stronger in the incompatible condition than in the compatible condition, $F(1, 19) = 18.33, p < .005$, and $F(1, 27) = 4.81, p < .037$, respectively.

The second-order effect failed to reach significance, $F(1, 76) = .52, p = .47$, but there was a significant interaction between first-order and second-order effects, $F(1, 76) = 150.51, p < .001$. Age group altered the interaction between first-order and second-order effects, $F(2, 76) = 5.62, p < .005$. Children differed from both adults, $F(1, 25) = 10.62, p < .003$, and adolescents, $F(1, 23) = 7.32, p < .013$, but the latter groups did not differ from each other ($p = .81$). It should be noted, that the higher order interaction that included task failed to reach an acceptable level of significance, $F(2, 76) = 2.15, p = .12$.

In sum, the current findings replicate the results of the first experiment in showing an age-related decrease in the first-order repetition effect and in the cost-benefit pattern associated with the long RSI. The consistency across experiments was examined further by performing an ANOVA that included “experiment” as an additional between-subjects

\textsuperscript{2} An analysis examining the effects of RSI order revealed that, in contrast to the results obtained in Experiment 1, the first-order repetition effect was not altered by RSI order. A design difference between the current experiments and the experiments reported previously by Soetens (e.g., Soetens et al., 1985; Soetens & Hueting, 1992) does not provide a satisfactory account of why the current experiments fail to produce a significant first-order alternation effect in adults.
factor. The between-subjects factor age group included only the two levels that were comparable between experiments (i.e., young children versus adults) and only compatible RTs were included. The ANOVA yielded a main effect of Experiment, $F(1, 83) = 9.95, p < .002$, that was qualified by an interaction with age group, $F(1, 83) = 5.89, p < .017$. The adults in Experiment 1 responded considerably slower than the adults in the second experiment (349 ms versus 277 ms, respectively), $F(1, 49) = 24.75, p < .001$. The child groups did not differ between experiments, $p > .69$. The only remaining interaction that included Experiment and reached significance was among experiment, age group, and first-order repetition, $F(1, 83) = 4.70, p < .033$. The repetition effect was stronger for the child group in Experiment 1 than in the children participating in the second experiment (54 versus 88 ms). The adult groups did not differ in this respect. Overall, the outcome of this analysis demonstrated considerable consistency across experiments.

Finally, the developmental trends that emerged from the two experiments are presented in Table 5. The table presents the first-order and second-order effects for the four age groups participating in the current study. The data of the two groups of youngest children and the two groups of adults were averaged across experiments. As can be seen, most of the age-related change in sequential effects seems to occur during childhood, with little change occurring from adolescence into adulthood.

**Table 5.** Developmental trends across Experiments 1 and 2: Mean RT differences for first-order and second-order effects (in milliseconds) as a function of RSI (50 versus 500 ms) for young children (7-9 years, averaged across experiments), older children (10-12 years, Experiment 1), adolescents (15-16 years, Experiment 2) and adults (averaged across experiments).

<table>
<thead>
<tr>
<th>Age group</th>
<th>7-9 years</th>
<th>10-12 years</th>
<th>15-16 years</th>
<th>18-25 years</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>A</td>
<td>B</td>
<td>C</td>
<td>D</td>
</tr>
<tr>
<td>50 ms RSI</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>First-order effect</td>
<td>79.7</td>
<td>53.1</td>
<td>53.0</td>
<td>21.6</td>
</tr>
<tr>
<td>(A-R)</td>
<td>CD</td>
<td>D</td>
<td>A</td>
<td>A</td>
</tr>
<tr>
<td>Second-order effect</td>
<td>56.6 / 49.3</td>
<td>26.4 / 46.3</td>
<td>22.3 / 47.5</td>
<td>34.7 / 25.3</td>
</tr>
<tr>
<td>(AR-RR / AA-RA)</td>
<td>CD</td>
<td>D</td>
<td>A</td>
<td>A</td>
</tr>
<tr>
<td>500 ms RSI</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>First-order effect</td>
<td>54.4</td>
<td>23.2</td>
<td>2.3</td>
<td>-4.3</td>
</tr>
<tr>
<td>(A-R)</td>
<td>CD</td>
<td>D</td>
<td>A</td>
<td>A</td>
</tr>
<tr>
<td>Second-order effect</td>
<td>51.1 / -80.3</td>
<td>32.0 / -66.6</td>
<td>24.1 / -45.5</td>
<td>27.3 / -38.5</td>
</tr>
<tr>
<td>(AR-RR / AA-RA)</td>
<td>CD</td>
<td>D</td>
<td>A</td>
<td>A</td>
</tr>
</tbody>
</table>

*Note. R, repetition; A, alternation. Significant differences between age groups are indicated by letters. Thus, the first-order repetition effect observed for the youngest children (Group A) differs significantly from the repetition effect observed for both the adolescents (Group C) and adults (Group D). This is indicated by the C/D superscript following the value of the repetition effect observed for the youngest children.*
GENERAL DISCUSSION

The primary goal of the current study was to examine developmental trends in sequential effects on the speed of responding. The results obtained for adult participants will be used to provide a context for discussing age-related changes in sequential effects. The adult findings are consistent with earlier studies in two ways. First, adults show a first-order repetition effect when the RSI is short, and it changes towards an alternation effect when the RSI is long. Second, adults show a second-order benefit-only pattern when the RSI is short, whereas they show a cost-benefit pattern when the RSI is long (e.g., Melis et al., 2002; Soetens et al., 1984).

The repetition effect and the benefit-only pattern have been taken as manifestations of automatic facilitation (e.g., Soetens et al., 1985). The predominant interpretation of automatic association assumes that its beneficial effect results from residual processing traces of previous S-R cycles (e.g., Kirby, 1976). The effect is assumed to decay rapidly, but when RSIs are very short, it has probably not faded out completely when the next stimulus arrives, giving rise to a benefit-only pattern. The alternation effect and the cost-benefit pattern have been interpreted to index subjective expectancy (e.g., Soetens et al., 1985). Subjective expectancy is conceived of as a tendency to expect particular events even when this is completely irrational, as in the case of a random serial presentation of stimuli. Thus, the first-order alternation effect has been explained by assuming that in a random series of stimuli, participants expect too many alternations, a situation that is similar to the gambler’s fallacy (Wagenaar, 1972). The cost-benefit pattern is then interpreted by assuming that individuals use their (irrational) expectations to prepare for the upcoming event. Thus, a run of alternations induces a strong expectancy for another alternation; when the next stimulus happens to be an alternation, the response is fast, but when the next stimulus is a repetition, the response is slow. Likewise, a run of repetitions induces expectancy for another repetition; when the expected repetition does indeed occur, the response is fast, but when the next stimulus is an alternation, the response is slow (e.g., Luce, 1986).

The current study also replicates the findings in the adult literature concerning the influence of S-R compatibility on sequential effects. The cost of making a spatially incompatible response to the stimulus changes the first-order alternation effect into a repetition effect and shifts the higher order cost-benefit pattern to a benefit-only pattern, depending on the exact duration of the RSI (for a review, see Soetens, 1990). In line with the literature, a repetition effect occurred in the long RSI condition when adult participants were required to make an incompatible response. Moreover, the repetition effect observed in the short RSI condition increased for incompatible S-R mapping.
relative to compatible S-R mappings. Likewise, the benefit-only pattern observed in the short RSI condition was more pronounced for spatially incompatible responses than for spatial compatible responses, but the cost-benefit pattern observed in the long RSI condition was not influenced by S-R compatibility. Similar patterns of results reported in the adult literature of sequential effects have been interpreted to suggest that the beneficial effect of automatic facilitation increases with greater task demands on the response choice stage of the choice reaction process (e.g., Soetens et al., 1985; Soetens, 1998).

The adult framework provides a reasonable fit of the developmental findings that emerged from the current experiments. For the short RSI, the results of both experiments showed an age-related decrease in the first-order repetition effect and in the second-order benefit-only pattern. The age-related decrease in the repetition effect is consistent with the early studies reported by Fairweather (1978) and (Kerr, 1979) (see also Kerr et al., 1980, 1982), and the age-related decrease in the benefit-only pattern is consistent with the preliminary findings obtained by Soetens and Hueting (1992). Thus, both first-order and second-order indexes of automatic facilitation point to a developmental decrease of the beneficial effect of residual S-R traces on the speed of responding.

This interpretation must be qualified, however, in view of the results that emerged from the S-R compatibility manipulation in Experiment 2. This manipulation was inspired by the recurrent finding that the repetition effect is more pronounced for incompatible responses than for compatible responses, suggesting that automatic facilitation is more beneficial when the task demands on S-R processing are higher (e.g., see reviews in Luce, 1986; Soetens, 1998; Soetens et al., 1985). This finding, and the observation supported by the present findings that the repetition effect decreases with advancing age, led us to predict an interaction between the effects of age group and S-R compatibility in their contribution to automatic facilitation. This prediction received only partial support. Consistent with the prediction, the results of the second experiment showed a developmental decrease in the second-order benefit-only pattern that was more prominent for incompatible responses than for compatible responses. But the first-order repetition effect showed an additive pattern of the effects of age group and S-R compatibility rather than the anticipated interaction. The S-R compatibility findings present a challenge to interpretations assuming that first-order and second-order effects obtained using a short RSI are mediated by a single mechanism.

The sequential effects literature has reported several instances of a dissociation between first-order and second-order effects on speeded responding on tasks using short RSIs.
An early illustration came from studies examining the interaction between practice and sequential effects on speeded responding (Soetens et al., 1985; Vervaeck & Boer, 1980). These studies indicated that, in young adults, practice reduces the higher order benefit-only pattern while leaving the repetition effect intact. Similarly, a more recent cognitive aging study showed a clear second-order benefit-only pattern in the elderly, whereas the first-order repetition effect was absent in this age group (Melis et al., 2002). These findings have been interpreted to suggest that first-order and second-order effects are mediated by separate mechanisms. More specifically, it is assumed that the first-order repetition effect is mediated by a kind of low-level mechanism that is rapidly to decay (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 monitoring mechanism (e.g., Kirby, 1980; Soetens, 1998). The former mechanism involves residual activation for a particular S-R trace that is especially beneficial when S-R translation is difficult (e.g., in children versus adults) or nonroutine (e.g., in tasks with complex S-R mappings) (Soetens, 1998; Soetens et al., 1985). The latter mechanism, initially proposed by Kirby (1980), is thought to consist of “response monitoring”; that is, the actual response executed on a particular trial is compared with the one required on that trial so as to ensure the desired performance level.

The notion of response monitoring received considerable support by 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. The current findings, showing a more prominent benefit-only pattern in young children than in adults and for incompatible responses than to compatible responses, are consistent with the recent brain imaging literature, suggesting a maturational course of performance monitoring and the brain circuitry on which it relies (e.g., Fernandez-Duque, Baird, & Posner, 2000) and increased demands on performance monitoring in conflict tasks (Bush, Luu, & Posner, 2000).

At this point, it is difficult to provide a unified account of the current pattern of first-order repetition effects. The observation that the repetition effect is altered by S-R compatibility is consistent with the idea that the first-order repetition effect is mediated by some sort of priming (e.g., Cho et al., 2002) that is more beneficial when task demands on response choice processing are high (e.g., Melis et al., 2002; Soetens, 1998). In addition, the developmental decrease in response repetition is consistent with the priming notion when it is assumed that the beneficial effect of priming is proportional.
to the duration of response choice processing (e.g., Kerr et al., 1980, 1982). However, the finding that age group and S-R compatibility exert additive effects on first-order repetition is not easy to reconcile with a unitary priming notion; the additive effects seem to point to multiple mechanisms rather than to a single priming mechanism. Replication of the current data pattern is required before accepting multiple priming mechanisms.

Turning now to the long RSI, the current findings replicated the pattern of results reported previously by Kerr and colleagues (Kerr et al., 1980, 1982). With the lengthening of the RSI, the repetition effect changed into an alternation effect in adults but not in children. This finding can be taken to suggest a developmental increase in subjective expectancy. In contrast, the second-order index of subjective expectancy suggests a developmental decrease in subjective expectancy by showing an age-related reduction in the cost-benefit pattern. At this point, however, it should be noted that the first-order and second-order indexes of subjective expectancies refer to different mechanisms. The prevalent interpretation of the first-order index of subjective expectancy—the alternation effect—refers to the gambler’s fallacy, that is, the tendency to expect more alternations than repetitions in a series of events (e.g., Jarvik, 1951). The higher order index of subjective expectancy—the cost-benefit pattern—has received a different interpretation in the sequential effects literature. Soetens et al. (1985) took the cost-benefit pattern to suggest that individuals expect runs of trials—either repetitions or alternations—to continue. Therefore, the current findings suggest that children, with advancing age, fall victim to the gambler’s fallacy. This interpretation received support from early probability learning studies demonstrating that the contribution of the gambler’s fallacy in predicting upcoming events increased during childhood (e.g., Derks & Paclicanu, 1967). Additional support comes from recent studies examining developmental change in random number generation. When adults are required to generate random numbers, they exhibit a strong tendency to avoid repetitions (Kareev, 1992; van der Linden, Beerten, & Pesenti, 1998; but see Nickerson, 2002). The tendency to favor alternations in random number generation is less pronounced in children (Towse & McLachlan, 1999).

Finally, adopting the Soetens and colleagues’ (1985) interpretation of the cost-benefit pattern, the current findings seem to suggest a developmental decrease in subjective expectancy. This interpretation is not very likely, however, in view of the early literature on probability learning indicating that children’s predictions are local, whereas adults attempt to base their predictions on higher order sequences, true or false (Crandall, Solomon, & Kellaway, 1961; Offenbach, 1965; Sullivan & Ross, 1970). An alternative interpretation assumes that the ability to switch responses contributes importantly to the cost-benefit pattern. Switching from the predicted response to the alternate
response takes time (e.g., Logan, 1994), and it has been observed that the inhibition of the activated response takes more time in children than adults (van den Wildenberg & van der Molen, 2004; Williams, Ponesse, Schacher, Logan, & Tannock, 1999) and the activation of the alternate response is particularly time-consuming in children relative to adults (Band et al., 2000).

In conclusion, the results of the two current experiments replicated the findings reported previously in the adult literature on sequential effects. For the short RSI, adults demonstrated the typical repetition effect and the benefit-only pattern that reflects automatic facilitation. For the long RSI, adults showed the usual alternation effect and the cost-benefit pattern that suggests subjective expectancy. Finally, consistent with the previous literature, S-R manipulation altered the effects of automatic facilitation, but subjective expectancy was not altered by the changing S-R mappings. The developmental analysis revealed a more complex pattern than was anticipated on the basis of the scarce literature examining sequential effects in children. The current findings were consistent with previous observations that children show a repetition effect where adults demonstrate an alternation effect (Fairweather, 1978; Kerr et al., 1980, 1982). In addition, the current findings were consistent with preliminary results showing a more prominent benefit-only pattern in children than in adults (Soetens & Hueting, 1992). Taken together, this pattern of results is consistent with the notion that the strength of automatic facilitation decreases with advancing age. Unexpectedly, children showed a more pronounced cost-benefit pattern than did adults, suggesting (at face value) an age-related decrease in subjective expectancy. This finding and the interpretation that seems to derive from it are difficult to reconcile with the current observation of a repetition effect where adults showed an alternation effect (i.e., the first-order effect associated with the long RSI). The latter pattern suggests a developmental increase in subjective expectancy rather than an age-related decrease. To provide a unified account of the pattern of findings associated with the long RSI, it was assumed that subjective expectancy is mediated by two dissociable mechanisms rather than a single mechanism. 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 second-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 should be activated. These processes are assumed to be more time-consuming in children than in adults. It would be of considerable interest to re-examine developmental change in the cost-benefit pattern using electrophysiological measures of expectancy [e.g., P300 component of the even-related brain-potential (Stauder, Molenaar, & van der Molen, 1993)] and preferential response activation [e.g., the lateralized readiness
potential (Coles, 1989; Ridderinkhof & van der Molen, 1997) to augment performance measures of sequential effects on speeded information processing (van der Molen, Bashore, Halliday, & Callaway, 1991).
Developmental change in sequential effects on speeded information processing is altered by response-to-stimulus interval but not practice
ABSTRACT

Two experiments were performed to assess age-related changes in sequential effects on choice reaction time (RT). Sequential effects portray the influence of previous trials on the RT to the current stimulus and have been interpreted in terms of 'automatic facilitation', giving rise to a repetition benefit, and 'subjective facilitation', resulting in an 'alternation benefit, depending on the response-to-stimulus interval (RSI) and the amount of practice received by the participant. The current study aimed at further investigating developmental change in sequential effects by manipulating RSI and the amount of practice. In Experiment 1, six age groups (5-6, 7-9, 10-12, 13-14, 15-17, and 18-25 yrs) performed a spatially compatible two-choice task with stimulus-to-response intervals (RSI) of 50, 150, 200, 250, 500, and 1000 ms. In Experiment 2, practice effects were investigated on three age groups (7-9, 10-12, and 18-25 yrs), performing the same task with RSIs of 50 and 500 ms on four successive sessions. Results confirmed adult findings showing that automatic facilitation shifts to subjective expectancy with a lengthening of RSI. Importantly, the timing of the shift occurred more rapidly with advancing age. In contrast to expectations, practice failed to affect the developmental trends in sequential effects. The results were interpreted in terms of a multi-facetted pattern consisting of developmental change in bottom-up and top-down influences on the choice reaction process.
INTRODUCTION

As children develop, they learn to interpret a wide range of incoming information from the world that can help them monitor their actions, and adjust them as needed. This adaptive behavior is essential to those cognitive functions that are concerned with selection, scheduling, and coordination of computational processes that are responsible for perception, memory and action. The ability to adjust to environmental demands has been conceptualized within the broader framework of ‘executive control’ and ‘cognitive flexibility’ (Carter et al., 1998; Mayr, 2004; Norman & Shallice, 1986). Cognitive flexibility is particularly sensitive to developmental change (Chevalier & Blaye, 2008; Cragg & Chevalier, 2012; Dempster, 1992; Huizinga & van der Molen, 2011; Kharitonova & Munakata, 2011; Munakata et al., 2012; Stuss, 1992; van der Molen & Ridderinkhof, 1998; Welsh, 2002; Zelazo et al., 2003). Age-related improvement in cognitive flexibility 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 et al., 2004; Heaton et al., 1993; Paniak et al., 1996; Rossellini & Ardela, 1993), inhibition and interference tasks (Cragg & Nation, 2008; Diamond et al., 2002; Garon, Bryson, & Smith, 2008; Ridderinkhof & van der Molen, 1995), and dimensional shift tasks and task-switch studies (Cepeda et al., 2001; Huizinga & van der Molen, 2007; Zelazo et al., 2004; but see Aron et al., 2004; Crone et al., 2004; Kray, Eber, & Lindenberger, 2004).

The current study is concerned with children’s flexibility in adjusting from one trial to the next in a series of standard choice reaction time (RT) trials. It is well-known that the performance on a specific trial depends on its immediate past history (for reviews, see Gao et al., 2009; Kirby, 1980; Luce, 1986; see also Soetens et al., 1985). More specifically, in choice tasks with two alternatives, first-order effects (i.e., the effect of the previous trial on the speed of responding on the current trial) arise from repetitions or alternations and systematic influences have been established for higher order effects extending further back in the trial’s history.

The literature on sequential effects established two distinct patterns depending on the response-to-stimulus interval (RSI) between trials (Luce, 1986; see also Perruchet et al., 2006; Tubau & Lopez-Moliner, 2009). When trials are presented in quick succession, the first-order effect consists of a repetition benefit (i.e., faster responding when successive trials require the same response) and 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). Both effects have been attributed to an “automatic facilitation” due to residual processing traces left by previous stimulus-response (S-R) cycles (e.g., Bertelson, 1961).
When trials are presented using a long RSI (e.g., 500 ms in adult participants), the first-order effect consists of an alternation benefit (i.e., faster responding when responses alternate compared to repeat), whereas the higher order effect displays a cost-benefit pattern (i.e., the speed of responding after a particular sequence is fast on the current trial for some sequences, but slow for the other). The first-order alternation effect has been taken as a manifestation of “subjective expectancy”; that is, 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 gradually decreased. This is the cost.

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. There are few, and relatively dated, studies examining developmental change in first-order sequential effects. These studies showed that the first-order repetition effect in children is considerably larger than in adults and, in contrast to adult participants, children continue to show a repetition effect with a lengthening of RSI (Fairweather, 1978; Kerr, 1979). Consistent with the theoretical framework advanced in the adult literature (e.g., Kirby, 1980; Soetens et al., 1985), the strong repetition effect observed in children has been interpreted in terms of automatic facilitation. More specifically, it has been suggested that residual activation of S-R traces due to trial repetition is particularly beneficial to children, as their central processing is relatively slow (Kerr et al., 1982).

In a previous study, we examined developmental change in sequential effects focusing on both first-order and higher order effects (Smulders et al., 2005). The first-order results, associated with a 50 ms RSI, were consistent with earlier studies suggesting that automatic facilitation is particularly beneficial in children. That is, the first-order repetition effect was considerably larger in children compared to older participants. The higher order benefit-only pattern exhibited a similar developmental trend. The repetition effect decreased when the RSI was lengthened to 500 ms, but continued to exist for children in contrast to adult participants. Quite unexpectedly, the results yielded a developmental decrease in the higher order cost-benefit pattern. The pattern of findings associated with the long RSI presents a challenge to the notion of subjective expectancy, in that the change in the first-order effect (i.e., a decreasing repetition
Developmental change in sequential effects

effect, ultimately leading to an alternation effect in adults) suggests a developmental increase in subjective expectancy, whereas the change in the higher order effect (i.e., a decreasing cost-benefit pattern) suggests a developmental decrease in subjective expectancy. In order to reconcile this apparent inconsistency we assumed that children’s larger benefits arising from higher order repetition sequences are due to greater automatic facilitation, while the larger costs associated with alternation sequences are due to difficulties children experience with switching from one response to another (cf. Smulders et al., 2005; p. 230).

The current article reports two experiments designed to assess developmental change in sequential effects in greater detail. The first experiment varied RSI along a considerable range to assess the transition from automatic facilitation, associated with short RSIs, to subjective expectancy, associated with long RSIs. Soetens et al. (1985) observed that the pattern of sequential effects associated with a short RSI is dominated by automatic facilitation, whereas subjective expectancy dominates sequential effects associated with a long RSI. The transition zone from automatic facilitation to subjective expectancy was around 100 ms for adult participants. For children we anticipate, based on our previous findings, that the transition zone is around 500 ms or beyond. The higher order effects are of particular interest. We anticipate a shift from a benefit-only pattern, associated with a short RSI, towards a cost-benefit pattern associated with a long RSI. Moreover, we expect 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 in our previous report (Smulders et al., 2005) then we have to 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 investigate the influence of practice. 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). Consequently, we expect practice to reduce the strength of automatic facilitation, especially in children. Accordingly, it is 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. It should be noted, however, that the pertinent literature is inconsistent in this regard. Soetens et al. (1985) observed that extended practice reduced both first-order repetition and alternation effects. In contrast, Suzuki and Goolsby (2003), focusing on first-order effects, observed that
changes were minimal even after long-term practice extending to several months of practice. They concluded from their findings that practice and first-order sequential effects affect the choice reaction process via different mechanisms.

In brief, the main goal of the current study 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 (Experiment 1) or by allowing participants more practice (Experiment 2).

**EXPERIMENT 1**

The first experiment was designed to assess the crossover from automatic facilitation to subjective expectancy in six different age groups, from early childhood to adulthood (i.e., from 5 to 25 years of age). Soetens et al. (1985) employed a standard choice RT task and used RSIs ranging from 50 ms to 1000 ms. It was observed that automatic facilitation shifted to subjective expectancy when RSI was relatively short (around 100 ms). A similar range of RSIs was used in the current experiment. We anticipated an early crossover for adults and an age-related delay in the transition from automatic facilitation to subjective expectancy for younger participants.

**METHOD**

**Participants**

Participants ($N = 137$) were recruited from six different age groups between 5 and 25 years of age. There were three child groups; 19 children between 5 and 6 years of age ($M = 5.2$ years; 13 girls); 22 children between 7 and 9 years of age ($M = 8.6$ years; 11 girls), and 19 children between the ages of 10 and 12 ($M = 11.3$ years; 10 girls). In addition, there were two adolescent groups; 20 adolescents between 13 and 14 of age ($M = 13.9$ years; 6 females), and 37 adolescents between 15 and 17 years of age ($M = 15.9$ years; 29 females). Finally, a group of 20 young adults between the ages of 18 and 25 took part in the experiment ($M = 22.6$ years; 12 females). The children and adolescents were selected with the help of their schools and with permission of their caregivers. All children had average or above average intelligence based on teachers reports. The adult participants (18-25 yrs) were undergraduate psychology students. They were recruited by flyers and received course credits for their participation. All participants reported to be in good health and had normal or corrected-to-normal vision. Informed consent was obtained prior to testing and the experimental procedure was approved by the local Ethics Committee. A preliminary analysis of the data, using gender as co-variate, indicated that gender did not systematically interact with the sequential effects
obtained in this experiment. Consequently, gender was not included in the analyses reported below.

**Apparatus and stimuli**

The experiment was run on 12-, and 15-in. screen PCs. A vertical, black line was presented through the center of the screen against a white background. The stimuli, red circles, were presented 5 cm to the left or right from the vertical line (1.5 cm diagonal). Participants viewed the monitor from a distance of 40-60 cm, and responded to the stimuli by pushing the ‘z’ key with their left-index finger or the right ‘/’ key with their right-index finger. These keys are on the bottom row of a qwerty keyboard.

**Design and procedure**

RT was recorded as the time between stimulus onset and the moment that one of the response keys was switched. The stimulus was response terminated. The response initiated the RSI, which was fixed either at 50, 150, 200, 250, 500 or 1000 ms. Participants performed in each RSI condition. The order of RSI conditions was counterbalanced across participants within each age group. An experimental session consisted of 24 experimental blocks of 100 trials each; four consecutive trial blocks for each RSI condition. Participants performed in each RSI condition, subjects performed a practice block of 50 trials. The first five trials in each experimental block were considered ‘warm-up’ and were excluded from statistical analyses. No error corrections were possible. Between blocks there was a 30-s rest period, and after three RSI conditions (i.e., 12 trial blocks) there was a 2-m. break. Participants received an on-screen instruction before starting the experiment. They were asked to respond quickly and to avoid errors. All participants were tested individually in a quiet laboratory or classroom. Including instructions and breaks, participants spent approximately one hour in the laboratory (psychology students) or classroom (children and adolescents).

**Data coding and analysis**

A computer program searched through the list of trials, and at each trial $T_n$ ($n$ ranges from 6 to 100), the program determined for trials $T_n$, $T_{n-1}$, and $T_{n-2}$ whether the response was correct or incorrect and whether it was left or right. For correct responses, the program then decided whether the responses on $T_n$ and $T_{n-1}$ were the same (i.e., left followed by left or right followed by right) or different (i.e., left followed by right or right followed by left). When the responses were the same, the program generated an “R” code for trial $T_n$ (with R standing for repetition). When the responses were different, the program generated an “A” code for trial $T_n$ (with A standing for alternation). The R and A codes were used for the analysis of first-order effects.
In addition, the program determined whether the responses on trials $T_{n-1}$ and $T_{n-2}$ were the same or different. When they were the same, the program generated an R code for trial $T_n$ preceding the code based on the comparison of trials $T_n$ and $T_{n-1}$; that is, RR when the latter comparison yielded an R code (for same responses) and RA when the latter comparison yielded an A code. Similarly, when the responses on trials $T_{n-1}$ and $T_{n-2}$ were different, the program generated an A code for $T_n$ preceding the code based on the comparison of the responses on trials $T_n$ and $T_{n-1}$ (AR or AA) These latter R and A codes were used for the analysis of second-order effects.

The RR, RA, AR, and AA codes represent the complete sequence consisting of the first- and second-order conditions under which the current RT resorts. Finally, it should be noted that when the response on trial $T_n$ was incorrect, the program moved to trial $T_{n+3}$ and the same procedure was repeated. That is RTs were only included in the analyses if no error was made on the current and the two preceding trials. The trial coding procedure is illustrated in Table 1 and 2.

Following trial coding, median RTs were computed for the RR, AR, AA, and RA sequences. The resulting RTs were then analysed using analysis of variance (ANOVA) that included two sequence factors; first-order sequence and second-order sequence. The first-order sequence factor consists of two levels: repetitions (i.e., the average of the median RTs of the RR and AR sequences) and alternations (i.e., the average of the median RTs of the RA and AA sequences). The second-order sequence factor also consists of two levels: repetition sequences (i.e., the average of the median RTs of the RA and RR sequences) and alternation sequences (i.e., the average of the median RTs of the AR and AA sequences).

### Table 1. Coding of trial sequences.

<table>
<thead>
<tr>
<th>Trial number $T_{n-2}$</th>
<th>Trial number $T_{n-1}$</th>
<th>Trial number $T_n$</th>
<th>First-order coding $(T_{n-1} &gt; T_{n})$</th>
<th>Second-order coding $(T_{n-2} &gt; T_{n-1})$</th>
<th>Trial sequence $(T_{n-2} &gt; T_{n-1} &gt; T_n)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left</td>
<td>Left</td>
<td>Left</td>
<td>R</td>
<td>R</td>
<td>RR</td>
</tr>
<tr>
<td>Right</td>
<td>Left</td>
<td>Left</td>
<td>R</td>
<td>A</td>
<td>AR</td>
</tr>
<tr>
<td>Left</td>
<td>Right</td>
<td>Left</td>
<td>A</td>
<td>A</td>
<td>AA</td>
</tr>
<tr>
<td>Right</td>
<td>Right</td>
<td>Left</td>
<td>A</td>
<td>R</td>
<td>RA</td>
</tr>
<tr>
<td>Left</td>
<td>Left</td>
<td>Right</td>
<td>A</td>
<td>R</td>
<td>RA</td>
</tr>
<tr>
<td>Right</td>
<td>Left</td>
<td>Right</td>
<td>A</td>
<td>A</td>
<td>AA</td>
</tr>
<tr>
<td>Left</td>
<td>Right</td>
<td>Right</td>
<td>R</td>
<td>A</td>
<td>AR</td>
</tr>
<tr>
<td>Right</td>
<td>Right</td>
<td>Right</td>
<td>R</td>
<td>R</td>
<td>RR</td>
</tr>
</tbody>
</table>

*Note: R, repetition; A, alternation; T, trial; and n, trial number.*
Table 2. Selection of trial sequences for statistical analysis.

<table>
<thead>
<tr>
<th>Trial</th>
<th>Response</th>
<th>First-order coding</th>
<th>Second-order coding</th>
<th>Trial sequence</th>
</tr>
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<td>-</td>
<td>-</td>
<td>-</td>
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<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>7</td>
<td>Left</td>
<td>R</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
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<td>A</td>
<td>R</td>
<td>RA</td>
</tr>
<tr>
<td>9</td>
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<td>R</td>
<td>A</td>
<td>AR</td>
</tr>
<tr>
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<td>R</td>
<td>R</td>
<td>RR</td>
</tr>
<tr>
<td>11</td>
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<td>R</td>
<td>R</td>
<td>RR</td>
</tr>
<tr>
<td>12</td>
<td>Left</td>
<td>A</td>
<td>R</td>
<td>RA</td>
</tr>
<tr>
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<td>Left</td>
<td>R</td>
<td>A</td>
<td>AR</td>
</tr>
<tr>
<td>14</td>
<td>Error</td>
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<td>R</td>
<td>-</td>
</tr>
<tr>
<td>15</td>
<td>Left</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>16</td>
<td>Right</td>
<td>A</td>
<td>-</td>
<td>-</td>
</tr>
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<td>A</td>
<td>AA</td>
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<td>AA</td>
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<td>A</td>
<td>A</td>
<td>AA</td>
</tr>
<tr>
<td>20</td>
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<td>A</td>
<td>A</td>
<td>AA</td>
</tr>
<tr>
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<td>A</td>
<td>AR</td>
</tr>
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<td>R</td>
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<td>RR</td>
</tr>
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<td>RR</td>
</tr>
<tr>
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<td>-</td>
<td>-</td>
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</table>

Output

<table>
<thead>
<tr>
<th>Median RT-R</th>
<th>Median RT-A</th>
<th>Median RT-RA</th>
</tr>
</thead>
</table>

Note. A, alternation; R, repetition. Output refers to the median RTs that enter the ANOVA. See text for further clarification.

RESULTS AND DISCUSSION

Error rates

Mean error percentages remained below 10%. Error percentages were submitted to a 6 (RSI; within subjects) x 6 (Age; between-subjects) ANOVA. The analysis revealed a main effect for age group, $F(5, 131) = 28.62, p < .001$. Mean error percentages decreased with advancing age from 7.2% in the youngest age group to 3.7% in the young adults. There was also a main effect of RSI, $F(5, 655) = 5.73, p < .001$. Mean error rate was somewhat
higher for the medium RSIs (5.3% and 4.9% in the 200 and 250 ms RSIs, respectively) compared to either the shortest and longest RSI (4.1% and 4.6%, respectively). The interaction between RSI and age group failed to reach significance, \( p = .08 \). Error rate correlated positively with RT across sequences and RSIs, indicating that there was no tradeoff between speed and accuracy.

**Response latencies**

On average, each trial block contained around 46 first-order repetitions and alternations, and about 23 unique combinations of first- and second-order sequences. Median RTs were calculated for each trial ending a sequence. This was done for each RSI, participant, and age group, separately. Mean RTs are presented in Table 3.

The first- and second-order effects are plotted in Figures 1 and 2, respectively. In Figure 1, it can be seen that all age groups show a repetition effect for the shorter RSIs and

<table>
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<th>Age Group</th>
<th>5-6 yrs</th>
<th>7-9 yrs</th>
<th>10-12 yrs</th>
<th>13-14 yrs</th>
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Developmental change in sequential effects

Table 3. (continued) Mean RTs and standard deviations (in milliseconds) for each transition sequence (first- and second-order) and RSI condition observed for each age group in Experiment 1.

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<th>Age Group</th>
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a tendency towards an alternation effect for the two longest RSIs. A shift towards an alternation benefit occurs only for the four oldest age groups (i.e., beyond 12 years of age). The second-order effect, plotted in Figure 2, shows a transition from a benefit-only to a cost-benefit pattern with increasing RSIs for all age groups. It can be seen that, with advancing age, this transition occurs at a shorter RSI.

The visual impressions were verified by ANOVA with repeated measures (General Linear Model), including RSI (6), first-order sequence (2) and second-order sequence (2), as within Ss factors, and age group (6), as between Ss factor. The ANOVA yielded a highly significant main effect of age group, $F(5, 131) = 100.91, p < .001$. Not surprisingly, RT decreased with advancing age from 708 ms in the youngest group to 295 ms in young adults. There was also a substantial main effect of RSI, $F(5, 655) = 29.45, p < .001$. RT decreased from 481 ms for the shortest RSI to 438 ms for the longest RSI. The first-order sequential effect was also significant, $F(1, 131) = 142.64, p < .001$. Overall, repetitions
Figure 1. First-order sequential effects observed for each age group and RSI condition in Experiment 1. Reaction time (RT) differences between first-order alternations and repetitions are plotted. A positive difference indicates a first-order repetition effect and a negative difference indicates a first-order alternation effect.

Figure 2. Second-order sequential effects for each age group and RSI condition in Experiment 1. RT differences between second-order AR vs. RR (left panel) and AA vs. RA sequences (right panel) are plotted. Two positive differences (left/right panels) indicate a higher order benefit-only pattern. A positive AR/RR difference (left panel) and a negative AA/RA (right panel) difference indicate a higher order cost-benefit pattern.
Developmental change in sequential effects

were considerably faster than alternations; 404 ms vs. 471 ms, respectively. Finally, the second-order sequential effect was highly significant, $F(1, 131) = 236.54$, $p < .001$. Sequences beginning with a repetition were faster than sequences beginning with an alternation; 424 ms vs. 451 ms, respectively.

As anticipated, increasing the length of the RSI changed both the first-order effect, $F(5, 655) = 33.16$, $p < .001$, and the pattern of second-order effects, $F(5, 655) = 57.93$, $p < .001$. Most importantly, the RSI sensitive patterns of first-order and second-order sequential effects revealed a significant interaction with age group, $F(25, 655) = 3.89$, $p < .001$, and $F(25, 655) = 4.30$, $p < .001$, respectively. The first- and second-order sequential effects, including the follow-up analyses, are presented in Table 4. The upper panel, showing the first-order effect, reveals that the transition from a repetition to an alternation benefit occurred at RSI-500 for participants beyond 12 years of age. The two youngest age groups continued to show a repetition benefit for RSIs up to 1000 ms.

Table 4. First- and second-order sequential effects for each age group and RSI condition.

<table>
<thead>
<tr>
<th>First-order sequential effects (A-R)</th>
<th>50 ms</th>
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<th>200 ms</th>
<th>250 ms</th>
<th>500 ms</th>
<th>1000 ms</th>
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<tr>
<td>5-6 yrs</td>
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<td>245</td>
<td>304</td>
<td>156.8</td>
<td>102.1</td>
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<tr>
<td>7-9 yrs</td>
<td>128.8</td>
<td>168.1</td>
<td>142.9</td>
<td>148.7</td>
<td>60.6</td>
<td>24.7*</td>
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<td>10-12 yrs</td>
<td>46.8</td>
<td>35.7</td>
<td>65.2</td>
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<td>35.5</td>
<td>18.2</td>
<td>-1*</td>
<td>-16.8</td>
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<td>16.3</td>
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<td>18-25 yrs</td>
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<td>17.1</td>
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<td>-15.1</td>
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</table>

<table>
<thead>
<tr>
<th>Second-order sequential effects (AR-RR vs. AA-RA)</th>
<th>50 ms</th>
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<th>250 ms</th>
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<tr>
<td>5-6 yrs</td>
<td>248 vs. 198</td>
<td>173 vs. 120</td>
<td>160 vs. 14</td>
<td>185 vs. 1</td>
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<tr>
<td>7-9 yrs</td>
<td>54 vs. 45</td>
<td>63 vs. 16</td>
<td>49 vs. 6</td>
<td>74 vs. -16*</td>
<td>69 vs. -70</td>
<td>71 vs. -89</td>
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<td>10-12 yrs</td>
<td>48 vs. 46</td>
<td>55 vs. 11</td>
<td>39 vs. -12</td>
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<td>13-14 yrs</td>
<td>25 vs. 30</td>
<td>34 vs. 9</td>
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<td>15-17 yrs</td>
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<td>24 vs. 4</td>
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<td>24 vs. 24</td>
<td>24 vs. -6</td>
<td>27 vs. -17</td>
<td>28 vs. -24</td>
<td>22 vs. -34</td>
<td>21 vs. -23</td>
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</table>

Note. Upper panel: A positive difference (A-R) indicates a repetition effect whereas a negative difference (bold) indicates an alternation effect. Non-significant ($p > .05$) differences are indicated by a *. Lower panel: Two positive differences (AR-RR and AA-AR) indicate a higher order benefit-only pattern whereas a positive (AR-RR) difference and a negative (AA-RA) difference (bold) indicate a higher order cost-benefit pattern. Non-significant ($p > .05$) cost-benefit patterns are indicated by a *. The gray shading indicates a significant alternation-effect (upper panel) or a cost-benefit pattern (lower panel).
The lower panel of Table 4., showing the second-order effects, shows a rather different pattern. For the youngest age group, the transition from a benefit-only pattern to a cost-benefit pattern occurred around 500 ms. For adults the transition occurred for shorter RSIs, between 50 and 150 ms. The transition occurred at intermediate RSIs for the other age groups; that is, 150-200 ms for the 10-17 year olds, 200-250 ms for the 7-9 year olds, and 250-500 ms for the 5-6 year olds.

In sum, the results that emerged from the first experiment are highly consistent with the findings reported previously by Soetens et al. (1985). Most importantly, the current experiment showed a delayed shift from a repetition to an alternation benefit for younger age groups. An alternation effect occurred at the longest RSI for the oldest child group (13-14 yrs olds), adolescents (15-17 yrs olds) and adults. The two younger child groups (7-9 and 5-6 years-olds) continued, however, to exhibit a robust repetition benefit even for the longest RSI.

The second-order effects revealed an orderly pattern of change across RSIs. Previously, Soetens et al. (1985) observed a clear benefit-only pattern associated with a 50 ms RSI and a cost-benefit pattern for RSIs of 200 ms and beyond. The current results showed a similar pattern associated with the same RSIs for adults. Importantly, and consistent with expectations, the transition was delayed for the other age groups but all age groups showed a clear cost-benefit pattern associated with the longest RSIs (500 and 1000 ms). The latter finding is important, in that it suggests that the first-order and second-order indices of automatic facilitation follow different developmental trajectories. The addition of basic processing speed (i.e., age group RT) as covariate in the analyses reported above did not change any of the significant effects in the analyses.

**EXPERIMENT 2**

This experiment was designed to study the effect of practice on the developmental change in sequential effects. Previous studies indicated that practice reduces the first-order repetition benefit (e.g., Kirby, 1980; Soetens et al., 1985). The hypothesis advanced here assumes that practice will strengthen central S-R pathways and, thus, will reduce automatic facilitation, thereby allowing subjective expectancy to manifest itself; possibly even in young children.
METHOD

Participants
Participants (N = 62) were recruited from three age groups between 7-25 years of age. There were two groups of children; 16 children between 7 and 9 years of age (M = 7.7 years; 3 girls); 22 children between 10 and 12 years of age (M = 11.3 years; 7 girls). Finally, a group of 24 young adults between the ages of 18 and 25 (M = 19.8 years; 21 females) enrolled in the experiment. The children were selected with the help of their schools and with permission of their caregivers. All children had average or above average intelligence based on teachers reports. The young adults were undergraduate psychology students and were recruited by flyers and received credit points for their participation. All participants reported to be in good health and had normal or corrected-to-normal vision. Informed consent was obtained prior to testing and the experimental procedure was approved by the local Ethics Committee. A preliminary analysis of the data, using gender as co-variate, indicated that gender did not systematically interact with the sequential effects obtained in this experiment. Consequently, gender was not included in the analyses reported below.

Apparatus and stimuli
All details were the same as in Experiment 1.

Design and procedure
RSI was fixed either at 50 or 500 ms. The order of RSI conditions was counterbalanced across participants. An experimental session consisted of 12 experimental blocks; each RSI condition consisted of six consecutive blocks, with each block containing 100 trials. Before each RSI condition, participants performed a practice block of 50 trials. Participants took four individual testing sessions, scheduled within five consecutive days (i.e., the second and third sessions were separated by one day). Thus, participants performed on a total of 4800 trials. The order of RSIs was consistent across sessions.

RESULTS AND DISCUSSION

Error rates
Mean error rates were submitted to a 2 (RSI; within subjects) x 3 (Age; between-subjects) x 4 (Practice; within-subjects) ANOVA. Although not significant, error rate increased somewhat with advancing age (from 3.7% for the youngest children to 4.5% and 4.9% for the older child group and adults, respectively). More errors were committed to RSI-500 than to RSI-50, $F(1, 59) = 10.41, p < .002$ (4.8% and 4.0%, respectively). There was a slight but significant increase in error rate with practice, $F(3, 177) = 2.97, p < .033$. 
Error rate increased from 3.9% in the first session to 4.4% in the fourth session. In all conditions, error rate correlated positively with RT across sequences, indicating that there was no tradeoff between speed and accuracy.

**Response Latencies**

Mean RTs are presented in Table 5 and sequence effects are plotted in Figures 3 and 4 for each sequence x age group x RSI condition x practice session combination. It can be seen that all three age groups showed a repetition effect and a benefit-only pattern associated with the 50 ms RSI. With a lengthening of the RSI to 500 ms, the repetition effect changed towards an alternation effect, but the repetition effect continued to dominate. The 500 ms RSI is associated with a clear cost-benefit pattern for all three age

### Table 5. Mean RTs and standard deviations (in milliseconds) for each transition sequence (first-order and second-order) and RSI condition observed for each age group and practice session in Experiment 2.

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<td>447</td>
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<td>AR</td>
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<tr>
<td>RA</td>
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<tr>
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<tr>
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<td>447</td>
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<td>381</td>
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</tbody>
</table>

84
groups. Finally, and in contrast to expectations, it can be seen that practice had only minor effects and did not produce a systematic change in the pattern of sequential effects.

Median RTs were calculated similar to the first experiment and the mean RTs were submitted to an ANOVA with age group (3) as a between subjects factor and practice session (4), RSI (2), first-order sequence (2) and second-order sequence (2) as within-subjects factors. Obviously, the ANOVA yielded a highly significant main effect of age group, $F(2, 59) = 58.49, p < .001$. RT decreased with advancing age from 505 ms to 361 ms and 315 ms, for young children, older children, and adults, respectively. Participants responded faster with more practice, $F(3, 177) = 8.57, p < .001$. RT decreased from 405 ms in the first session to 377 ms in the last session. The effect of practice on RT was more pronounced for adults than children, $F(6, 177) = 4.56, p < .001$. Practice increased the speed of responding linearly from 342 to 290 ms for adults, from 386 to 341 ms for older children, and, after a decrease in the speed of responding between practice session 1 and 2, from 522 to 499 ms for young children also. Responses were faster following the long RSI (389 ms) compared to the short RSI (402 ms), $F(1, 59) = 14.96, p < .001$. The effect of practice interacted significantly with RSI, $F(3, 177) = 13.09, p < .001$. Practice increased the speed of responding from 427 to 371 ms for the short RSI, but did not affect reaction time in the long RSI condition. Both the first-order effect, $F(1,$
Chapter 3

Second-order effects

Figure 4. Second-order sequential effects for each age group in function of practice for 50 ms (upper) and 500 ms RSI (lower) in Experiment 2. RT differences between second-order AR vs. RR and AA vs. RA sequences are plotted. Two positive differences indicate a higher order benefit-only pattern. A positive AR/RR difference and a negative AA/RA difference indicate a higher order cost-benefit pattern.

\( F(1, 59) = 65.32, p < .001, \) and the second-order effect, \( F(1, 59) = 39.85, p < .001, \) were highly significant. These effects were included in an interaction with RSI, \( F(1, 59) = 137.20, p < .001. \) Finally, the ANOVA yielded a significant four-way interaction among RSI, practice, first-order effect, and second order effects, \( F(3, 177) = 3.29, p < .022. \) Subsequent analy-
ses were done for the short and long RSIs, separately, to assess the effect of practice on automatic facilitation and subjective expectancy.

Follow-up analyses for each RSI separately showed that whereas practice failed to influence the first-order effect ($p > .192$) for the 50 ms RSI, it did affect the second-order effect, $F(3, 177) = 2.88, p < .037$. The benefit-only pattern was somewhat smaller during the last practice session compared to the previous sessions. Importantly, the interaction between age group and practice failed to reach significance ($p > .16$). Collectively, the results associated with the 50 ms RSI indicate that extended practice did not result in the anticipated change of automatic facilitation toward subjective expectancy.

A similar analysis performed on the sequential effects associated with the 500 ms RSI revealed that practice did not alter the first-order effect, $p > .289$, but it did change the cost-benefit pattern significantly, $F(3, 177) = 3.22, p < .024$. That is, the cost-benefit pattern decreased with practice. Finally, the interaction between the second-order sequential effect and practice was not altered by age, $p > .447$.

In sum, practice had a sizable effect on the speed of responding that was more pronounced for adults compared to children. Practice did not alter the first-order sequential effects but it did change the second-order effects. That is, the benefit-only pattern was somewhat smaller in the last practice session compared to previous sessions and the cost-benefit pattern decreased systematically with extended practice. In contrast to expectations, however, the effects of practice on sequential effects did not discriminate between age groups.

**GENERAL DISCUSSION**

The basic patterns of sequential effects were similar to the results reported in previous studies. That is, sequential effects associated with a short RSI consist of a first-order repetition effect and a higher-order (here second-order) benefit-only pattern (Kirby, 1980; Luce, 1986; Soetens et al., 1984, 1985). The first-order repetition effect and the second-order benefit-only pattern are taken both as manifestations of “automatic facilitation”. Automatic facilitation is typically interpreted in terms of a low-level mechanism. Repeating the same stimulus or response has a beneficial effect because of memory traces left by the previous S-R cycle. Consequently, central processes may be shortcut or connection weights between processing nodes may be strengthened after repetitions (e.g., Bertelson, 1961; Cho et al., 2002; Soetens et al., 1985).
In line with previous developmental studies (Fairweather, 1978; Kerr, 1979), we observed a developmental age-related decrease in the first-order repetition effect and, consistent with our earlier study (Smulders et al., 2005), we obtained a decrease in the second-order benefit-only pattern with advancing age. These findings indicate that the beneficial effect of automatic facilitation decreases when children are growing older. One interpretation, advanced by Kerr et al. (1982), suggests that, as central processing becomes faster, the gain associated with residual S-R traces is getting less.

With a lengthening of RSI, the first-order repetition effect changes towards an alternation effect and the higher order benefit-only patterns changes into cost-benefit patterns (e.g., Kirby, 1980; Soetens et al., 1985). The sequential effects associated with long RSIs have been interpreted in terms of “subjective expectancy”. That is, presented with a random series of binary stimuli, participants tend to expect more alternations than repetitions, giving rise to a first-order alternation effect (e.g., Burns & Corpus, 2004; Jarvik, 1951; Keele, 1969; Sommer et al., 1999; Squires et al., 1976). The higher order cost-benefit pattern has been explained as a consequence of a gradual change in expectancy level (e.g., Audley, 1973). That is, individuals expect a continuation of runs of repetitions or alternations – the longer the run, the faster the responses and the slower they are when runs are interrupted (Soetens, 1998).

Our findings are consistent with the RSI-related trends observed in previous studies. When RSI was varied systematically from 50 ms 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 at the longest RSI, not for the two youngest child groups. 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 150-250 ms RSI range, with the exact transition RSI depending on the participants’ age.

Our findings are important by indicating that sequential effects in children are not mediated only by a lower-order automatic facilitation mechanism but under appropriate conditions, also by subjective expectancy. The current findings suggest that subjective expectancy is already in place in young children but easily overshadowed by automatic facilitation. Another interesting aspect of the current data refers to the difference in the timing of the transition from first-order repetition- to alternation vs. the transition from second-order benefit-only to cost benefit effect. This timing difference may suggest that first-order and second-order sequential effects follow different developmental trajectories. We will return to this issue below.
The second experiment of the current study was designed to examine the effects of practice on developmental changes of the first- and second-order sequential effects. It was assumed that practice reduces the time needed for central processing and, thus, would decrease the impact of automatic facilitation, in particular in children. The current findings are only partly consistent with these expectations. Practice reduced the second-order sequential effects, as anticipated, but failed to alter the first-order effects. Moreover, practice did not interact with advancing age in changing the pattern of sequential effects although the interaction between practice and age was substantial in their effect on mean RT.

Previously, Soetens et al. (1985), using a similar experimental set up (i.e., location stimuli and 50 ms vs. 500 ms RSIs) reported practice-related reduction in the strength of sequential effects that was more pronounced for automatic facilitation than subjective expectancy. More specifically, Soetens et al. observed a rapid decrease of the higher-order benefit-only pattern followed by a decrease in the first-order repetition effect. The first-order alternation effect disappeared completely for highly trained participants while there was only a modest decrease for the higher order cost-benefit pattern.

One possible interpretation of the apparent discrepancy between our data and the findings reported by Soetens et al. (1985) would be that more practice is needed for the first-order effects to change, in particular in children. Thus, Soetens et al. (1985) observed that practice reduced higher order patterns first and first-order effects later. Their participants received about 7000 trials whereas in the current study (only) 4800 trials were used. It should be noted, however, that Suzuki and Goolsby (2003) failed to observe substantial reductions in first-order effects even after extended practice of several months. But these authors used more complicated choice tasks yielding much slower responses (> 500 ms in adults) and trials were separated by longer intervals (2 to 2.5 s). The current data agree with the results of Soetens et al. (1985) in showing a decrease in both the benefit-only and the cost-benefit sequential patterns. As Soetens et al. (1985) reasoned these findings argue against the notion that automatic facilitation (mediating the benefit-only pattern) and subjective expectancy (mediating the cost-benefit pattern) are mutually exclusive. Practice will strengthen central S-R links thereby reducing automatic facilitation and, according to Soetens et al. (1985) with extended participants begin to realize that trial runs are random rather than having an intelligible structure and, thus, subjective expectancy will gradually decrease. It is interesting to note that the practice-related decrease in the cost-benefit pattern did not differentiate between age groups. This observation suggests that even young children are keeping a record of trial sequences; perhaps a rudimentary monitoring ability. In this regard, the current findings contribute to the rapidly growing (cognitive neuroscience) literature.
on developmental change in cognitive control (Amso & Casey, 2006; Davies et al., 2004; Fassbender, Foxe, & Garavan, 2006; Hare & Casey, 2005; Santesso et al., 2006; van de Laar et al., 2011).

In returning to the issue of the timing of transitions in sequential effects we will argue that the framework developed in a recent computational study by Gao et al. (2009) may provide a unified account of the present data. In this study, a connectionist network was used to examine sequential effects that consisted of a decision mechanism and two top-down biasing mechanisms. The decision mechanism receives feedback from previous trials that is provided by the biasing mechanisms. One bias is related to conflict monitoring (influenced by sequence violations) and the other to expectancy (influenced by sequence length). The network includes also residual neural activity that might influence processing on the next trial. Simulations using this network indicated that first-order automatic facilitation is due to residual activity, but higher order automatic facilitation is not. Higher order automatic facilitation (indexed by the benefit-only pattern) results from an inhibition bias associated with conflict monitoring. Importantly, this pattern of findings implies that the transition RSI values for first- and higher order automatic facilitation can differ, a suggestion that was also made by Soetens and Notebaert (2005).

Indeed, 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 second-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 explained by assuming that, in young children, the decision mechanism works more slowly, implying longer-lasting residual activity and, thus, repetition effects that continue to persist for longer RSIs. Adopting the Gao et al. (2009) framework, the age-related change in the RSI transition value associated with second-order sequential effects can be interpreted to suggest 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 nondecision (i.e., sensorimotor) processes and the other effect consists of speeding up all processing components in the network. The former effect is manifested in an overall shortening in RT and a differential RSI effect on mean RT. In this regard, our current 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. Finally, the current observation that practice failed to substantially change sequential effects sug-
gests that, with the present practice dose 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.

In conclusion, results that emerged from the present study contribute to the growing literature suggesting that higher order sequential effects are not simply derivatives of the first-order sequential effects (e.g., Cho et al., 2002; Crone et al., 2004; Gao et al., 2009; Smulders et al., 2005; Soetens & Notebaert, 2005). The first-order repetition effect is mediated by a lower-order mechanism that Gao et al. (2009) associated with post-response residual activity. Gao et al. (2009) argued that neural findings provide support for the notion of (the decay in) residual activity. Thus, it has been observed that neurons accumulating evidence for a decision to be made experience rapid decay following that decision (e.g., Roitman & Shadlen, 2002). The higher order sequential effects are mediated by a different mechanism of top-down biasing. 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 with the prefrontal cortex (e.g., Baldo & Dronkers, 2006; Barbey, Koenigs, & Grafman, 2011). Developmental studies indicate monitoring mediated by the anterior cingulated cortex is slow to mature (e.g., Eshel, Nelson, Blair, Pine, & Ernst, 2007) and that prefrontal cortex mechanisms mediating on-line memory show a protracted developmental course (e.g., Huizinga et al., 2006). In sum, the current developmental analysis of sequential effects suggests that, within the context of the Gao et al. (2002) model, the observed developmental change pertains to the speed of three separate mechanisms; sensorimotor processing (overall practice effect), post-response residual activity (first-order sequential effects) and inhibition bias (second-order sequential effects). Future developmental research might take advantage of the Gao et al. (2009) model to assess the relative contribution of each of these mechanisms to the changes that can be observed with advancing age.
What happens when children encounter an error?
ABSTRACT

The current study presents the results of two experiments designed to assess developmental change in post-error slowing (PES) across an age range extending from 5 to 25 years. Both experiments employed two-choice tasks and manipulated response-to-stimulus intervals (RSIs). The results showed that PES decreased with advancing age; a disproportional developmental trend was observed in experiment 2 while the age-related change in PES in experiment 1 was similar to the developmental decrease in basic response speed. In both experiments, age and RSI effects on PES did not interact. This pattern of results was interpreted to suggest that PES at long RSIs is due to increased caution and at short RSIs to a combination of increased caution and the time it takes to orient towards the error. The developmental change in PES at longer RSIs was interpreted to suggest that as children grow older they are becoming more effective in setting appropriate response thresholds.
INTRODUCTION

The ability to adjust performance to a dynamically changing environment is a hallmark of intelligent behavior. A key aspect of this ability refers to error detection and remedial action 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 et al., 2013). Post-error slowing (PES) attracted various interpretations but the notion of ‘increased response caution’ is probably most prominent (Dutilh et al., 2012). This interpretation is readily integrated with various models of cognitive control (e.g., Botvinick et al., 2001).

The seminal work on error processing (e.g., Laming, 1968; Rabbitt, 1966, 1968; Rabbitt & Vyas, 1970; Welford, 1980) 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. Participants do not know how fast they can respond until they commit an error and then they have to slow down in order to prevent further errors. 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. Rabbitt and Rodgers (1977) considered several interpretations of PES. One is that response monitoring, i.e., the evaluation of whether the response matched the intended one, takes longer following an error and may interfere with processing on the post-error trial. A related interpretation suggested that participants, knowing that they committed an error, try to correct it by making the intended response. Accordingly, PES would be due to interference between error correction and responding to the signal on the post-error trial. A third interpretation assumed that participants are distracted following an error, which negatively affects their speed of responding on the post-error trial. It should be noted, however, that these interpretations related to data obtained using very short response-to-stimulus intervals (RSIs). Hence, Laming (1979) indicated that these interpretations may not apply for RSIs longer than half a second or so. For longer RSIs a fourth interpretation would be more appropriate. That is, PES under those conditions is due to a re-adjustment of response boundaries, i.e., the criteria that must be satisfied before a response is executed. Laming (1979) demonstrated that his data were consistent with the response caution interpretation and this has been confirmed by a recent application of diffusion modeling to PES data derived from a lexical decision task (Dutilh et al., 2012).

The primary aim of the current study is to examine developmental change in PES. To attain this goal, we will briefly review developmental or child studies of error processing with an eye on age-related change in PES. At this point, it should be noted that most
studies examining error processing in children focus on its neural concomitants. The
developmental or child studies relevant to PES build upon a large body of research
employing electrocortical indices of error processing (Overbeek et al., 2005). The adult
electrocortical studies revealed that error detection is associated with a negative brain
potential, coined ‘error negativity’, Ne (Falkenstein et al., 1995) or ERN (Gehring et al.,
1993), followed by a positive brain potential, ‘error positivity’ (Pe), that has been associ-
ated with error awareness (Nieuwenhuis et al., 2001). Brain imaging revealed that the
ERN is generated within the posterior medial prefrontal cortex (e.g., Ridderinkhof et al.,
2004). Collectively, these findings have been interpreted to suggest that the ERN and
Pe are manifestations of an error detection system that is linked to lateral regions of
prefrontal cortex implicated in the implementation of strategic performance adjust-
ments, which may result in trading off speed for accuracy in order to prevent future
errors (see review in Ullsperger et al., 2014).

The cognitive neuroscience studies of performance monitoring and adjustment
provide the context for a rapidly growing literature on developmental change in ERN
and PES (for reviews Ferdinand & Kray, 2014; Tamnes et al., 2013). The ERN research,
including in Table 1, revealed a developmental increase in ERN during childhood into
adolescence while PES showed little change with advancing age. It should be noted,
however, that the majority of these studies focused on individual differences rather
than developmental change. The developmental increase in the ERN has been inter-
preted to reflect the maturation of brain mechanisms implicated in error-monitoring
(i.e., the dorsal medial prefrontal cortex). The observation that PES was relatively age
invariant suggested the idea that, initially, the mechanisms involved in error monitoring
and performance adjustments are disconnected to become intertwined only later in

A handful of performance studies, including in Table 1, are most relevant for the current
purpose and, thus, will be reviewed here in somewhat greater detail. Fairweather (1978)
was first in examining developmental change in PES. In contrast to the bulk of devel-
opmental ERN studies, typically employing conflict tasks, his participants performed on
a series of standard choice reaction tasks. For the two-choice task, he observed a sub-
stantial decrease in PES with advancing age, from about 600 ms in 5-year olds to around
225 ms in 12-year olds. His findings led Fairweather (1978) to conclude that the basic
mechanisms involved in error-monitoring and performance adjustment are in place in
young children. He interpreted the developmental decrease in PES to suggest that with
advancing age the implementation of remedial action becomes more efficient.
Table 1. Studies examining post-error slowing and/or error-related negativity (ERN) in different age groups. NR = not reported; NA = not applicable.

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Age range</th>
<th>Study</th>
<th>Trend</th>
<th>PES</th>
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<tbody>
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<td>Albrecht et al. (2008)</td>
<td>8 to 15</td>
<td>ERN/ADHD</td>
<td>NR</td>
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<td>Decrease</td>
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<td>ERN/Lead exposure</td>
<td>NR</td>
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<td>4 to 8</td>
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<td>Brooker et al. (2011)</td>
<td>4 to 8</td>
<td>ERN/Affective behaviors</td>
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<td>Bruce, McDermot, Fisher, and Fox (2008)</td>
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<td>ERN/Typical</td>
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<td>ERN/ADHD and Autism</td>
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<td>Groom et al. (2010)</td>
<td>16</td>
<td>ERN/ADHD</td>
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<td>Groom et al. (2013)</td>
<td>9 to 15</td>
<td>ERN/ADHD</td>
<td>NR</td>
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Table 1. (continued) Studies examining post-error slowing and/or error-related negativity (ERN) in different age groups. NR = not reported; NA = not applicable.

<table>
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<th>Author(s)</th>
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<th>Trend</th>
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<td>Performance</td>
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<td>ERN/OCD</td>
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<td>NR</td>
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<td>10 to 18</td>
<td>ERN/OCD</td>
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<td>Hogan et al. (2005)</td>
<td>12 to 22</td>
<td>ERM/Typical</td>
<td>Present only on difficult task</td>
<td>NR</td>
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<td>Horowitz-Kraus (2011)</td>
<td>13 and 25</td>
<td>ERM/Dyslexia</td>
<td>NR</td>
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<tr>
<td>Horowitz-Kraus and Breznitz (2014)</td>
<td>12</td>
<td>ERM/Dyslexia</td>
<td>NR</td>
<td>NA</td>
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<tr>
<td>Hum, Manassis, and Lewis (2013)</td>
<td>8 to 12</td>
<td>ERM/Anxiety</td>
<td>NR</td>
<td>NA</td>
</tr>
<tr>
<td>Jones et al. (2003)</td>
<td>3 to 4</td>
<td>Performance</td>
<td>Present (in older)</td>
<td>Increase</td>
</tr>
<tr>
<td>Jonkman, van Melis, Kemner, and Markus (2007)</td>
<td>10</td>
<td>ERM/ADHD</td>
<td>Absent</td>
<td>NA</td>
</tr>
<tr>
<td>Kamijo et al. (2014)</td>
<td>7 to 9</td>
<td>ERM/Obesity</td>
<td>Present</td>
<td>NA</td>
</tr>
<tr>
<td>Kim et al. (2007)</td>
<td>7 to 11 and 21 to 25</td>
<td>ERM/Typical</td>
<td>NR</td>
<td>NA</td>
</tr>
<tr>
<td>Ladouceur, Dahl, Birmaher, Axelson, and Ryan (2006)</td>
<td>8 to 14</td>
<td>ERM/Anxiety</td>
<td>Present</td>
<td>NA</td>
</tr>
<tr>
<td>Ladouceur et al. (2007)</td>
<td>8 to 13, 14 to 18, and 19 to 49</td>
<td>ERM/Typical</td>
<td>Present</td>
<td>No change</td>
</tr>
<tr>
<td>Ladouceur et al. (2012)</td>
<td>7 to 17</td>
<td>ERM/Depression</td>
<td>Present</td>
<td>NR</td>
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<tr>
<td>Ladouceur, Dahl, and Carter (2004)</td>
<td>9 to 17</td>
<td>ERM/Typical</td>
<td>Present</td>
<td>NR</td>
</tr>
<tr>
<td>Laurens et al. (2010)</td>
<td>9 to 12</td>
<td>ERM/Schizophrenic antecedents</td>
<td>Present</td>
<td>NA</td>
</tr>
<tr>
<td>Liotti, Pliszka, Perez, Kothmann, and Woldorff (2005)</td>
<td>9 to 11</td>
<td>ERM/ADHD</td>
<td>NR</td>
<td>NA</td>
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<tr>
<td>McDermott et al. (2009)</td>
<td>15</td>
<td>ERM/Anxiety</td>
<td>NR</td>
<td>NA</td>
</tr>
<tr>
<td>McDermott et al. (2013)</td>
<td>8</td>
<td>ERM/Foster care</td>
<td>Present</td>
<td>NA</td>
</tr>
<tr>
<td>Meyer et al. (2012)</td>
<td>8 to 13</td>
<td>ERM/Anxiety</td>
<td>Present</td>
<td>NR</td>
</tr>
</tbody>
</table>
Table 1. (continued) Studies examining post-error slowing and/or error-related negativity (ERN) in different age groups. NR = not reported; NA = not applicable.

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Age range</th>
<th>Study</th>
<th>Trend</th>
<th>PES</th>
</tr>
</thead>
<tbody>
<tr>
<td>O’Connell et al. (2004)</td>
<td>11</td>
<td>Performance/SCR/ADHD</td>
<td>Present</td>
<td>NA</td>
</tr>
<tr>
<td>Ornstein et al. (2009)</td>
<td>10</td>
<td>Performance/TBI</td>
<td>Present</td>
<td>NA</td>
</tr>
<tr>
<td>Pontifex et al. (2010)</td>
<td>9, 19, and 65</td>
<td>ERN/Typical</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>Pontifex et al. (2011)</td>
<td>10</td>
<td>ERN/Aerobic Fitness</td>
<td>Present (?)</td>
<td>NA</td>
</tr>
<tr>
<td>Richardson, Anderson, Reid, and Fox (2011)</td>
<td>7 to 9</td>
<td>ERN/Typical</td>
<td>Present (minimal)</td>
<td>NA</td>
</tr>
<tr>
<td>Rosch and Hawk (2013)</td>
<td>10 to 12</td>
<td>ERN/ADHD</td>
<td>NR</td>
<td>NA</td>
</tr>
<tr>
<td>Rubia, Halari, Mohammad, Taylor, and Brammer (2011)</td>
<td>10 to 15</td>
<td>fMRI/ADHD</td>
<td>Absent</td>
<td>NA</td>
</tr>
<tr>
<td>Santesso and Segalowitz (2008)</td>
<td>15 to 16 and 18 to 20</td>
<td>ERN/Typical</td>
<td>Present</td>
<td>Increase</td>
</tr>
<tr>
<td>Santesso et al. (2006)</td>
<td>10 and 18 to 33</td>
<td>ERN/Typical</td>
<td>Present</td>
<td>No change</td>
</tr>
<tr>
<td>Schachar et al. (2004)</td>
<td>7 to 16</td>
<td>Performance/ADHD</td>
<td>Present</td>
<td>Decrease</td>
</tr>
<tr>
<td>Senderekka, Grbavcic, Szewczyk, Gerc, and Chmylk (2012)</td>
<td>6 to 12</td>
<td>ERN/ADHD</td>
<td>NR</td>
<td>NA</td>
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<tr>
<td>Shen, Tsai, and Duann (2011)</td>
<td>6 to 10</td>
<td>ERN/ADHD</td>
<td>NR</td>
<td>NA</td>
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<tr>
<td>Sokhadze et al. (2012)</td>
<td>9 to 21</td>
<td>ERN/Autism</td>
<td>Present</td>
<td>NA</td>
</tr>
<tr>
<td>South, Larson, Krauskopf, and Clawson (2010)</td>
<td>14</td>
<td>ERN/Autism</td>
<td>Present</td>
<td>NA</td>
</tr>
<tr>
<td>Spinelli et al. (2011)</td>
<td>10</td>
<td>fMRI/ADHD</td>
<td>Present</td>
<td>NA</td>
</tr>
<tr>
<td>Stieben et al. (2007)</td>
<td>8 to 12</td>
<td>ERN/Externalisation</td>
<td>Present</td>
<td>NA</td>
</tr>
<tr>
<td>Torpey, Hajcak, and Klein (2009)</td>
<td>5 to 7</td>
<td>ERN/Typical</td>
<td>NR</td>
<td>NA</td>
</tr>
<tr>
<td>Torpey, Hajcak, Kim, Kujawa, and Klein (2012)</td>
<td>5 to 7</td>
<td>ERN/Typical</td>
<td>Present</td>
<td>NA</td>
</tr>
<tr>
<td>Torpey et al. (2013)</td>
<td>6</td>
<td>ERN/Temperament</td>
<td>Present</td>
<td>NA</td>
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<tr>
<td>van de Laar et al. (2012)</td>
<td>7, 11, 20 and 75</td>
<td>Performance</td>
<td>Present</td>
<td>No change</td>
</tr>
<tr>
<td>van de Vooorde, Roeyers, and Wiersema (2010)</td>
<td>9 to 10</td>
<td>ERN/ADHD</td>
<td>Absent</td>
<td>NA</td>
</tr>
<tr>
<td>van Meel, Hanlenfeld, Oosterlaan, and Sergeant (2007)</td>
<td>8 to 12</td>
<td>ERN/ADHD</td>
<td>Present</td>
<td>NA</td>
</tr>
<tr>
<td>van Meel et al. (2012)</td>
<td>6 to 9, 10 to 12, and 18 to 26</td>
<td>ERN/Typical</td>
<td>NR</td>
<td>NA</td>
</tr>
</tbody>
</table>
Table 1. (continued) Studies examining post-error slowing and/or error-related negativity (ERN) in different age groups. NR = not reported; NA = not applicable.

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Age range</th>
<th>Study</th>
<th>Trend</th>
<th>PES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wiersema, van der Meere, and Roeyers (2005)</td>
<td>7 to 13</td>
<td>ERN/ADHD</td>
<td>Present</td>
<td>NA</td>
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<tr>
<td>Wiersema et al. (2007)</td>
<td>7 to 8, 13 to 14, and 23 to 24</td>
<td>ERN/Typical</td>
<td>Present</td>
<td>No change</td>
</tr>
<tr>
<td>Wild-Wall, Oades, Schmidt-Wessels, Christiansen, and Falkenstein (2009)</td>
<td>8 to 18</td>
<td>ERN/ADHD</td>
<td>Present</td>
<td>NR</td>
</tr>
<tr>
<td>Yordanova et al. (2011)</td>
<td>7 to 16</td>
<td>Performance/ADHD</td>
<td>Absent</td>
<td>NA</td>
</tr>
<tr>
<td>Zhang, Wang, Cai, and Yan (2009)</td>
<td>7 to 11</td>
<td>ERN/ADHD</td>
<td>NR</td>
<td>NA</td>
</tr>
<tr>
<td>Narayanan and Laubach (2008)</td>
<td>Rat</td>
<td>PES present</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moon et al. (2006)</td>
<td>Mouse</td>
<td>PES present</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jedema et al. (2011)</td>
<td>Monkey</td>
<td>PES present</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The most detailed study of developmental change in PES was done by Brewer and Smith (1989). These authors examined error detection and performance monitoring in separate experiments using four-choice reaction tasks. In the first experiment, participants were asked to signal their errors by depressing a detection button when they felt they committed one. Error detection rate was seen to increase rapidly from 38.5% in five-year olds to 91.1% in 11-year olds while error rates were similar across age groups. These findings indicate that children do detect their errors although the youngest children are grossly inaccurate in doing so. The results of the second experiment showed response speeding towards errors and PES in the adult participants. This pattern was present also in young children, albeit less clear. The data seem to indicate that the performance tracking mechanism is present already from a very young age. But Brewer and Smith (1989) noted also important differences between age groups. Young children continued fast responding following an error more frequently relative to older age groups. Furthermore, sequences of correct RTs were not close to average but much slower. Finally, young children made multiple errors in succession more frequently than other age groups. Collectively, these data suggest inaccurate error detection and inefficient performance adjustments in young children.

Three other developmental studies examining PES used conflict rather than standard choice RT tasks. Jones et al. (2003) reported a developmental increase in PES examining 3- to 4-years olds performing on a go-nogo task. They interpreted this trend to suggest a developmental increase in cognitive control. It should be noted, however, that this conclusion is based on a limited number of trials (20 go vs. 20 nogo trials) and exceptionally high error rates (78%). Moreover, the age range under investigation was restricted to only one year. Schachar et al. (2004) examined PES across a more extended age range, 7 – 16 years, using a stop-signal task. They obtained a positive correlation between advancing age and response slowing following a failed inhibit. In contrast, van de Laar et al. (2011), using a similar stop-signal task, observed that response slowing following failed inhibits was age-invariant. Finally, Gupta et al. (2009) employed a task-switching paradigm including error feedback. They observed that PES decreased across an age range between 6 and 11 years and interpreted this pattern in terms of orienting towards the error signal (see Rabbitt & Rodgers, 1977). The remaining performance studies of PES in children did not have a developmental focus. Two studies showed that PES was present in children aged between 8 and 11 years (O’Connel et al., 2004; Ornstein et al., 2009) but one study failed to observe PES in children aged between 7 and 16 years (Yordanova et al., 2011). All in all, the performance studies investigating PES in children yielded a heterogeneous pattern of results.
The current, admittedly cursory, review of studies examining PES in children indicates that, given the paucity of developmental data, little definitive can be said about age-related change in PES. Both developmental decrease and invariance have been observed and a few studies reported even an increase in PES. The latter observation, an age-related increase in PES, would be compatible with developmental neuroscience studies examining error monitoring. These studies revealed a developmental increase in the ERN, an electrocortical manifestation of error detection or response conflict (for reviews Crone, 2014; Ferdinand & Kray, 2014; Tamnes et al., 2013). The developmental increase in ERN amplitude has been associated with the functional maturation of anterior cingulate cortex (ACC), a region of the medial frontal cortex that has been suggested to serve as an anatomical hub where performance-monitoring information is integrated to inform the highly interconnected networks subserving subsequent action selection (e.g., Luna, Marek, Larsen, Tervo-Clemmens, & Chahal, 2015). Within this framework, one would be led to predict a developmental increase in PES. On the hypothesis that the brain mechanisms implicated in error monitoring are not yet fully developed in young children most of their errors should go unnoticed and, thus, they lack the information needed for performance adjustments. Consequently, the speed of responding following an (unnoticed) error should not differ from the speed of responding following a correct response.

In view of the heterogeneous pattern of age-related change in PES, the primary goal of the present study was to perform a systematic assessment of developmental change in PES from childhood into adulthood. A standard two-choice RT task was used to generate PES patterns. We employed a standard choice RT task rather than a conflict task that is most prominent in the developmental literature on error processing. This was done for, primarily, two reasons. First, standard choice tasks generated stable PES patterns in adults (e.g., Laming, 1979). Secondly, the heterogeneous pattern that emerged from the child literature on error-processing might relate to the use of conflict tasks. The obvious advantage of using conflict tasks is a pronounced error rate and, thus, this type of task is cost-effective with regard to experimental time. Less trials are needed for obtaining sufficient errors and that is especially profitable when working with young children. A disadvantage, however, is that errors might be less salient compared to standard choice tasks, in particular for younger children. In this regard, the use of conflict tasks might obscure potential developmental trends in PES. Indeed, Brewer and Smith (1989) used a four-choice task and observed that the influence of performance tracking was already visible in 5-year olds. Finally, it should be noted that we used a standard two-choice rather than a standard multiple-choice task that has been standard in the adult literature. We opted for a two-choice task to avoid potential confusion between responses, so as to reduce the demands on response monitoring (e.g., Fairweather, 1978).
Consistent with the early adult literature on PES (e.g., Laming, 1968; Rabbitt & Vyas, 1970), we manipulated RSI from 50 to 1000 ms 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 or implement appropriate measures to ensure a more cautious response on the subsequent response. Two experiments will be conducted to assess the robustness of the age-related change in PES should such a trend occur. The assessment of the robustness of developmental change in PES seems warranted in view of the heterogeneous pattern that emerged from the literature available to date (see Table 1).

**EXPERIMENT 1**

Three age groups participated in the first experiment covering an age-range between 5 and 25 years. This range includes the ages examined by Davies et al. (2004) and Wiemersema 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 (5-12 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.

**METHOD**

**Participants**

Participants (N = 87) were recruited from three age groups; between 5 and 25 years of age. There was one group of 42 children between 5 and 12 (M = 8.5 (SD = 2.33) years; 21 girls). In addition, there was a group of 25 adolescents between the ages of 13 and 17 (M = 14.4 (SD = 1.28) years; 16 females). Finally, a group of 20 young adults between the ages of 18 and 25 (M = 21.9 (SD = 1.47) years; 10 females) enrolled in the experiment. A preliminary χ²-analysis evaluating potential gender differences across age groups failed to produce a significant outcome (p > .50). The children and adolescents were selected with the help of their schools and with permission of their caregivers. All children had average or above average intelligence based on teachers’ reports. The adolescents were recruited from a high school. The young adults (18-25 yrs) were undergraduate
psychology students. They were recruited by flyers and received course credits for their participation. All participants reported to be in good health and had normal or corrected-to-normal vision. Informed consent was obtained from the adolescent and adult participants and from the primary caregivers for the children. All procedures were approved by the Ethical Review Board of the University.

**Apparatus and task**
The experiment was run on 12-, and 15-in. screen PCs. Although the screens were different in size, the task-relevant displays were identical across PCs. A vertical, black line was presented through the center of the screen against a white background. The stimuli, red circles, were presented 5 cm to the left or right from the vertical line (1.5 cm). Participants viewed the monitor from a distance of 40-60 cm, and responded to the stimuli by pushing the ‘z’ key with their left-index finger or the ‘/’ key with their right-index finger. These keys are on the bottom row of a ‘qwerty’ keyboard. Participants performed on a relatively standard two-choice task; a red circle presented to the left of the vertical line asked for a left-hand button press while a red circle presented to the right of the vertical line required a right-hand button press.

**Design and procedure**
RT was recorded as the time between stimulus onset and the moment that one of the response keys was pushed. The stimulus was response terminated. The response initiated the RSI, which was fixed within experimental blocks either at 50, 150, 200, 250, 500 or 1000 ms. Participants performed under each RSI condition. The computer pseudo-randomized the order of RSI conditions across participants. An experimental session consisted of 24 experimental blocks; each RSI condition consisted of 4 consecutive blocks, with each block consisting of 100 trials. It was assumed that a total of 2400 trials would be sufficient to generate stable PES patterns (e.g., Dutilh et al., 2012). Before each RSI condition, participants performed a practice block of 50 trials. The first five trials in each experimental block were considered ‘warm-up’ and were excluded from statistical analyses. No error corrections were possible.

Between blocks there was a 30-s rest period, and after three RSI conditions (12 blocks) there was a 2-min break. A white screen crossed by the vertical black line initiated a new trial block. Participants received an on-screen instruction before starting the experiment. They were instructed to respond to the left stimulus by using their left hand and to the right stimulus by using their right hand. They were asked to respond quickly and to avoid errors. All participants were tested individually in a quiet laboratory or classroom, with similar ambient conditions (e.g., light-, noise- and temperature levels).
Participants spent approximately one hour in the laboratory (psychology students) or classroom (children and adolescents), including instructions and breaks.

**RESULTS**

Error rates and mean RTs are presented in Table 2 for each age group by RSI combination. The N in the table refers to the number of trial sequences, consisting of an error surrounded by correct responses, which entered into the analyses.

**Error rates**

Error rates were square-root transformed for skewness and submitted to ANOVA with Age group (3), as between Ss factor, and RSI (6) as within Ss factor. Adolescents ($M = 4.5\%, SD = 0.7\%$) make less errors than children ($M = 6.8\%, SD = 0.9\%) and adults ($M = 7.0\%, SD = 1.0\%)$, however, the ANOVA did not yield a significant main effect of Age group, $p > .06$. The main effect of RSI was not significant either, $p > .14$. Moreover, the interaction between the effects of age group and RSI did not reach an acceptable level of significance, $p > .21$.

**Table 2.** Error rate (total number of error trials), mean RT (ms) and N for each age group and RSI condition (Experiment 1).

<table>
<thead>
<tr>
<th>Age Group</th>
<th>RSI 50</th>
<th></th>
<th>RSI 150</th>
<th></th>
<th>RSI 200</th>
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<tbody>
<tr>
<td></td>
<td>Error</td>
<td>N</td>
<td>RT</td>
<td>Error</td>
<td>N</td>
<td>RT</td>
</tr>
<tr>
<td>5-12 yrs</td>
<td>35.4</td>
<td>8.6</td>
<td>763.1</td>
<td>25.3</td>
<td>10.6</td>
<td>615.8</td>
</tr>
<tr>
<td>13-17 yrs</td>
<td>14.5</td>
<td>7.2</td>
<td>394.8</td>
<td>18.0</td>
<td>10.1</td>
<td>382.2</td>
</tr>
<tr>
<td>18-25 yrs</td>
<td>22.3</td>
<td>11.9</td>
<td>351.0</td>
<td>27.9</td>
<td>17.8</td>
<td>306.6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Age Group</th>
<th>RSI 250</th>
<th></th>
<th>RSI 500</th>
<th></th>
<th>RSI 1000</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Error</td>
<td>N</td>
<td>RT</td>
<td>Error</td>
<td>N</td>
<td>RT</td>
</tr>
<tr>
<td>5-12 yrs</td>
<td>27.0</td>
<td>11.4</td>
<td>773.4</td>
<td>23.8</td>
<td>12.3</td>
<td>633.3</td>
</tr>
<tr>
<td>13-17 yrs</td>
<td>19.5</td>
<td>12.2</td>
<td>339.2</td>
<td>18.6</td>
<td>11.7</td>
<td>325.0</td>
</tr>
<tr>
<td>18-25 yrs</td>
<td>35.2</td>
<td>21.3</td>
<td>287.7</td>
<td>28.5</td>
<td>19.0</td>
<td>277.6</td>
</tr>
</tbody>
</table>

*Abbreviations*: yrs refers to years; RT to reaction time; RSI to response-to-stimulus interval (ms); N to the number of errors surrounded by correct responses (i.e., E-3, E-2, E-1, E, E+1, E+2 E+3).

3 It should be noted that the total number of errors is slightly larger than the N reported in the table. This is due to the requirement that all responses on trials surrounding an error should be correct (see Table 2; see also Brewer and Smith (1989)).
The RTs associated with trial sequences surrounding an error (i.e., 3 trials preceding the error, the error, and 2 trials following the error) are presented in Figure 1. For each age group errors are faster than correct responses on adjacent trials. The first response following an error is especially slow. Little change can be observed between the responses preceding the error.

**Complete RT sequence**

Median RTs were subjected to ANOVA with Age group (3) as between Ss factor, and RSI (6) and Trials (7; three trials before the error (E-3, E-2, and E-1), the error trial (E), and three subsequent trials (E+1, E+2, and E+3)), as within Ss factors. The analysis showed a developmental increase in the speed of responding, \( F(2, 84) = 34.35, p < .001, \eta^2_p = .45 \), and faster responses with a lengthening of RSI, \( F(5, 420) = 3.95, p < .011, \eta^2_p = .17 \). Moreover, a developmental decrease in the RSI effect was found, \( F(10, 420) = 3.20, p < .011, \eta^2_p = .07 \). Importantly, the effect of Trial was highly significant, \( F(6, 504) = 14.25, p < .001, \eta^2_p = .15 \), and was included in interactions with RSI, \( F(30, 2520) = 1.99, p < .002, \eta^2_p = .20 \), and Age group, \( F(12, 504) = 3.72, p < .001, \eta^2_p = .08 \). The higher order interaction including Age group, Trial and RSI was not significant, \( p > .97 \).

**Pre-Error RT**

Pre-error change in the speed of responding was evaluated by comparing RTs associated with the correct trials that immediately preceded the error (i.e., E-3, E-2, and E-1). The analysis indicated that the main effect of Trial was not significant and was not altered by the effects of RSI or Age group, \( ps > .57 \). Hence, the response speeding towards an error that has been observed in some studies (e.g., Brewer & Smith, 1989; Shiels, Tamm, & Epstein, 2012; but see Laming, 1979) is absent in the current data.

**Error RT**

The analysis aimed at the error trial, indicated that the speed of responding was significantly faster on the error trial compared to the average RT of the responses associated with the preceding trials (i.e., E-3, E-2, and E-1), \( F(1, 84) = 16.50, p < .001, \eta^2_p = .16 \). This Trial effect discriminated between age groups, \( F(2, 84) = 4.94, p < .009, \eta^2_p = .11 \), but not between RSI conditions, \( p > .99 \). The higher-order interaction was not significant either, \( p > .99 \). The RT difference (error vs. pre-errors) was larger for children (184.58 ms) compared to adolescents (47.23 ms) and adults (47.33 ms), \( ps < .04, \eta^2_p > .084 \). Adolescents and adults did not differ in this regard, \( p > .98 \). It should be noted, however, that the interaction between Trials and Age group did not survive when basic speed (i.e., age group RT) was included as a covariate, \( p > .93 \). This result indicates that the

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4 All \( p \)-values associated with post-hoc comparisons are Bonferroni-corrected.
What happens when children encounter an error?

Figure 1. Reaction time difference (ms), including standard error bars, relative to group average for each pre- and post-error trial, error trial, and response-to-stimulus interval (RSI) condition. Plots are presented for each age group, separately, in panel a, b, and c.
errors of children were not disproportionally faster compared to the two other age groups.

**Post-error RT**

PES was evaluated by comparing RT on the correct trial that immediately followed the error (i.e., E+1) to the average RT associated with the responses on the three trials preceding the error (i.e., E-3, E-2, and E-1). The analysis indicated that, as anticipated, the speed of responding was considerably slower on the post-error trial compared to the average speed of responding before the error (644 ms vs. 414 ms, respectively), $F(1, 84) = 55.85, p < .001, \eta^2_p = .40$. Most importantly, the analysis yielded a developmental decrease in PES, $F(2, 84) = 13.26, p < .001, \eta^2_p = .24$, which is plotted in Figure 2 (panel a). Subsequent analysis revealed that each age group differed significantly from the other, $p_s < .003, \eta_s^2p > .13$.

PES was influenced by RSI, $F(5, 420) = 3.55, p < .006, \eta^2_p = .18$. Contrast analyses revealed that PES was significantly smaller for RSI-1000 compared to the RSI-150 till RSI-500 ms, $p_s < .022, \eta_s^2p > .06$. Surprisingly, PES did not discriminate between the shortest vs. longest RSI (see Figure 2, panel b). The higher-order interaction between Trial, Age group and RSI was not significant, $p = .83$.

**Post-error recovery**

An analysis focusing on post-error recovery included the average of the three trials at the beginning of the sequence (i.e., E-3, E-2, and E-1) and the two trials subsequent to the post-error trial (i.e., E+2 and E+3). This analysis was done to evaluate the time it took for participants to attain a ‘safe’ level of responding again. The effect of Trial was highly significant, $F(2, 168) = 20.99, p < .01, \eta^2_p = .16$. This effect was not altered by Age group or RSI condition, $p_s > .54$. Subsequent analyses showed that RTs associated with E+2 and E+3 were significantly longer than the average RT of the pre-error trials, $p_s < .01, \eta_s^2p > .21$. Thus, it took at least two trials for participants to adjust from an error.

**Follow-up analyses**

We conducted three follow-up analyses for a complete assessment of the apparent age-related change in PES. First, although the $\chi^2$-analysis on gender failed to produce a significant outcome, we included gender as a covariate in the analysis. This did not impact the significant Age group x Trial type interaction, $F(2, 83) = 13.59, p < .001, \eta^2_p > .25$. Next, we included group RT as covariate. This analysis showed that the interaction between Age group and Trial did not reach significance anymore, $p > .64$. Hence, the age-related decrease in PES does not differ from the age-related decrease in the basic speed of responding. Thus, young children did not show a disproportional slowing fol-
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1. Following the error. Finally, it should be noted that error rates generated by the standard choice task were relatively low and differed across individuals. From the full sample, we selected those participants having a minimum \(N\) of 5 per cell. The analysis of the data

\[\text{Post-error Slowing (PES)}\]

\[\begin{array}{c|c|c|c}
\text{Age Group} & \text{Reaction time difference (ms)} \\
\hline
5-12 yrs & \text{Bar graph} \\
13-17 yrs & \text{Bar graph} \\
18-25 yrs & \text{Bar graph} \\
\end{array}\]

\[\text{Post-error Slowing (PES)}\]

\[\begin{array}{c|c|c|c|c|c|c}
\text{RSI} & \text{Reaction time difference (ms)} \\
\hline
RSI-50 & \text{Bar graph} \\
RSI-150 & \text{Bar graph} \\
RSI-200 & \text{Bar graph} \\
RSI-250 & \text{Bar graph} \\
RSI-500 & \text{Bar graph} \\
RSI-1000 & \text{Bar graph} \\
\end{array}\]

\[\text{Panel a. Post-error Slowing (PES), including standard error bars, for each age group. *Denotes significant differences in PES between indicated age groups. Panel b. Post-error Slowing (PES) as a function of response-to-stimulus interval (RSI). *Denotes significant differences between indicated RSI conditions. PES, both in a and b, has been computed as the average reaction time difference (ms) between the mean RT for trials E-3,-2,-1 vs. trial E+1.}\]

5 Total number of participants of the restricted sample was 58; 23 children (5-12 yrs; 12 girls), 17 adolescents (13-17 yrs; 10 females), and 18 young adults (18-25 yrs; 9 females). A \(\chi^2\)-analysis evaluating potential gender
of this restricted sample did not change the pattern obtained for the full sample. That is, a significant Age group x Trial interaction, $F(2, 55)=20.47, p < .001, \eta^2_p > .28$, that remained when including gender as covariate, $F(2, 54) = 10.96, p < .001, \eta^2_p > .29$, but did not reach significance when basic speed was included as covariate, $F(2, 54) = 3.13, p > .05, \eta^2_p > .10$.

**INTERIM SUMMARY**

The results that emerged from the first experiment are consistent with previous reports examining developmental change in the speed of responding in showing (1) a developmental increase in the speed of responding, (2) faster responses to longer RSIs, and (3) a developmental decrease in the RSI effect (e.g., Smulders et al., 2005). In addition, consistent with previous reports on PES, the current results showed that (4) errors are particularly fast and followed by response slowing. Furthermore (5) PES was smaller to the longest RSI compared to the shorter RSIs (e.g., Rabbitt & Rodgers, 1977). However, (6) in contrast to expectations PES did not discriminate between the shortest and longest RSI and (7) response speeding on trials just preceding an error was not observed (e.g., Laming, 1979). Most importantly, the results showed that (8) PES decreased with advancing age but (9) this developmental trend did not survive a test controlling for basic speed differences across age groups. Finally, (10) it took at least two trials to recover from an error but this effect did not discriminate between age groups. The current finding of a developmental decrease in PES should be qualified by the observation that this trend did not deviate from the age group differences in basic response speed. Our review identified only four studies that tested age-related change in PES (Carrasco et al., 2013; Fairweather, 1978; Gupta, Kar, & Srinivasan, 2009; Schachar et al., 2004) but none of these studies examined whether the observed age-related decrease in PES was disproportional. Experiment 2 was designed to re-address this issue. More specifically, the goal of this experiment was to test the robustness of the downward developmental trend in PES and to examine whether a substantial increase in observations would produce a disproportional trend.

**EXPERIMENT 2**

The primary goal of this experiment was to assess the robustness of the data-pattern that emerged from the previous experiment. The same two-choice task was used but the number of RSIs was reduced to two conditions (50 vs. 500 ms) and number of trials was increased from 4 blocks of 100 trials per RSI (previous experiment) to 24 blocks differences across age groups failed to produce a significant outcome ($p > .85$).
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of 100 trials per RSI (current experiment). Each participant performed the task on four separate sessions. The number of trials was increased in an attempt at obtaining a developmental PES pattern that would survive the rigorous test of controlling for basic speed differences between age groups. The increase in trial number served also the purpose of re-examining the somewhat erratic RSI x PES pattern that emerged from the first experiment. Although PES was reduced for RSI-1000 compared to the shorter RSIs it did not differ from the shortest RSI-50. The current comparison between RSI-50 vs. RSI-500 was selected because PES should be reduced from RSI-50 to RSI-500 and should not alter significantly beyond RSI-500 (see Laming, 1979).

METHOD

Participants
Participants (N = 63) were recruited from three age groups between 7-25 years of age. There were two groups of children; 16 children between 7 and 9 years of age (M = 7.9 (SD = 0.83) years; 5 girls); 23 children between 10 and 12 years of age (M = 11.2 (SD = 0.78) years; 9 girls). Finally, a group of 24 young adults between the ages of 18 and 25 (M = 19.8 (SD = 1.9) years; 20 females) enrolled in the experiment. A χ²-analysis evaluating potential gender differences across age groups produced a significant outcome, χ²(2)=13.69, p < .001, phi = .47. Thus, Gender will be included as covariate in subsequent statistical analyses. Although the specific age groups are somewhat different than those participating in the first experiment, the age-range under investigation is approximately similar.

Task, design and procedure
Participants performed on the 2-choice task used in Experiment 1. RSI was fixed within experimental blocks either at 50 or 500 ms. Participants performed under each RSI condition. The order of RSI conditions was counterbalanced across participants. An experimental session consisted of 12 experimental blocks; each RSI condition consisted of 6 consecutive blocks, with each block containing 100 trials. Before each RSI condition, participants performed a practice block of 50 trials. Between blocks there was a 30-s rest period, and after 12 blocks there was a 2-min break. Participants performed on a total of 4800 trials (i.e., 4 sessions x 6 blocks x 2 RSI conditions x 100 trials), during four individual testing sessions, scheduled within five consecutive days (i.e., the second and third sessions were separated by one day). The order of RSIs was consistent across sessions. All other details were similar to Experiment 1.
RESULTS

Error rates and mean RTs are presented in Table 3 for each age group by RSI combination (across session).

Error rates

Mean error rates (%) were submitted to a 2 (RSI; within subjects) x 3 (Age group; between-subjects) ANOVA. A main effect of Age group was absent, \( p > .62 \). RSI did affect error rate significantly (4.3% and 4.8% for RSI-50 and RSI-500 ms respectively), \( F(1, 60) = 4.66, p < .035, \eta^2_p = .072 \). The interaction between the effects of Age group and RSI did not reach significance, \( p > .19 \).

Complete RT sequence

The RTs associated with trial sequences surrounding an error (i.e., 3 trials preceding the error, the error, and 3 trials following the error) are presented in Figure 3. For each age group errors are faster than correct responses on the adjacent trials. The first response following an error is very slow. Median RTs were subjected to ANOVA with Age group (3), as between Ss factor, and RSI (2) and Trial (7; three trials before the error (E-3, E-2, and E-1), the error trial (E), and three subsequent trials (E+1, E+2, and E+3), as within Ss factors.

The analysis showed a developmental increase in the speed of responding, \( F(2, 60) = 25.07, p < .001, \eta^2_p = .50 \), and faster responses to longer RSIs, \( F(1, 60) = 14.82, p < .001, \eta^2_p = .23 \). The RSI effect decreased with advancing age, \( F(2, 60) = 8.31, p < .001, \eta^2_p = .25 \). The effect of Trial was highly significant, \( F(6, 360) = 70.66, p < .001, \eta^2_p = .58 \), and was included in interactions with RSI, \( F(6, 360) = 3.57 p < .002, \eta^2_p = .07 \), and Age group, \( F(12, 360) = 5.03, p < .001, \eta^2_p = .17 \). The higher order interaction including Age group,

<table>
<thead>
<tr>
<th>Age Group</th>
<th>RSI-50 Error Rate</th>
<th>RSI-500 Error Rate</th>
<th>N</th>
<th>N</th>
<th>RT RSI-50</th>
<th>RT RSI-500</th>
</tr>
</thead>
<tbody>
<tr>
<td>7-9 yrs</td>
<td>103.2</td>
<td>103.2</td>
<td>33.8</td>
<td>52.5</td>
<td>593.0</td>
<td>607.9</td>
</tr>
<tr>
<td>10-12 yrs</td>
<td>93.6</td>
<td>132.0</td>
<td>52.0</td>
<td>75.7</td>
<td>424.2</td>
<td>360.2</td>
</tr>
<tr>
<td>18-25 yrs</td>
<td>110.4</td>
<td>110.4</td>
<td>57.8</td>
<td>83.7</td>
<td>385.7</td>
<td>324.3</td>
</tr>
</tbody>
</table>

Abbreviations. yrs refers to years; RT to reaction time; RSI to response-to-stimulus interval (ms); N to the number of errors surrounded by correct responses (i.e., E-3, E-2, E-1, E, E+1, E+2, E+3).
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 Trial and RSI was not significant, $p > .39$. Collectively, these findings are identical to the pattern of results obtained in Experiment 1.

Pre-error RT

Pre-error speeding was evaluated by comparing RTs associated with the correct trials that immediately preceded the error (i.e., E-3, E-2, and E-1). The analysis indicated that the speed of responding did not differ significantly across trials, $p > .10$ and was not altered by the effects of RSI or Age group, $ps > .16$.

Error RT

The analysis of the speed of responding on the error trial indicated that the speed of responding was significantly faster on the error trial compared to the average RT associated with the three trials preceding the error trial (i.e., E-3, E-2, and E-1), $F(1, 60) = 52.78, p < .001, \eta^2_p = .45$. The Trial effect was not significantly altered by the effects of Age group and RSI, $ps > .23$.

Post-error RT

PES was evaluated by comparing RT on the correct trial that immediately followed the error (i.e., E+1) to the average RT of the responses associated with the three trials at the beginning of the sequence. The analysis indicated that the speed of responding was considerably slower on the post-error trial compared to the average speed of
responding on the three trials preceding the error (619 ms vs. 409 ms, respectively), $F(1, 60) = 118.59, p < .001, \eta^2_p = .65$ (PES effect). As anticipated, the analysis yielded a developmental decrease in PES, $F(2, 60) = 9.88, p < .001, \eta^2_p = .23$, which is plotted in Figure 4. Subsequent analysis revealed that each age group differed significantly from the others, $ps < .035, \eta^2_p > .10$. Finally, PES was influenced by RSI, $F(1, 60) = 15.00, p < .001, \eta^2_p = .19$. As can be seen in Figure 4, PES was significantly smaller for RSI-500 compared to the RSI-50 condition (i.e., 160 ms vs. 262 ms, respectively). The higher order interaction between Trial, Age group and RSI was not significant, $p > .47$.

**Post-error recovery**

The analysis focusing on the speed of post-error recovery (i.e., a comparison between the average RT of the three trials preceding the error vs. the RTs of the 2nd and 3rd trials following the error) yielded a highly significant main effect of Trial, $F(2, 120) = 19.24, p < .001, \eta^2_p = .29$. This effect did not discriminate between Age Groups and RSI conditions, $ps > .27$. Subsequent analyses showed that RTs associated with E+2 and E+3 differed significantly from the average RT of the pre-error trials, $ps < .002, \eta^2_p > .13$. Thus, it took at least two trials for participants to adjust from an error.

**Figure 4.** Post-error Slowing (PES), including standard error bars, for each age group and response-to-stimulus interval (RSI) condition. PES has been computed as the reaction time difference (ms) between the mean RT for trials E-3,-2,-1 vs. trial E+1.
Follow-up analyses

We conducted four sets of follow-up analyses. Similar to the previous experiment, we evaluated the potential influence of gender and group RT in assessing developmental change in PES. And similar to the previous experiment, we evaluated developmental change in PES for a restricted sample of participants; viz. only participants with a minimum N of 5. Finally, given the substantial amount of trials presented to our participants we evaluated the potential influence of time on task.

Recall that gender differed significantly between age groups. However, the analysis including gender as covariate did not really affect the Age group by Trial interaction; this interaction remained highly significant, $F(2, 59) = 9.44, p < .001, \eta^2_p > .24$).

Importantly, the analysis using group RT as covariate revealed that the Trial type by Age group interaction remained significant, $p < .003, \eta^2_p = .17$, indicating a disproportional age effect for PES.

The analysis on the restricted sample revealed that the pertinent Age group x Trial interaction remained significant, $F(2, 42) = 6.24, p < .004, \eta^2_p > .23$. Importantly, this interaction survived when correcting for group differences in basic speed, $F(2, 41) = 5.64, p < .007, \eta^2_p > .21$, and gender, $F(1, 41)= 7.68, p < .001, \eta^2_p > .27$.

Finally, it could be argued that our developmental pattern of findings might be compromised by the effects of fatigue or boredom in view of the considerable amount of trials. To address this issue, we conducted an analysis including Session (4) as an additional within Ss factor. Fatigue or Boredom should be manifested by an increase in RT across sessions. The results revealed the opposite; the analysis showed a significant decrease in RT from 490 to 422 ms, $F(3, 180) = 4.50, p < .006, \eta^2_p > .07$. Thus, the overall pattern suggests a beneficial effect of practice rather than a detrimental effect of fatigue or boredom. The effect of Session was qualified, however, by a significant interaction with Age group, $F(6, 180) = 2.99, p < .008, \eta^2_p > .09$. Young adults and older children showed a significant decrease with session, $p_s < .001$, while RT was relatively stable across sessions for the younger children, $p > .92$. Hence, the current pattern of PES results observed for the younger children is not influenced by time-on-task. For reasons of completeness we ran a similar analysis on error rates that showed a significant effect of Session, $F(3, 186) = 3.59, p < .015, \eta^2_p > .05$. However, error rate differed only

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6 The total number of participants for the restricted sample was 45; 7 young children (7-9 yrs; 3 girls), 17 older children (10-12 yrs; 6 girls), and 21 young adults (18-25 yrs; 18 females). A $\chi^2$-analysis evaluating potential gender differences across age groups produced a significant outcome, $\chi^2(2)=10.97, p < .004, phi = .49$. 

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between session 1 (3.9%) and 3 (5.1%), \( p < .006 \), not between other sessions, \( ps > .11 \). Session did not interact with Age group, \( p > .06 \).

**INTERIM SUMMARY**

The pattern of results that emerged from the second experiment is largely consistent with expectations; (1) Errors were faster than responses on preceding trials and the response on the trial immediately following an error was particularly slow (PES), (2) PES was now significantly more pronounced for the short RSI-50 compared to the long RSI-500, (3) PES decreased with advancing age, (4), in contrast to the results obtained in Experiment 1, this developmental trend did survive a test controlling for basic speed differences across age groups, and finally (5) it took all participants at least 2 trials to adjust to the error but this effect did not discriminate between age groups.

**DISCUSSION**

The current experiments yielded a consistent pattern of results consisting of a relatively fast error followed by PES. Response speeding towards the error was not observed but it should be noted that pre-error speeding is not a ubiquitous feature of the response pattern associated with errors. Although pre-error speeding seems part and parcel of the performance-tracking notion (e.g., Rabbitt & Rodgers, 1977) and is reported in some studies (e.g., Brewer & Smith, 1989; Dudschig & Jentzsch, 2009), it has been noted already by Laming (1979) that pre-error speeding is not a prerequisite for PES to occur (see also Rabbitt, 1966).

Most importantly, with regard to our developmental perspective, both experiments yielded a decrease in PES with advancing age. The results of the second experiment indicated that this trend was disproportional and, thus, cannot be interpreted in terms of developmental change in the speed of responding per se. The current findings are consistent with the results reported previously by Fairweather (1978) who interpreted PES in terms of interference due to error-correction responses. Presumably, young children are more sensitive to this interference than older ones. It should be noted, however, that Fairweather (1978) used a relatively short RSI (200 ms) and, thus, his interpretation might not apply to results obtained using longer RSIs. Brewer and Smith (1989), using a longer RSI, observed a pattern of response speeding towards the error and slowing following the error for adults that was less clear in children. These findings led Brewer and Smith (1989) to conclude that young children are less able in tracking their performance and regulating their speed accordingly. Unfortunately, the apparent age-related changes in PES were not evaluated statistically.
The current RSI x PES patterns differed across the two experiments. The RSI data from the first experiment showed that PES differed significantly between RSI-1000 vs. the shorter RSIs but, unexpectedly, not from the shortest RSI-50. Increasing trial numbers in Experiment 2 yielded the expected pattern. That is, PES associated with RSI-50 was considerably larger compared to PES related to RSI-500. Thus, the RSI-PES pattern that emerged from Experiment 2 is consistent with the extant PES literature (e.g., Rabbitt & Rodgers, 1977). We anticipated that the RSI effect on PES would be more pronounced for children compared to young adults but both experiments showed that the higher order interaction between Trial type, Age group and RSI was far from significant. Our prediction was based on the idea that errors attract reactions to the error—error corrections (Rabbitt, 1966), error monitoring (Welford, 1980), orienting (Notebaert et al., 2009)—that may interfere with the response on the post-error trial. On the account that children are more sensitive to interference (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 current data revealed an interesting pattern. Both experiments yielded two-way interactions between Trial type and RSI and between Trial type and Age group in the absence of three-way Trial type x RSI x Age group interactions. This pattern suggests 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. The orienting account of PES has been proposed by Notebaert et al. (2009) who obtained evidence to suggest 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. Orienting is short-lived and dissipates over time. Hence, on long RSI trials, 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 response caution only.

Two further issues remain to be addressed. The first is the heterogeneous pattern of findings reported by studies examining PES in children. It is difficult to present a unified account of these findings but task differences might be an important factor contributing to the heterogeneity. The few studies reporting a developmental decrease in PES employed relatively standard choice reaction tasks (Brewer & Smith, 1989; Fairweather,
1978). Berwid et al. (2014), however, used a two-choice task but reported stability rather than developmental change. It should be noted, however, that this age-invariance was based on only 40 trials and about 13% errors. Thus, the limited amount of observations might have prevented the detection of developmental change. Indeed, the current data testify of the importance of the number of trials as the increase in the number of trials in Experiment 2 resulted in (1) a developmental trend in PES going beyond the global age-related change in the speed of responding and (2) a substantial reduction in PES with a lengthening of RSI from 50 to 500 ms.

The current review indicated that most previous studies examining performance monitoring in children used various types of conflict tasks. Typically, these studies observed that PES was age-invariant (see Table 1). There are a few notable exceptions, however. Gupta et al. (2009) observed a developmental decrease in PES employing a task-switching paradigm. In contrast to most other studies, however, performance feedback was presented to signal errors. Jones et al. (2003) examined PES across a very limited age range (3 to 4 years) using a child-friendly go-nogo task. They observed an age-related increase in PES. But the limited amount of trials (i.e., 20 go vs. 20 nogo trials) and the huge differences in error proportions between age groups (i.e., 22, 76, 91%) presents a serious challenge to the reliability of the developmental pattern of PES reported in this study.

Two accounts, not mutually exclusive, might be offered for the recurrent absence of developmental change in PES reported by studies using a conflict paradigm. One possibility would be that, relative to standard choice tasks, errors are less easily detected in conflict paradigms thereby obscuring developmental changes in PES. This possibility could be examined using a conflict paradigm in combination with an error-signaling requirement (e.g., Ullsperger et al., 2014). An alternative possibility would be that participants, when confronted with a conflict task, are more cautious than when asked to perform on a standard choice task. Enhanced caution has been observed by van de Laar et al. (2011) when comparing RTs obtained using a standard choice task vs. RTs on go trials when stop-signal trials were inserted into the standard choice task. The change in the macro speed-accuracy tradeoff associated with conflict might obscure developmental changes in micro-speed accuracy tradeoff associated with performance monitoring. One notable exception, however, is provided by Schachar et al. (2004) who did obtain a developmental decrease in PES using a conflict task whereas other studies (see Table 1) did not, including the one reported by van de Laar et al. (2011). We do not have a ready explanation for this apparent discrepancy.
The other issue that needs to be addressed refers to the finding that PES can be observed in the absence of an ERN. Most studies, summarized in Table 1, observed that the ERN, but not PES, discriminated between age groups. This observation seems to suggest that the mechanism thought to generate the ERN is not a conditio sine qua non for PES to occur. Indeed, a lesion study showed alterations in ERN while patients could still be aware of their errors (Stemmer, Segalowitz, Witzke, & Schonle, 2004). Furthermore, Nieuwenhuis et al. (2001) reported, in typical participants, an ERN on trials even when the error on those trials was not rated as erroneous. These and similar findings have been interpreted to suggest a dissociation between implicit vs. explicit error detection (Ullsperger et al., 2014). With regard to development, 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 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. Although the alleged developmental shift from explicit to implicit error monitoring provides an elegant explanation for the age-related increase in the ERN it remains to be seen how this shift may alter developmental change in the strategic adjustments following an error. It could be hypothesized that, relative to explicit error monitoring, the more accurate and less taxing implicit monitoring might free-up resources for more efficient performance adjustments thereby decreasing PES. Future brain-potential research should address this hypothesis by examining the relative amplitudes of ERN and Pe vis-à-vis developmental change in PES.

CONCLUSION

Our review of developmental PES studies suggested a heterogeneous pattern of results. The majority of studies, mostly using conflict paradigms, showed developmental stability of PES and few studies, some using standard choice tasks, reported a developmental decrease. Tentatively, we advanced the hypothesis that conflict tasks induce greater caution that may obscure developmental differences in PES. It would be of considerable interest to examine the interplay between micro- and macro speed-accuracy tradeoff (e.g., Jentzsch & Leuthold, 2006; Wickelgren, 1977) in relation to developmental change in PES. Finally, on a methodological note, it should be added that trial numbers are important. A robust developmental trend in PES seems to require a substantial number of trials as evidenced by the current data (see Band, van der Molen, & Logan, 2003, for a similar observation regarding the stop-signal paradigm).
The current results of Experiment 2 were consistent with previous reports showing that PES is most pronounced when RSIs are short (e.g., Danielmeier & Ullsperger, 2011; Jentzsch & Dudschig, 2009). We suggested that errors elicit an orienting reaction (Notebaert et al., 2009) resulting in a short-lived de-activation of the motor system (e.g., Danielmeier, Eichele, Forstmann, Tittgemeyer, & Ullsperger, 2011) contributing to PES at short RSIs. It would be of interest to examine the temporal dynamics of the de-activation of the motor system and its release using brain potentials recorded over the primary motor cortex (van de Laar, van den Wildenberg, van Boxtel, Huizenga, & van der Molen, 2012). Although PES was smaller for the longer compared to the shorter RSI it was still substantial. Moreover, it should be noted that the RSI effect on PES did not differentiate between age groups. Typically, PES observed for longer RSIs is interpreted to result from criterion adjustments (e.g., Dutilh et al., 2012; Jentzsch & Dudschig, 2009; Laming, 1979); that is, the participant responds to an error by increasing response thresholds on the subsequent trial so as to ensure more accurate performance.

Most importantly, the current results of Experiment 2 showed a disproportional decrease in PES with advancing age. This finding indicates that young children are capable of detecting their errors but suggests that they are less able to implement performance adjustments. The current findings seem to suggest that it is not only a matter of efficiency, as the speed of PES recovery, indexed by the speed of responding on the two trials following the post-error trial, did not differ between age groups. The current findings suggest that when children encounter an error they have difficulty in regulating their speed of responding on the immediately subsequent trial.

Some speculation is in order with regard to the putative brain mechanisms mediating the response to an error. Recently, Agam et al. (2013) examined the pattern of brain network activation over a series of trials surrounding an error. They observed that responses preceding an error and the error response itself were associated with activation of the brain default mode network that has been linked to an internal processing focus (Buckner, Andrews-Hanna, & Schacter, 2008) while the correct response following an error was associated with the activation of the dorsal attention network that has been linked to effortful task-oriented attention (Szczepanski, Pinsk, Douglas, Kastner, & Saalman, 2013). Interestingly, the speed of performance adjustment following an error was correlated with greater microstructural integrity of the posterior cingulum cortex (PCC) suggesting its privileged position to mediate network interactions around errors (cf. Agam et al., 2013). It was hypothesized that the PCC is a critical mechanism mediating the balance of activity between the default mode and attention networks in response to others, and thereby reducing internal focus, increasing task orientation resulting in more careful and thus slower responding to prevent future errors.
This brain-network framework might provide a useful, albeit speculative, account of the current pattern of findings. Our results demonstrated that PES occurs in all age groups suggesting that children and adults do not differ in error detection. PES was larger in children relative to adults suggesting that age groups differ in error adjustment. Within the context of brain networks interactions, slower error adjustment in children might arise from a difficulty to de-activate the default mode network and engage the task-oriented attention network. Recent studies of the functional architecture of the maturing brain indicated that the negative correlation between default mode and task-oriented networks, typically seen in adult participants, is considerably less pronounced in younger age groups (Chai, Ofen, Gabrieli, & Whitfield-Gabrieli, 2014). Furthermore, it has been observed that fractional anisotropy, a putative measure of neural fiber coherence, diameter and myelination, of the cingulum bundle increase with advancing age in childhood and, importantly, is positively correlated with measures of executive functioning (Lebel et al., 2012; Peters et al., 2014). Collectively, these findings may suggest that maturation of the PCC plays a pivotal role in the ability to adjust performance in response to an error. It would be of considerable interest to apply a brain network analysis to developmental change in PES in order to obtain a more detailed view on the mechanisms mediating the child’s exaggerated response to an error.
How do children deal with conflict?
A developmental study of trial-to-trial conflict adaptation
ABSTRACT

This study examined age-related differences in the ability to deal flexibly with conflict, elicited in three tasks requiring the inhibition of prepotent responses; a Simon task, an S-R compatibility (SRC) task and a hybrid Choice-reaction/NoGo task. The primary focus was on developmental change in the ability to adjust performance following a conflict trial, i.e., a trial on which response- and location information do not correspond in the Simon task, a trial requiring a response opposite to the direction indicated by the stimulus in the SRC task, and a NoGo trial in the hybrid Choice-reaction/NoGo task. A secondary aim was to assess whether conflict adjustment follows different developmental trajectories depending on the type of conflict elicited by the tasks. Three age groups (7-9, 10-12 and 18-25-years of age) participated in this study; different participants were recruited for each of the three experiments; one task per experiment. In each experiment, the response-to-stimulus interval was manipulated (50 vs. 500 ms) across trial blocks to assess the time needed for conflict adjustment. The results showed sequential modulation of conflict on all three tasks, although the specific patterns differed between tasks. Importantly, the magnitude of sequential modulation decreased with advancing age, but this developmental trend did not survive when considering age-group differences in basic response speed. The current results contribute to the emerging evidence suggesting that patterns of conflict adaptation are task specific and challenge current interpretations of developmental change in conflict adaptation in terms of top-down control.
INTRODUCTION

The focus of the current study is on executive control of response conflict that may arise on trials of speeded response tasks and, more specifically, on conflict adaptation as manifested in the performance on trials following a conflict trial. Our main aim is to assess developmental trends in conflict adaptation from childhood into young adulthood and to examine whether this trend depends on the specific type of response conflict encountered by the participant.

The typical pattern observed in adult studies of conflict adaptation consists of a substantial reduction in the performance decrement on conflict trials when such a trial is preceded by another conflict trial relative to a non-conflict trial (Duthoo et al., 2014). Although this pattern attracted various interpretations (Egner, 2007; Braem et al., 2014, for reviews; Egner, 2014, for an attempt at reconciliation of different perspectives), the predominant hypothesis suggests that individuals 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 the 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 this view (e.g., Kerns et al., 2004) and the collateral hypothesis of individual differences in top-down cognitive control (e.g., Egner, 2011; Wang, Chou, Potter, & Steffens, 2015).

Surprisingly, there is only a handful studies examining conflict adaptation in children. Collectively, these studies yielded the anticipated pattern of findings reported in the adult literature. That is, a sizeable reduction of the conflict effect on trials following a conflict trial relative to the conflict observed on trials following a non-conflict trial. Stins et al. (2007) presented 12-year-olds with two conflict tasks; a Simon task and an Eriksen flanker task. In the Simon task, a red or green disk was presented left or right from fixation. Children were asked to respond to the color of the disk with a left or right response. The speed and accuracy of their response was evaluated on congruent trials (i.e., trials on which the location of the stimulus corresponded with the location of the response) and incongruent trials (i.e., trials on which the locations of stimulus and response were opposite). In the Eriksen task children were asked to respond to the direction of left- or right-pointing arrows presented at fixation. On half of the trials,
the target arrow was flanked by itself (i.e., congruent trials) and on the other half of the trials the target arrow was flanked by arrows pointing in the opposite direction (i.e., incongruent trials). Stins et al. (2007) observed that conflict adaptation was present on both the Simon task and the Eriksen flanker task. These findings seem to indicate that the mechanisms involved in conflict adaptation are in place already in 12-year-olds.

Iani et al. (2014) examined conflict adaptation in 1st and 2nd graders using a Simon task. They observed that the Simon effect was more pronounced in 1st relative to 2nd graders (65 ms vs. 41 ms, respectively). For 1st graders, the Simon effect decreased from 99 ms on trials preceded by a congruent trial to 33 ms on trials preceded by an incongruent trial. For 2nd graders the corresponding values were, respectively, 72 ms and 12 ms. The size of the conflict adaptation effect did not discriminate between groups. This pattern of findings extends the results reported by Stins et al. (2007) by showing that conflict adaptation is already present in 6-year olds. Iani et al. (2014) interpreted their findings in terms of on-line adjustments in top-down control following response conflict (p. 123).

A similar study has been performed by Ambrosi et al. (2016) who used three different tasks—an Eriksen flanker task, a Simon task and a version of a Stroop task—to assess conflict adaptation in a group of 5- to 6-year-olds. The Stroop task required participants to make a left- vs. right-hand response to the canonical color of a line drawing of a carrot or salad while ignoring the color displayed on the screen. The results reported by Ambrosi et al. (2016) showed a sizable conflict-adaptation effect for the Simon and Stroop tasks (respectively, 114 ms and 156 ms), whereas the effect was considerably less pronounced for the Eriksen flanker task (53 ms). This pattern of results is consistent with previous reports suggesting conflict adaptation in young children. Moreover, the results reported by Ambrosi et al. (2016) indicate that, although conflict adaptation occurs on all three tasks, the size of the effect differs across tasks suggesting specificity in the conflict elicited by each of the tasks (p. 123).

Finally, Cragg (2016) examined developmental change in the resolution of conflict using an Eriksen flanker task. Three age groups (7-, 10- and 20-year olds) performed on an Eriksen task in which interference could occur at the level of stimuli or responses. The results revealed that the sensitivity to stimulus interference decreased between 7 to 10 years while the effect of response interference did not differentiate between age groups. In addition, conflict adaptation was observed for all age groups and the size of this effect was similar across age groups.

The studies reviewed above indicated that conflict adaptation is present already in young children, but they did not evaluate developmental trends in conflict adaptation.
Two studies examined age-related change in conflict adaptation on tasks eliciting a conflict between stopping and going. Huizinga and van der Molen (2011) focused on flexible rule use. They employed an alternating runs paradigm in which a choice task was mixed with a NoGo task. This paradigm allowed them to assess transitions from a NoGo trial to choice reactions relative to sequences of choice reactions. They observed that choice reactions following a NoGo trial were considerably slower than choice reactions following another choice reaction (673 ms vs. 571 ms, respectively). Moreover, the conflict adaptation effect decreased with approximately 100 ms with advancing age from 7-year olds to young adults. Importantly, this developmental trend survived when controlling for age group differences in basic response speed. Huizinga and van der Molen (2011) interpreted their findings to suggest that the inhibition required on NoGo trials results in a lower readiness to respond on the subsequent choice reaction trial. Children would have greater difficulty in the fine-tuning of response thresholds (Huizinga & van der Molen, 2011; p. 499-500).

Van de Laar et al. (2011) examined conflict adaptation using a stop-signal task. In this task, participants were required to respond to the direction of a left- or right-pointing arrow. On a small proportion of trials the color of the arrow changed just following its onset. In one task, the color change indicated to the participants that a response should be withheld (i.e., Global stopping task). In another task, one color of the stop-signal informed the participant to refrain from responding while stop-signals of another color could be ignored (i.e., Selective stopping task). The results indicated that responses following a successful inhibit on a stop-signal trial were slower than responses on choice trials following another choice trial (i.e., 30 ms for the Global stopping task and 26 ms for the Selective stopping task). In contrast to the results observed by Huizinga and van der Molen (2011), there was only a small, and non-significant, developmental trend in the size of the conflict adaptation effect. In this regard, the results reported by van de Laar et al., (2011) contribute to the findings indicating that conflict adaptation varies across tasks depending on the conflict elicited by the task, which in turn may alter the developmental trend that can be observed.

Larson et al. (2012) used a standard Stroop task to examine conflict adaptation in two age groups; 8- to 11-year-olds and 19- to 30-years-olds. The results showed conflict adaptation in both age groups. The Stroop effect in adults decreased from 98 ms following an incongruent trial to 58 ms following a congruent trial. The corresponding values were, respectively, 110 ms and 59 ms in children. The conflict adaptation effect did not discriminate between age groups. Accordingly, Larson et al. (2012) echoed the conclusion of previous studies suggesting that in spite of the underdeveloped neural
mechanisms implicated in cognitive control, children seem to effectively regulate conflict adaptation processes (p. 355).

The results reported by Waxer and Morton (2011) present a challenge to the notions suggesting that conflict adaptation is already present in children. These authors examined developmental change in conflict adaptation using a version of the Dimensional Change Card Sort (Zelazo, 2006). On this task, participants were presented with two target pictures that differ in color and shape (e.g., a blue rabbit and a red truck). They were required to match a series of test pictures to the target pictures by either shape or color. Half of the trials elicited conflict, as the test stimulus could be sorted by either color or shape (e.g., a red rabbit), and half of the trials were neutral, as the test stimulus matches one target stimulus on one dimension (e.g., a blue bar). Three age groups participated in the experiment: 9 to 11-year-olds, 14- to 15-year-olds and young adults. The results revealed that adults and adolescents demonstrated conflict adaptation; that is, the conflict effect decreased following a conflict trial relative to a neutral trial. In contrast, children showed the opposite of conflict adaptation; the conflict effect was larger following a conflict trial relative to a neutral trial. Waxer and Morton (2011) interpreted their data in terms of top-down control, but they suggested that children resort to reactive rather than proactive control measures. That is, adults and adolescents were assumed to use prior conflict to prepare them for potential conflict on the subsequent trial whereas children respond to conflict as it occurs (Waxer and Morton, 2011; p. 1653).

The pattern of results that seems to emerge from the above review examining conflict adaptation in children makes a couple of important points. First, most studies observed conflict adaptation in children suggested that the control mechanisms implicated in conflict adaptation are already in place during childhood (but see Waxer & Morton, 2011). Secondly, only few studies examined developmental change in conflict adaptation and the outcomes of those studies are inconsistent. Thus, Larson et al. (2012) and Cragg (2016) reported that the magnitude of conflict adaptation did not discriminate between adults and children. In contrast, Huizinga and van der Molen (2011) and Waxer and Morton (2011) did report developmental change in conflict adaptation but trends were opposite. Huizinga and van der Molen (2011) observed a developmental decrease whereas Waxer and Morton (2011) reported that in their sample of young children conflict adaptation was absent. Thirdly, research on children’s conflict adaptation showed substantial differences in conflict adaptation between tasks (e.g., 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). Conflict tasks may differ with regard to the dimensional overlap between the relevant stimulus and response, the irrelevant stimu-
lus or between relevant and irrelevant stimuli (Kornblum & Stevens, 2002). Within this context, the conflict generated in the Simon task is between the irrelevant stimulus (i.e., its location of the respond stimulus) and the relevant response (i.e., a left or right reaction). In a Stroop task, the conflict is quite different due to the dimensional overlap between the relevant stimulus and response, the irrelevant stimulus and response and the relevant and irrelevant response. The conflict elicited in an Eriksen flanker task differs again from the previous ones, in that it is generated by representations of separate stimuli belonging to the same response set (see also Magen & Cohen, 2007). Different types of conflict may require separate modes of control and, indeed, this has been established both in behavioral research (e.g., Funes, Lupianez, & Humphreys, 2010) and neuroscience (e.g., Fan, McCandliss, Flombaum, Thomas, & Posner, 2003). Accordingly, Egner (2014), in reviewing the available evidence, concluded that conflict adaptation involves a complex machinery of bottom-up and top-down modulatory influences the exact implementation of which depends upon the specific conflict encountered. From a developmental perspective one might add that age-related changes in conflict adaptation may depend upon the specific conflict encountered and the modes of cognitive control that are available to the child.

THE CURRENT STUDY

The primary goal of the current study was to examine age-related change in conflict adaptation using three different conflict tasks that are sharing a common implementation format but differ in the type of conflict elicited by the task. That is, participants 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. The tasks were administered in separate experiments. In the first experiment, participants performed on a version of a standard Simon task. That is, participants responded to the color of the arrow while ignoring the direction indicated by the arrow. Because of the possible overlap between the response and the (irrelevant) directional information associated with the arrow stimulus, responses are relatively fast when the response and arrow direction are congruent and slow when they are incongruent (for a review, Lu & Proctor, 1995). In the second experiment, a stimulus-response compatibility (SRC) task was used in which there is overlap between the relevant stimulus and response set. In this task, the color of the arrow defined the S-R mapping rule; one color signals that the direction of the arrow indicates the responding hand while the other color signals that the opposite response should be executed. Typically, using a blocked presentation of SRC, responses are much faster on compatible relative to incompatible trials (for a review, Proctor & Reeve, 1990), but the speed advantage on compatible trials disappears with a mixed presentation of SRC (e.g,
In the third experiment, a hybrid Choice-reaction/NoGo task was used. In this task, left-pointing arrows in one color required a left-hand response while left-pointing arrows in the other color required response inhibition and, vice versa, right-pointing arrows in the one color required response inhibition while right-pointing arrows in the other color required a right-hand response. In this task, conflict is elicited by the automatic activation of the response indicated by the direction of the response and the need to suppress this response when the color of the arrow signals that a response to the arrow should be inhibited. This task involves a demanding conjunction analysis of relevant stimulus features (arrow direction and arrow color) and, thus, it can be anticipated that participants are prone to make a substantial amount of commission errors (e.g., McNab et al., 2008).

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 cognitive control increases with advancing age (e.g., Davidson et al., 2006; Luna et al., 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. Thus, the conflict in the Simon task arises from the overlap between an irrelevant stimulus feature (the direction of the arrow) and the location of the response, whereas in the other two tasks the conflict results from the interference between the S-R mappings in accordance with the instructions and the overlap between relevant stimulus features and the set of responses. Differences in conflict adaptation between the latter two tasks are anticipated as well. On incompatible trials in the SRC task, the conflict is between two competing responses; i.e., a pre-potent response indicated by the direction of the arrow vs. the opposite response according to the task instructions. On NoGo trials in the hybrid Choice-reaction/NoGo task, the conflict is between response activation to the stimulus vs. the inhibition of this response required by the task instructions. Moreover, the conjunction analysis required on this task may impose stronger demands on working memory, thereby increasing the conflict-adaptation effect (e.g., Ambrosi et al., 2016; Duthoo et al., 2014). Finally, given the hypothesis that conflict adaptation involves 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 stimulus-to-response (RSI) was very short (i.e., 50 ms) while
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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.

EXPERIMENT 1: CONFLICT ADAPTATION ON A SIMON TASK

The current version of the Simon task required participants to respond to the color of left- or right-pointing arrows while ignoring the directional information associated with the arrows. On half of the trials the location of the response, right- or left-hand response, corresponds with the direction indicated by the arrow, right or left, respectively, whereas on the other half of the trials the location of the response does not correspond with arrow direction. The former type of trials is dubbed ‘congruent’ and the latter ‘incongruent’. Numerous studies indicate that the task-irrelevant spatial information associated with respond stimuli in a Simon paradigm 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 location indicated by the stimulus (e.g., Eimer, 1999; Miles & Proctor, 2012).

On the hypothesis assuming that the ability to inhibit a pre-potent response develops rapidly during childhood (e.g., Dempster, 1992; van der Molen, 2000), one would be led to predict a decrease in the Simon effect with advancing age. Unfortunately, the relatively scant developmental literature yielded inconsistent findings. Jerger et al. (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 et al. (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 et al. (2006) presented age groups with visual implementations of a 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).

One aim of this 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. Recently, Ambrosi et al. (2016) observed a substantial Simon effect (48 ms) in 5-year olds and, most interestingly, the Simon effect was 105 ms on trials following a congruent trial whereas it was annihilated on trials following an incongruent trial. Thus, it was anticipated that a similar pattern would be observed here for the long RSI. Moreover, the current results should reveal a developmental trend assuming that conflict adaptation is a manifestation of top-down cognitive control. Such a developmental trend should be absent for the short RSI as both children and adults would need more time for the instantiation of appropriate conflict adaptation.

**METHOD**

**Participants**

Three age groups (N = 65) between 7-25 years of age participated in the experiment; a group of 21 young children between 7 and 9-years of age (M = 7.9 years; 12 girls), a group of 20 older children between 10 and 12-years of age (M = 11.4 years; 12 girls), and a group of 24 young adults between the ages of 18 and 25 (M = 21.0 years; 17 females) enrolled in the experiment. The children were selected with the help of their schools and with permission of their caregivers. All children had average or above average intelligence based on teacher reports. The young adults were undergraduate psychology students. They were recruited by flyers and received course credits for their participation. All participants reported to be in good health and had normal or corrected-to-normal vision. Informed consent was obtained from adult participants and primary caregivers of the children. All procedures were approved by the Ethical Review Board of the University.

**Apparatus and stimuli**

The experiment was run on 12-, and 15-in. screen computers and laptops. Stimuli were presented at the center of the screen, against a white background. The stimuli were left- vs. right-pointed arrows in red or blue and measuring 1.5 cm length and width. Participants viewed the monitor from a distance of 40-60 cm, and responded to the stimuli by pushing the ‘z’ key with their left-index finger or the ‘/’ key with their right-index finger. These keys are on the bottom row of a ‘qwerty’ keyboard. The computer coded response accuracy and registered the speed of responding to the nearest millisecond. Reaction time (RT) was recorded as the time between stimulus onset and the moment that one of the response keys was switched. The response triggered the offset of the stimulus and started the response-to-stimulus interval (RSI), which was fixed at either 50 or 500 ms.
**Design and procedure**

Participants performed a choice RT task in which they made a binary response to the color of the arrow while ignoring arrow directions. Red arrows required a left-hand response and blue arrows a right-hand response, or vice versa (counterbalanced across participants). An experimental session consisted of 10 experimental blocks; 5 short RSI blocks (50 ms) and 5 long RSI blocks (500 ms). Each RSI condition started with a 50-trial practice block, followed by the five experimental blocks consisting of 100 trials. The order of the RSI conditions was counterbalanced across participants.

**RESULTS AND DISCUSSION**

For each age group and RSI, trials were sorted for Current trial congruence (congruent vs. incongruent current trials), and Preceding trial congruence (congruent vs. incongruent preceding trials).

**Error rate**

Errors and trials following an error were excluded from RT sorting. Error rates and median RTs are presented in Table 1, for each of the above trial categories. Error rates were square-root transformed prior to further analysis. Error rates were relatively low (5.0%) and decreased with advancing age (5.8, 5.1, and 4.3 % for children, older children, and adults).

<table>
<thead>
<tr>
<th>Table 1.</th>
<th>Mean RT (ms) and Error Rate (%) for each trial sequence, RSI and age group (Experiment 1).</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>RT (ms)</strong></td>
<td>RSI-50</td>
</tr>
<tr>
<td><strong>Trial Sequences</strong></td>
<td>C-C</td>
</tr>
<tr>
<td>Age Group</td>
<td>7-9 yrs</td>
</tr>
<tr>
<td>7-9 yrs</td>
<td>558.30</td>
</tr>
<tr>
<td>10-12 yrs</td>
<td>529.30</td>
</tr>
<tr>
<td>18-25 yrs</td>
<td>435.38</td>
</tr>
</tbody>
</table>

*Note. C-C: current Congruent trial preceded by a Congruent trial; C-IC: current Incongruent trial preceded by a Congruent trial; IC-C: current Congruent trial preceded by an Incongruent trial; IC-IC: current Incongruent trial preceded by an Incongruent trial.*
adults, respectively), $F(2, 62) = 6.19$, $p < .004$, $\eta^2_p = .17$. The Simon congruency effect on error rate did not reach significance; 5.1 and 5.0% on congruent vs. incongruent trials, respectively, $p > .35$, and was not influenced by congruency on the preceding trial, $p > .92$. Error rates correlated positively with RTs. Thus, the current findings rule out explanations in terms of speed accuracy trade-off.

**Response speed**

The speed of responding increased with advancing age, $F(2, 62) = 80.84$, $p < .001$, $\eta^2_p = .72$. Adults responded faster ($M = 437$ ms) than both older ($M = 581$ ms) and younger children ($M = 626$ ms). Follow-up tests indicated that each age group differed significantly from the other; $ps < .001$ for comparisons between adults vs. both groups of children, and $p < .023$ for the comparison between both child groups, $\eta^2_{ps} > .17$. RTs were longer to the short RSI, 566 ms, compared to the long RSI, 530 ms, $F(1, 62) = 33.50$, $p < .001$, $\eta^2_p = .35$. The RSI effect increased with advancing age; young children, 13 ms, older children, 31 ms, young adults, 62 ms, $F(2, 62) = 5.79$, $p < .005$, $\eta^2_p = .16$.

The RTs revealed a pronounced Simon congruency effect, $F(1, 62) = 1527.80$, $p < .001$, $\eta^2_p = .96$. The speed of responding on incongruent trials was considerably slower than on congruent trials ($M = 588$ ms and $M = 508$ ms, respectively). Importantly, the Simon effect was altered significantly by Age group, $F(2, 62) = 41.89$, $p < .001$, $\eta^2_p = .58$. The Simon effect was smaller for adults ($M = 55$ ms) compared to the older ($M = 97$ ms) and young children ($M = 88$ ms), who did not differ significantly, $p > .11$. The Simon effect was larger for long compared to short RSIs; respectively, 95 ms vs. 64 ms. But this effect was observed only for children, $ps < .001$, not adults, $p > .58$.

As anticipated, the Simon effect was altered significantly by Congruency on the immediately preceding trial, $F(1, 62) = 383.74$, $p < .001$, $\eta^2_p = .86$. The Simon effect was considerably larger on trials preceded by a congruent trial ($M = 121$ ms) relative to an incongruent trial ($M = 38$ ms). Notably, the Trial sequence effect interacted with the effect of Age group, $F(2, 62) = 34.21$, $p < .001$, $\eta^2_p = .53$ and RSI, $F(1, 62) = 36.79$, $p < .001$, $\eta^2_p = .37$. This interaction was qualified by a higher-order interaction comprising RSI, Age group and Trial sequence, $F(2, 62) = 24.52$, $p < .001$, $\eta^2_p = .44$. This interaction is plotted in Figure 1. It can be seen that there is a sizeable Simon effect on trials following a congruent trial associated with both the 50 ms RSI (left panel of the figure) and the 500 ms RSI (right panel). The Simon effect is considerably smaller on trials following an incongruent trial for the 500 ms RSI and basically annihilated on trials following an incongruent trial for the 50 ms RSI. The data suggest that the trial-to-trial modulation decreases with advancing age for both RSIs.
Follow-up analyses were performed for both RSIs, separately. The analysis performed on the data associated with the 50 ms RSI indicated that the trial-to-trial modulation of the Simon effect was significant in all three age groups ($p < .001$). In addition, the size of the trial-to-trial modulation effect decreased with advancing age, $F(2, 62) = 43.47$, $p < .001$, $\eta^2_p = .58$, with each age group differing significantly from the other ($p < .002$). However, a subsequent analysis, controlling for age-group differences in basic response speed, revealed that the apparent age-related change in conflict-adaptation was not disproportional. The analysis of the results associated with the 500 ms RSI yielded a significant conflict-adaptation effect in all three age groups ($p < .001$), but the apparent age-related trend failed to reach significance ($p > .16$).

At this point, it should be noted that conflict adaptation has been argued to be due primarily to the repetition of features across trial sequences rather than top-down control (e.g., Mayr, Awh, & Laurey, 2003). Indeed, it has been observed that the apparent conflict adaptation effect occurs only or more strongly on trials repeating features of the immediately preceding trial. Accordingly, conflict-adaptation would be due to a lower-order repetition priming rather than conflict-driven control adjustments (for a review Schmidt et al., 2015). The current data-set did not contain a sufficient number of trials for a full examination of the repetition-priming account of conflict adaptation. Thus, we averaged data across the two RSIs and categorized trial sequences in terms of repetitions vs. alternations of arrow direction. The analysis revealed that the Simon
effect following congruent trials was somewhat larger, albeit significantly, for feature repetitions relative to alternations, respectively 126 ms vs. 116 ms, $F(1, 62) = 4.45, p < .04, \eta^2_p = .07$. This pattern reached significance in adults only, $p < .028, \eta^2_p > .19$, but not in both child groups, $p_s > .11$.

In conclusion, the current results yielded a pronounced Simon effect that decreased in magnitude with advancing age replicating previous results (Davidson et al., 2006; Jerger, 1999; but see Band et al., 2000). Consistent with adult studies, the current results showed that the Simon effect was considerable reduced on trials following an incongruent trial relative to a congruent trial (e.g., review in Kerns, 2006). This sequential modulation pattern was different between the 50 ms and 500 ms RSI. For both RSIs, there was a robust Simon effect on trials preceded by a congruent trial. For the 500 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 the RSI was 50 ms. The apparent age-related change in the sequential modulation pattern failed to reach significance for the results associated with the 500 ms but showed a significant downward trend for the results associated with the 50 ms. It should be noted, however, that this trend was not disproportional.

Three results that emerged from this experiment are noticeable. First, the results associated with the 50 ms RSI showed that the Simon effect observed on trials following a congruent trial was annihilated on trials following incongruent trials. This result stands in contrast with findings reported in the adult literature suggesting that conflict adaptation does not occur when the RSI is short. Thus, Notebaert et al. (2006) observed that conflict modulation, which was clearly present when the RSI was 200 ms, was absent when RSI was reduced to 50 ms. From this observation, it was concluded that conflict modulation needs some time to be configured. However, the current findings present a challenge to this conclusion. The apparent discrepancy between the current findings and the results reported previously by Notebaert et al. (2006) could be due to the use of different tasks. Notebaert et al. (2006) examined the time course of conflict adaptation using a version of a Stroop task whereas a Simon-task was used in the present Experiment. In this regard, the current finding would add to the literature emphasizing the domain specificity of conflict-adaptation effects (e.g., Braem et al., 2014).

The second result that stands out refers to the observation that the size of the conflict modulation in children did not differ from adults. If anything, the size of the effect was larger in young children compared to adults, albeit not significant for the 500 ms RSI and not disproportional for the 50 ms RSI. Given the abundant literature suggesting that cognitive control follows a protracted developmental course (Albert & Steinberg,
How do children deal with conflict?

2011; Anderson, 1998; Best & Miller, 2010; Best, Miller & Naglieri, 2011; Hughes, 2011; Huizinga et al., 2006; Luciana & Nelson, 2002; Lyons & Zalazo, 2011; Romine & Reynolds, 2005; Tamnes et al., 2010; Vuontela et al., 2013) and studies suggesting that young children readily resort to reactive control rather than adopting a proactive control strategy (Chatham et al., 2009; Munakata et al., 2012), one would be led to predict that the conflict-adaptation effect would be larger in adults compared to children, not smaller.

Finally, the analysis examining the potential contribution of repetition vs. alternation effects in conflict adaptation revealed that these effects interact with conflict modulation in adults but not in the child groups. This observation is in accord with the results reported by Waxer and Morton (2011). These authors examined whether associative priming influenced their results by removing exact stimulus repetition trials from the analysis of developmental change in conflict adaptation. This restricted analysis indicated that associative priming did not meaningfully change the developmental pattern observed when considering the full dataset.

EXPERIMENT 2: CONFLICT ADAPTATION ON A S-R COMPATIBILITY (SRC) TASK

In the present version of the SRC task, the stimuli were identical to those used in the previous experiment. Participants were asked to respond to the direction of the central arrow stimuli. The arrows were presented in two different colors; one color instructed 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 instructed 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). Importantly, arrow color was mixed within trial blocks. The mixing of compatible and incompatible trials has been observed to annihilate the response speed advantage of compatible over incompatible trials when presented in pure blocks (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). More specifically, compatibility mixing reduces the speed of responding on compatible trials relative to blocked presentation, whereas presentation mode has only a minor effect on the speed of responding on incompatible trials. This pattern has been taken to suggest that compatibility mixing induces 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 et al., 1994).
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), for example, 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. Casey et al. (2002) reported that the cost of an incompatible relative to a compatible mapping 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 with advancing age. At this point, it is difficult to provide a ready interpretation of the apparent inconsistencies between studies. 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.

The goal of this experiment was to examine developmental change in conflict adaptation using an SRC task with a mixed presentation of compatible and incompatible trials. Consistent with previous studies, we anticipated that the typical SRC pattern associated with pure blocks (i.e., slower responses on incompatible relative to compatible trials) would be greatly reduced, or even absent, when using mixed SRC blocks (e.g., van Duren & Sanders, 1992; Stoffels, 1996). When examining trial sequence effects, we predicted obtaining a greatly reduced or even reversed SRC effect on trials following an incompatible trial relative to a compatible trial (e.g., Jennings, van der Molen, van der Veen, & Debski, 2002; Mansfield et al., 2012). On the hypothesis that the reduction of the SRC effect following an incompatible trial reflects top-down cognitive control (De Jong, 1995; Jennings et al., 2002; Mansfield et al., 2012), we predicted that the reduction of the SRC effect following an incompatible trial would be more prominent with advancing age.
METHOD
Participants
Participants \((N = 64)\) were recruited from three age groups. There were two groups of children; 23 children between 7 and 9 years of age \((M = 8.2\) years; 14 girls\) and 21 children between 10- and 12-years of age \((M = 11.7\) years; 11 girls\). Finally, a group of 20 young adults between the ages of 18 and 25 \((M = 22.3\) years; 15 females\) enrolled in the experiment. The children were selected with the help of their schools and with permission of their caregivers. All children had average or above average intelligence based on teacher reports. The young adults were undergraduate psychology students. They were recruited by flyers and received course credits for their participation. All participants reported to be in good health and had normal or corrected-to-normal vision. All procedures were approved by the Ethical Review Board of the University.

Apparatus and stimuli
All details concerning the apparatus and stimuli were the same as in Experiment 1.

Design and procedure
Participants were asked to respond to the direction indicated by blue arrows and in the opposite direction to red arrows, or vice versa (counterbalanced across participants). All other design details were the same as in Experiment 1.

RESULTS AND DISCUSSION
For each age group, trials were sorted for Current compatibility (compatible vs. incompatible current trials), Preceding compatibility (compatible vs. incompatible preceding trials), and RSI (50 vs. 500 ms). Errors and trials following an error were excluded from RT sorting. Error rates and median RTs are presented in Table 2, for each of the above categories. Error rates were square-root transformed prior to analyses.

Error rate
In Table 2 it can be seen that error rates are relatively low (≤ 8.2%). Error rates decreased with advancing age (from 7.5% in young children, to 7.2% in older children and 5.8% in adults), \(F(2, 61) = 12.53, p < .001, \eta^2_p = .29\). Error rate was only slightly higher on incompatible \((M = 6.9\)%) than compatible trials \((M = 6.7\)%), \(F(1, 61) = 15.22, p < .001, \eta^2_p = .20\), and this effect differed across age groups, \(F(2, 61) = 22.46, p < .001, \eta^2_p = .42\). Adults and young children made more errors on incompatible than compatible trials \((5.7\% \text{ vs. } 5.9\% \text{ for adults, } 7.2\% \text{ vs. } 7.8\% \text{ for young children, } ps < .001\)\). Older children showed the opposite pattern \((7.3\% \text{ vs. } 7.0\%), p < .016\). The interaction between RSI and
Current compatibility was not significant, $p > .20$, but both effects were included in a complex higher-order interaction; Current compatibility x Preceding compatibility x Age group and RSI, $F (2, 61) = 32.99, p < .001, \eta^2_p = .52$.

In the bottom panel of Table 2, it can be seen that error rate in young children and adults, but not older children, is somewhat lower on incompatible trials preceded by another incompatible trial relative to incompatible trials followed by a compatible trial when RSI is short. This pattern changes into its opposite when RSI is long (i.e., both young children and adults did not show any error rate differences between both trial sequences, but older children made more errors on IC-IC as compared to C-IC sequences). Finally, error rates correlated negatively with the speed of responding indicating that the RT patterns reported below cannot be attributed to shifts in speed-accuracy tradeoff.

**Response speed**

The speed of responding increased with advancing age, $F(2, 61) = 190.72, p < .001, \eta^2_p = .86$. Adults responded faster ($M = 687$ ms) than older ($M = 805$ ms) and younger children ($M = 956$ ms). Follow-up tests indicated that each age group differed significantly from the other ($ps < .001$). Responses were faster to a long RSI ($M = 753$ ms) compared to a short RSI ($M = 879$ ms), $F (1, 61) = 163.04, p < .001, \eta^2_p = .73$. The RSI effect was stronger in children compared to young adults, $F (2, 61) = 4.70, p < .013, \eta^2_p = .13$. 

---

**Table 2.** Mean RT (ms) and Error Rate (%) for each trial sequence, RSI and age group (Experiment 2).

<table>
<thead>
<tr>
<th>Trial Sequences</th>
<th>Age Group</th>
<th>C-C</th>
<th>C-IC</th>
<th>IC-C</th>
<th>IC-IC</th>
<th>C-C</th>
<th>C-IC</th>
<th>IC-C</th>
<th>IC-IC</th>
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<tr>
<td></td>
<td>7-9 yrs</td>
<td>836.71</td>
<td>1142.96</td>
<td>1143.62</td>
<td>887.81</td>
<td>773.83</td>
<td>1007.30</td>
<td>1062.33</td>
<td>797.29</td>
</tr>
<tr>
<td></td>
<td>10-12 yrs</td>
<td>745.28</td>
<td>956.03</td>
<td>988.34</td>
<td>768.70</td>
<td>614.56</td>
<td>821.95</td>
<td>854.45</td>
<td>692.09</td>
</tr>
<tr>
<td></td>
<td>18-25 yrs</td>
<td>651.29</td>
<td>878.46</td>
<td>875.96</td>
<td>674.67</td>
<td>511.20</td>
<td>676.27</td>
<td>688.81</td>
<td>541.15</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Trial Sequences</th>
<th>Age Group</th>
<th>C-C</th>
<th>C-IC</th>
<th>IC-C</th>
<th>IC-IC</th>
<th>C-C</th>
<th>C-IC</th>
<th>IC-C</th>
<th>IC-IC</th>
</tr>
</thead>
<tbody>
<tr>
<td>RT (ms)</td>
<td>7-9 yrs</td>
<td>6.6</td>
<td>8.1</td>
<td>6.2</td>
<td>7.1</td>
<td>8.0</td>
<td>7.9</td>
<td>8.2</td>
<td>7.8</td>
</tr>
<tr>
<td></td>
<td>10-12 yrs</td>
<td>7.1</td>
<td>7.0</td>
<td>7.9</td>
<td>7.0</td>
<td>7.9</td>
<td>6.3</td>
<td>6.5</td>
<td>8.1</td>
</tr>
<tr>
<td></td>
<td>18-25 yrs</td>
<td>5.9</td>
<td>6.3</td>
<td>5.8</td>
<td>5.3</td>
<td>5.8</td>
<td>6.0</td>
<td>5.2</td>
<td>6.1</td>
</tr>
</tbody>
</table>

Note: C-C: current Compatible trial preceded by a Compatible trial; C-IC: current Incompatible trial preceded by a Compatible trial; IC-C: current Compatible trial preceded by an Incompatible trial; IC-IC: current Incompatible trial preceded by an Incompatible trial.
As anticipated, there was little difference in the speed of responding between compatible, 801 ms, vs. incompatible trials, 831 ms, \( p > .16 \). The apparent elimination of the typical SRC effect (i.e., slower responses on incompatible than compatible trials), due to the mixed presentation of SRC mappings, was present for each age group; i.e., the main effect of SRC did not interact with the effect of Age group (\( p > .90 \)). Importantly, there was a highly significant trial-by-trial modulation of the SRC effect, \( F(1, 61) = 565.64, p < .001, \eta^2_p = .90 \). Compatible responses were considerably faster than incompatible responses when the preceding trial was compatible (\( M = 689 \) ms vs. \( M = 914 \) ms, respectively). When the current trial followed an incompatible trial, however, the SRC effect changed into its opposite (\( M = 936 \) ms for compatible trials vs. \( M = 727 \) ms for incompatible trials). This pattern is consistent with previous studies (e.g., Jennings et al., 2002; Mansfield et al., 2012) and indicates that the S-R compatibility effect is not eliminated by the mixed presentation of SRC. The trial sequence effect was altered by RSI, \( F(1, 61) = 9.70, p < .003, \eta^2_p = .14 \). For the 50 ms RSI, the SRC effect was 248 ms for trials preceded by a compatible trial and -226 ms when the preceding trial was incompatible. For the 500 ms RSI, these values were, respectively, 202 ms and -192 ms.

There was a highly significant interaction between the effects of Current SRC, Preceding SRC, and Age group, \( F(2, 61) = 7.47, p < .001, \eta^2_p = .20 \), suggesting a developmental trend in conflict adaptation. This interaction is plotted in Figure 2. The figure indicates that SRC on the preceding trial alters the SRC effect on the current trial and this effect is stronger for the youngest children relative to the two older age groups. It should be noted, however, that the higher-order interaction did not survive when Group RT was included as covariate, \( p > .54 \). The higher-order interaction including RSI was not significant (\( p > .63 \)).

Finally, as in the previous experiment, we averaged the data across RSIs to evaluate repetition effects on the trial sequence effect on S-R compatibility. The analysis indicated that response repetition significantly altered the trial sequence effect on S-R compatibility, \( F(1, 61) = 192.4, p < .001, \eta^2_p = .75 \). That is, for response repetitions the S-R compatibility effect was 325 ms when the preceding trial was compatible relative to -307 ms when the preceding trial was incompatible. For response alternations, these values were much smaller; respectively, 125 ms and -110 ms. These effects did not discriminate between age groups, \( p > .11 \).

In conclusion, the current results are consistent with the recurrent finding that mixing SRC trials within blocks eliminates the typical SRC effect (e.g., De Jong, 1995; Stoffels, 1996; van Duren & Sanders, 1992) or changes the SRC effect into its opposite (e.g., Mansfield et al., 2012). The current study adds to this literature by showing that the
reversal of the SRC effect associated with mixed blocks occurs in each of the participating age groups. Importantly, the results showed a trial-by-trial modulation effect. That is, a typical SRC effect was observed following a compatible trial, but a reversal of the SRC effect occurred on trials following an incompatible trial. This finding is consistent with previous findings (e.g., Jennings et al., 2002; Mansfield et al., 2012) and suggests that mixing does not eliminate SRC effects.

The sequential modulation effect decreased with advancing age and was not influenced by associative priming. However, the developmental trend in conflict adaptation was not disproportional when considering global group differences in the speed of responding. Finally, in contrast to expectations derived from the results reported by Notebaert et al. (2006), the conflict adaptation effect was larger on trial blocks with a 50 ms RSI relative to effect associated with a 500 ms RSI. This pattern is similar to the findings obtained in the previous experiment using a Simon task and, thus, suggests that it is not task-specific.

**Figure 2.** Reaction time difference (ms), including standard error bars, between current incompatible vs. compatible trials (i.e., SRC effect) for preceding incompatible (IC) and compatible (C) trials, and for each age group.
EXPERIMENT 3: CONFLICT ADAPTATION ON A HYBRID CHOICE-REACTION/NOGO TASK

We used a hybrid Choice-reaction/NoGo task task derived from van Boxtel, van der Molen, Jennings, and Brunia (2001). In this task, a left- or right-pointing arrow is presented in red or blue color. The combination of arrow direction and color determines whether a response should be executed or withheld. Thus, a red and left-pointing arrow may require a left-hand response while a red and right-pointing arrow requires response inhibition or a blue and right-pointing arrow may require a right-hand response while a blue and left-pointing arrow may ask for response inhibition. Adult findings derived from a variety of Go/NoGo tasks showed that the speed of responding is delayed on Go trials following a NoGo trial relative to a Go trial (e.g., Hoffmann et al., 2003; Kleinsorge & Gajewski, 2004; Rieger & Gauggel, 1999; Rieger et al., 2003; Schuch & Koch, 2003).

In the developmental literature, 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 et al., 2010; Huizinga & van der Molen, 2011; Iida, Miyazaki, & Uchida, 2010; Johnstone et al., 2007; Jonkman et al., 2003; Levin et al., 1991; Luria, 1961; Span et al., 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).

Huizinga and van der Molen (2011) examined developmental change in the speed of responding on choice reaction trials when these trials were preceded by a NoGo trial vs. another choice reaction trial. They observed that choice reactions were significantly delayed when preceded by response inhibition on a NoGo trial relative to response execution on a choice-reaction trial. Moreover, the conflict-adaptation effect was disproportionally larger in young children relative to adolescents and adults. In one important respect, however, the current implementation of the hybrid Choice-reaction/NoGo task was different from the one used by Huizinga and van der Molen (2011). That is, the current task required a demanding conjunction analysis of the direction and color information provided by the arrow stimulus in order to retrieve the appropriate response. The conjunction analysis may impose substantial demands on working memory taking away capacity needed for the configuration of conflict-adaptation measures. Given the protracted course of working-memory development (e.g., Huizinga et al., 2006), we assumed that the absorption of capacity due to the conjunction analysis will disproportionally reduce the capacity young children have available for conflict
adaptation. Huizinga and van der Molen (2011) interpreted the slowing of choice reactions on trials following a NoGo trial in terms of a reduced readiness to respond. The larger effect observed for young children was then interpreted to suggest that they have greater difficulties in fine-tuning response thresholds following conflict. On the hypothesis that working-memory, conflict-adaptation, and working-memory demands interact (e.g., Gulbinaite, van Rijn, & Cohen, 2014; Weldon, Mushlin, Kim, & Sohn, 2013), we anticipated to observe a pronounced downward trend in the conflict-adaptation effect with advancing age.

**METHOD**

**Participants**

Participants ($N = 66$) were recruited from three age groups; between 7-25 years of age. There were two groups of children; 20 children between 7 and 9-years of age ($M = 8.4$ years; 16 girls) and 24 children between 10 and 12-years of age ($M = 11.3$ years; 13 girls). Finally, a group of 22 young adults between the ages of 18 and 25 ($M = 21.8$ years; 17 females) enrolled in the experiment. The children were selected with the help of their schools. All children had average or above average intelligence based on teachers reports. They received a small present for their participation. The young adults were undergraduate psychology students. They were recruited by flyers and received course credits for their participation. All participants reported to be in good health and had normal or corrected-to-normal vision. Informed consent was obtained from adult participants and primary caregivers of the children. All procedures were approved by the Ethical Review Board of the University.

**Apparatus and stimuli**

All details concerning the apparatus and stimuli were the same as in Experiment 1.

**Design and procedure**

Participants performed a hybrid Choice-reaction/NoGo task. Red arrows pointing to the right required a right-hand response and blue arrows pointing to the left required a left-hand response. In order to elicit a conflict situation, participants should refrain from responding to blue arrows pointing to the right or red arrows pointing to the left. This set-up was counterbalanced across participants. On successful inhibits on NoGo trials, the stimulus was terminated and the RSI started with a delay of 3 s following stimulus onset. The order of arrow directions and colors was pseudo-random. All other design and procedural details were the same as in the previous experiments.
RESULTS AND DISCUSSION

For each participant, trials were sorted for Trial sequence (Choice-Choice vs. NoGo-Choice) and RSI (50 vs. 500 ms). Errors and trials following an error were excluded from RT sorting. Median RTs and error rates (choice errors and commission errors) are presented in Table 3 for each of the above categories.

Error rates

Error rates were low (less than 6%) and did not reveal a negative correlation with RT suggestive of a speed-accuracy tradeoff. Error rates were square-root transformed prior to analyses. Error rates are presented as a function of trial sequence (Choice-Choice, NoGo-Choice, Choice-NoGo and NoGo-NoGo) in Table 3 for each age group and both RSIs.

Choice errors

The rate of choice errors decreased with advancing age; from 7.8%, to 5.6% and 3.4% for young children, older children, and adults, respectively, $F(2, 63) = 45.81, p < .001, \eta^2_p = .59$. Error rates were affected by Trial sequence, $F(1, 63) = 33.23, p < .001, \eta^2_p = .35$, but this effect was qualified by an interaction with Age group, $F(2, 63) = 95.04, p < .001, \eta^2_p = .75$. Adults made somewhat more errors following a NoGo trial (from 2.8 to 4.1 %), $p < .001, \eta^2_p = .94$, whereas young children showed the opposite (from 8.2 to 7.5 %), $p < .001, \eta^2_p = .76$. Error rates of older children were about equal across trial sequences (5.6 %), $p > .9$. RSI did not alter these trends ($ps > .09$).

Commission errors

The rate of commission errors decreased with advancing age (from 9.4%, to 5.6%, and 3.9% for young children, older children, and adults, respectively), $F(2, 63) = 55.19, p < .001, \eta^2_p = .64$. This trend is consistent with previous reports indicating that the ability to stop motor responses on NoGo trials increases when children are growing older (e.g., Jonkman et al., 2003). Error rate was affected by Trial sequence, $F(1, 63) = 24.00, p < .001$, $\eta^2_p = .28$, but this effect was qualified by an interaction with Age group, $F(2, 63) = 6.19, p < .004, \eta^2_p = .16$. Moreover, the three-way interaction with RSI was also significant, $F(2, 63) = 42.76, p < .001, \eta^2_p = .58$. For the short RSI commission errors tended to decrease for NoGo-NoGo sequences relative to Choice-reaction/NoGo sequences in children while this pattern was opposite for young adults. In contrast, for the long RSI, there was no difference between trial sequences in the proportion of commission errors in adults while the pattern observed for children seems opposite to the pattern.
Table 3. Mean RT (ms; upper table) and Error Rate (choice and commission %; lower table) for each trial sequence, RSI and age group (Experiment 3).

<table>
<thead>
<tr>
<th>Age Group</th>
<th>Trial Sequence</th>
<th>RT (ms)</th>
<th></th>
<th></th>
<th>Errors (choice) (%)</th>
<th></th>
<th></th>
<th>Errors (comm.) (%)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>RSI-50 ms</td>
<td>RSI-3 s</td>
<td>RSI-500 ms</td>
<td>RSI-3 s</td>
<td>RSI-50 ms</td>
<td>RSI-3 s</td>
<td>RSI-500 ms</td>
<td>RSI-3 s</td>
</tr>
<tr>
<td>7-9 yrs</td>
<td>Choice Reaction-Choice Reaction</td>
<td>783.31</td>
<td>909.64</td>
<td>716.09</td>
<td>839.05</td>
<td>7.5</td>
<td>7.0</td>
<td>8.9</td>
<td>8.0</td>
</tr>
<tr>
<td>10-12 yrs</td>
<td>Choice Reaction-NoGo-Choice Reaction</td>
<td>597.17</td>
<td>725.66</td>
<td>578.79</td>
<td>668.58</td>
<td>5.3</td>
<td>5.4</td>
<td>5.9</td>
<td>5.8</td>
</tr>
<tr>
<td>18-25 yrs</td>
<td>Choice Reaction-NoGo-NoGo</td>
<td>443.99</td>
<td>478.68</td>
<td>382.60</td>
<td>424.76</td>
<td>2.5</td>
<td>3.8</td>
<td>3.0</td>
<td>4.3</td>
</tr>
</tbody>
</table>

Note: Choice Reaction-Choice Reaction: current Choice Reaction trial preceded by a Choice Reaction trial; NoGo-Choice Reaction: current Choice Reaction trial preceded by a NoGo trial; Choice Reaction-NoGo: current NoGo trial preceded by a Choice Reaction trial; NoGo-NoGo: current NoGo trial preceded by a NoGo trial. RSI in Choice-reaction/NoGo task: 50 or 500 ms for Choice Reaction to Choice Reaction or Choice Reaction to NoGo sequences but for sequences starting with NoGo there was an inter-trial interval of 3 s.
associated with the short RSI. That is, the proportion of commission errors tended to increase for NoGo-NoGo sequences relative to Choice-reaction/NoGo sequences.

**Response speed**

The speed of responding increased with advancing age, $F(2, 63) = 448.33, p < .001, \eta^2_p = .93$. Adults ($M = 433$ ms) responded faster than older ($M = 643$ ms) and younger children ($M = 812$ ms). Post-hoc analysis indicated that each age group differed significantly from the others ($ps < .001$). Responses were faster for long ($M = 602$ ms) compared to short RSIs ($M = 656$ ms); $F(1, 63) = 49.38, p < .001, \eta^2_p = .44$. This RSI effect was not affected by Age group, $p > .25$.

Importantly, the anticipated Trial sequence effect was highly significant, $F(1, 63) = 102.05, p < .001, \eta^2_p = .62$. Responses on Choice trials following a NoGo trial were considerably slower than when preceded by a Choice trial ($M = 674$ ms and $M = 584$ ms, respectively). The Trial sequence effect interacted with Age group, $F(2, 63) = 8.62, p < .001, \eta^2_p = .22$. The interaction of the Trial sequence effect and Age group is plotted in Figure 3. It can be seen that the effect observed for children almost triples the effect for adults. However, the interaction did not survive when using average group RT as covariate, $p > .29$. Finally, the Trial sequence effect was somewhat larger in the short ($M = 97$ ms) compared to long ($M = 85$ ms) RSI blocks, but this effect was far from

**Figure 3.** Reaction time difference (ms), including standard error bars, between NoGo-Choice Reaction vs. Choice-Reaction-Choice Reaction trials (i.e., Trial sequence effect) for each age group.
significant, $p > .53$. Moreover, the three-way interaction with Age group did not reach significance either, $p > .61$.

As in the two previous experiments, we averaged data across the two RSIs and categorized trial sequences in terms of repetitions vs. alternations of arrow direction. The results indicated that, in contrast to predictions based on the repetition priming account, responses on choice trials following a NoGo trial were somewhat shorter rather than longer for repetition ($M = 663$ ms) vs. alternation ($M = 686$ ms) sequences. Importantly, Age group was not included in the higher-order interaction with Trial sequence and the Repetition vs. Alternation effect, $p > .07$.

At this point, it should be noted that the comparison between Choice-Choice sequences vs. NoGo-Choice sequences vis-à-vis RSI is confounded by the long inter-trial interval following NoGo trials. That is, the RSI following a Choice trial was either 50 ms or 500 ms whereas the inter-trial interval following a NoGo trial was 3 s. Thus, it could be argued that the apparently larger modulation effect in children (i.e., the difference in RT between Choice-Choice sequences vs. NoGo sequences) was due to age-related changes in response preparation rather than cognitive control. However, the few results available to date suggest there is little developmental change for the age groups and time intervals relevant to the current analysis (e.g., Adam, Ament, & Hurks, 2011).

In conclusion, the current findings, obtained using a hybrid Choice-reaction/NoGo task, are consistent with the adult literature examining the speed of responding on respond trials that are preceded by either a NoGo trial vs. respond trial. This literature indicates that responses are typically slower on Go trials preceded by a NoGo trial relative to a respond trial (e.g., Gade & Koch, 2005; Hoffmann et al., 2003; Jamadar, Hughes, Fulham, Michie, & Karayanidis, 2010; Kleinsorge & Gajewski, 2004; Rieger & Gauggel, 1999; Rieger et al., 2003; Schuch & Koch, 2003; Verbruggen & Logan, 2008).

**GENERAL DISCUSSION**

This study set out to assess developmental change in conflict adaptation. Within the developmental literature, conflict adaptation is considered to be a manifestation of top-down cognitive control and, given the protracted developmental course of brain mechanisms implicated in top-down cognitive control, it is assumed that with advancing age children are better able to deal with conflict when it arises and to prepare 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 adjust-
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The major goal of the present study was to systematically assess developmental change in conflict adaptation. We used a different conflict task in each of the three experiments reported in this study, as the specific implementation of conflict adaptation may depend on the specific conflict elicited by the task (e.g., Egner, 2008; Braem et al., 2014) and, thus, may contribute to the inconsistencies observed in the developmental literature (current review). 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, Proctor, & Vu, 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). Accordingly, group differences were anticipated to be absent for the 50 ms RSI condition, as 50 ms would be too short for all age groups to effectively put the required performance adjustment into operation.

Conflict adaptation and the Simon task. The current implementation of the Simon task required participants to respond to the color of left- or right-pointing arrows while ignoring the directional information of the arrow. In this version of the Simon task, the conflict is elicited by the location of the required response and the directional information associated by the arrow. Consistent with the literature (Vu & Proctor, 2004), the speed of responding was considerably slower on incongruent trials (with conflicting stimulus and response features) relative to congruent trials (without conflict). This pattern was observed for all three age groups, but the Simon effect was significantly larger in children compared to adults. This finding is consistent with previous developmental
studies of the Simon effect (e.g., Araujo, Mandoske, & White, 2015; Gathercole et al., 2014; Jerger et al., 1999; but see Band et al., 2000).

The size of the Simon effect was reduced considerably on trials following an incongruent relative to a congruent trial. This finding is in line with the adult literature on conflict adaptation using various versions of the Simon task (e.g., Kerns, 2006; Soetens, Maetens, & Zeischka, 2010; Sturmer, Leuthold, Soetens, Schrote, & Sommer, 2002; Duthoo et al., 2014, for a review). Importantly, the reduction of the Simon effect following an incongruent trial was observed for all three age groups. This observation is consistent with previous studies reporting conflict adaptation in children performing on a Simon task (e.g., Ambrosi et al., 2016; Iani et al., 2014). A subsequent analysis, taking the potential contribution of association priming into account, indicated that age-related changes in conflict-adaptation were not altered by the repetition vs. alternation of arrow direction across trials. This observation is similar to the results reported by Waxer and Morton (2011). A secondary analysis controlled for group differences in the speed of responding. This analysis revealed that the developmental trend in the conflict adaptation effect was not disproportional.

In contrast to expectations, the reduction of the Simon effect on trials following an incongruent trial was more pronounced when RSI was 50 ms relative to the 500 ms RSI condition. This pattern was observed for all three age groups. The dual-route model, proposed by Kornblum et al. (1990), may provide a possible interpretation of the apparent annihilation of the conflict adaptation effect in the 50 ms RSI condition. This model assumes that a slow, controlled processing route is activated by task-defined features of the stimulus (i.e., the color of the arrow) connected to a designated response whereas a fast, automatic route is activated by the spatial features of the stimulus (i.e., the direction of the arrow) connected to a response on the basis of pre-existing stimulus-response associations. On incongruent trials, the fast, automatic route has to be suppressed to allow for the execution of the appropriate response along the slow, controlled processing route. Possibly, the inhibition of the fast, automatic route 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.

Conflict adaptation and the SRC task. The implementation of the current version of the SRC task was similar to the Simon task, in that participants were asked to respond to colored arrows, but the important difference is that now both the color and direction of the arrow determine the response. Conflict is then elicited when color and direction point to opposite responses. On compatible trials, the color of the arrow indicates that a response is required in the direction of the arrow whereas on incompatible trials the
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Color indicates that the opposite response should be executed. The adult literature indicates that on pure blocks the speed of responding is considerably slower on incompatible than compatible trials (Kornblum et al., 1990), whereas mixing trials may result in the annihilation of the SRC effect (e.g., van Duren & Sanders, 1992). The current results are consistent with the literature in showing that mixing compatibility resulted in the overall elimination of the SRC effect. More specifically, however, 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). The preparatory bias consists of the suppression of the compatible mapping that has to be released when a compatible, not an incompatible, mapping is called for (De Jong, 1995). This preparatory bias has been interpreted in terms of proactive control; that is, a willful strategy facilitating incompatible mappings (Mansfield et al., 2012).

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 the pattern of trial-to-trial modulation of SRC on the speed of responding would be less manifest in children than adults. The results were opposite. 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.

The trial-to-trial modulation of the SRC effect was more pronounced for the 50 ms relative to the 500 ms RSI. Similar to the data-pattern observed for the Simon effect, the current SRC pattern is in conflict with notions suggesting that the implementation of control operations following conflict are time consuming (e.g., Notebaert et al., 2006). Indeed, the current findings seem to present a challenge to the idea that the mixing of SRC results in a preparatory bias favoring incompatible mappings. In order to provide an account for the current findings reference can be made to the task-switching literature (for a review, Vandierendonck, Liefooghe, & Verbruggen, 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, Styles, & Hsieh, 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).

Conflict adaptation and the hybrid Choice-reaction/NoGo task. The current hybrid Choice-reaction/NoGo task required participants to perform a conjunction analysis involving the color and direction of the arrow stimulus. Thus, they were required to respond in the direction of the arrow, but only when the arrow was of a certain color, while they had to inhibit their response when the arrow was of a different color. The current findings indicated that, in spite of the requirement to perform a conjunction analysis, all age groups performed the task well, even the youngest children. Overall, both the choice and commission error rates remained below 10%. The proportion of commission errors decreased with advancing age, consistent with notions suggesting that the ability to inhibit speeded responses increases when children are getting older (e.g., Casey et al., 1997; Cragg & Nation, 2008; Jonkman et al., 2003).

RTs revealed a pronounced delay when choice-reaction trials were preceded by a NoGo trial relative to a choice-reaction trial. This finding is consistent with the Go/NoGo literature showing that responses on a Go trial are typically delayed when the Go trial follows response inhibition on a NoGo trial (e.g., Gade & Koch, 2005; Hoffmann et al., 2003; Jamadar et al., 2010; Kleinsorge & Gajewski, 2004; Rieger & Gauggel, 1999; Rieger et al., 2003; Schuch & Koch, 2003; Verbruggen & Logan, 2008). It should be noted, however, that for the current data, a straightforward comparison between the speed of responding on choice-reaction trials preceded by another choice-reaction trial vs. choice-reaction trials preceded by a NoGo trial is complicated by a design issue. That is, RSI was either 50 ms or 500 ms for choice-reaction to choice-reaction sequences whereas the time-interval between a NoGo stimulus and the subsequent choice-reaction stimulus was 3 s. Thus, the delay observed for responses on Go trials preceded by a NoGo trial could be due to a longer wait reducing response readiness, to more caution, also reducing response readiness, or to a mixture of both. However, attributing the substantial delay in responding to a longer wait does not seem plausible in view of findings reported by Näätänen et al. (1974). These authors examined the effect of foreperiod (i.e., the interval between a warning and a response signal) on the speed
of responding using various delays (.25, .5, 1, 2, and 4 s). Their results showed that the speed of responding increased with a lengthening of the foreperiod. A similar pattern has been reported by Adam and colleagues, who examined the speed of responding to time-intervals between .2 and 2 s (Adam et al., 2011). Moreover, it was observed that children (age between 9 and 13 years) showed the same trend. In brief, attributing the delay in responding on a choice-reaction trial preceded by a NoGo trial to cognitive control is more likely than an interpretation in terms of reduced response readiness associated with a longer wait.

The current findings yielded a 40 ms delay in the speed of responding on choice-reaction trials preceded by NoGo trials versus the speed of responding on choice-reaction trials preceded by another choice-reaction trial. This sizeable difference basically tripled in children. There are few studies examining developmental change in the speed of responding following response inhibition on the immediately preceding trial. Consistent with the present findings, these studies revealed a developmental decrease in the delay of responding on Go trials preceded by a NoGo trial. Huizinga and van der Molen (2011) examined switching from a NoGo trial to a choice-reaction trial and observed a pronounced delay on choice-reaction trials following a NoGo trial for adults (about 60 ms) and this delay almost doubled for 11-year olds and increased close to 160 ms for 7-year olds. In contrast to the present findings, however, the developmental trend survived when controlling for age-group differences in basic respond speed. Huizinga and van der Molen (2011) interpreted their data to suggest that the readiness to respond decreases following the encounter of a NoGo trial (see also Jamadar et al., 2010) resulting in an increase in response thresholds. The more pronounced delay in the speed of responding observed in children is then explained by assuming that adults are better able to fine-tune their response thresholds (cf. Huizinga & van der Molen, 2011; p. 499).

**CONCLUSION**

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. More specifically,
Gratton et al. (1992) argued that an encounter with a conflict trial would increase the expectation that another conflict trial follows and this expectation initiates top-down control adjustments reducing the potential influence of conflicting information. Another perspective, proposed by Botvinick et al. (2001), assumed a cognitive mechanism enabling the detection of conflict when it occurs resulting into the signaling of control mechanisms involved in top-down adjustments to reduce the effects of potential conflict on the immediately subsequent trial. Cognitive neuroscience studies revealed that the anterior cingulate cortex (ACC) responds to conflict signaling other brain areas, including the prefrontal cortex (PFC), to reduce conflict and improve performance (e.g., Kerns, 2006). Developmental cognitive neuroscience amassed evidence to suggest that both the ACC and PFC follow a protracted maturational course (for a review Crone & Steinbeis, 2017). Collectively, the behavioral and cognitive neuroscience literatures suggest 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. This pattern of results is most compatible with the findings reported previously by Wilk and Morton (2012). These authors investigated age-related changes in conflict adaptation by manipulating the probability of compatible vs. incompatible trials in mixed compatibility trial blocks. Consistent with previous studies (e.g., Gratton et al., 1992; Logan & Zbrodoff, 1979), it was observed that increasing the probability of incompatible trials greatly reduced the compatibility effect. Importantly, the size of this conflict-adaptation effect was comparable across ages from 9 to 34 years. In contrast, the neural activation pattern associated with conflict adaptation revealed substantial changes with advancing age. More specifically, it was observed that activity in the anterior insula, anterior cingulate, lateral prefrontal cortex and intraparietal sulcus was associated with conflict-adjustments in older but not younger participants. Consequently, there is an apparent dissociation between the behavioral and neural manifestations of developmental change in conflict-adaptation. Wilk and Morton (2012) raised the possibility that children and adults may entertain different control modes in achieving the same goal or, alternatively, that age-related changes in structural or functional connectivity
between brain regions might have contributed to different neural activation patterns for children and adults.

The current, albeit statistically nonsignificant, 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). Thus, when conflict is encountered the control settings that are then used by the system to efficiently ensure the resolution of conflict are then carried over to the next trial when the demands of this trial are similar to the previous one. 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 sum, 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, Kuhns, Schafer, & Mayr, 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).
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; Vervaek & 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., Lupiane, 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; Riddlerinkhof 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
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-faceted pattern consisting of developmental change in bottom-up and top-down influences on the choice reaction process was proposed. It was as-
sumed 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., 2014). 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 incongruent/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 pattern 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 (Botvinick 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., Riddetinkhof 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 & Budeascu, 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 to 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, Infanto, & 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 (e.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, disappointingly, 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 it 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.
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 participat-
ing in the study and for each of the tasks that were used, although specific patterns dif-
fered 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 cur-
rent 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 AAAA vs. AAAR 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, & Huizenga, 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 particular, 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.


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SUMMARY

The current thesis aimed at expanding our knowledge of age-related changes in trial-by-trial effects on the speed of performance. More specifically, this thesis was 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 (DMC). The model distinguishes two modes of control; i.e., reactive vs. proactive control.

Chapter 1 offered a general introduction addressing the key topics covered in this thesis. The concept of cognitive control and the developmental changes therein was explained, and the three main topics (including the questions addressed in this thesis) that were central to the four empirical chapters (2-5) were introduced.

Chapter 2 and 3 together contained four experiments that aimed to investigate systematically the developmental trends in basic processing mechanisms underlying sequential effects in serial reaction time tasks (i.e., automatic facilitation and subjective expectancy). The experiments in Chapter 2 were aimed at assessing developmental trends in the strength of these mechanisms, by manipulating response-to-stimulus (RSI) interval and stimulus-response compatibility (SRC). The primary goal of the experiments presented in Chapter 3 was to assess how developmental change in these underlying mechanisms evolve, by manipulating RSI in small steps and introducing practice-sessions. The results presented in Chapters 2 and 3 contributed to the relatively scant developmental literature on sequential effects. This literature was primarily concerned with first-order sequential effects and indicated that young children’s performance is dominated by a repetition benefit (i.e., automatic facilitation). This observation was replicated. We also included analyses of higher-order effects. These analyses revealed a benefit-only pattern (i.e., automatic facilitation) 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, this pattern was not influenced by extensive practice. Interestingly, the benefit-only pattern continued to dominate the performance pattern in young children across RSI lengths whereas, consistent with previous findings, the adult benefit-only pattern changed into a cost-benefit pattern (i.e., subjective expectancy) with a lengthening of RSI.
Summary

We considered but rejected the idea of interpreting our findings in terms of the DMC-model. We 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 assumed that sequential-effect patterns associated with short RSIs and young children are 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. We had to admit that this interpretation is utterly abstract and in need of further investigation.

Chapter 4 was concerned with the examination of developmental change in post-error slowing. First, we reviewed the developmental literature for information on post-error slowing and observed that the 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 indicated 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. 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 could not be excluded based on the current findings, we believed 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. 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.

Chapter 5 presented a study that systematically assessed developmental change in conflict adaptation. The developmental literature showed an inconsistent pattern of results. 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 and, thus, may contribute to the inconsistencies observed in the developmental literature. The findings demonstrated conflict adapta-
tion 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. Accordingly, one would assume that young children do not exhibit conflict adaptation. But the current findings convincingly indicated that they do. Consequently, these findings presented a challenge to the idea that conflict adaptation is realized via top-down cognitive control or, within the framework of the DMC, 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. Within this context, conflict adaptation was assumed to result from memory-driven effects. Although this account does not exclude a potential role of proactive control, its contribution was not or minimally manifested in the current data.

Chapter 6 provided a general discussion based on the results of the empirical chapters. An attempt was made to integrate results across studies and to derive some conclusions regarding the developmental changes in reactive and proactive control processes.

Taken together, the thesis presented trial-by-trial approaches in examining age-related change on the speed of performance. In all the 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. 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.
SAMENVATTING

Dit proefschrift had als voornaamste doel om meer inzicht te verkrijgen in leeftijdsgebonden veranderingen in cognitieve controle. De nadruk lag op de flexibiliteit van het cognitieve systeem. Deze flexibiliteit werd bestudeerd door gebruik te maken van zogenaamde ‘trial-by-trial’ effecten op de snelheid en nauwkeurigheid van reacties op stimuli in relatief eenvoudige taken die ook door kinderen goed uitgevoerd konden worden. De bestudeerde ‘trial-by-trial’ effecten waren sequentiële effecten (hoofdstukken 2 en 3), post-error vertraging (hoofdstuk 4) en conflict-adaptatie (hoofdstuk 5). De resultaten van de studies in dit proefschrift zijn geïnterpreteerd in relatie tot de huidige theorievorming op het gebied van cognitieve controle. Daarnaast werd getracht om de bevindingen in verband te brengen met het zogeheten ‘dual-mechanisms of control model’ (DMC) dat recent ook opgeld doet in de cognitieve ontwikkelingspsychologie. Het model maakt onderscheid tussen twee vormen van cognitieve controle; reactieve versus proactieve controle.

Hoofdstuk 1 gaf een algemene inleiding in de kernonderwerpen van dit proefschrift. Centraal stonden het concept van cognitieve controle en de leeftijdsgerelateerde veranderingen die zich hierin voor kunnen doen. De drie onderzoeksthema’s die aan bod komen in de vier empirische hoofdstukken werden geïntroduceerd, inclusief de vragen die in dit proefschrift worden gesteld.

Hoofdstukken 2 en 3 bevatten gezamenlijk vier experimenten gericht op het onderzoeken van ontwikkelingstrends in de mechanismen die ten grondslag liggen aan sequentiële effecten in seriële reactietijdtaken. In het onderzoek bij volwassenen traden in de literatuur twee mechanismen op de voorgrond—automatische facilitatie en subjectieve verwachting. De eerste betreft een proces veroorzaakt door resterende geheugensporen van voorafgaande stimulus-respons cycli. Dit mechanisme blijkt vooral te ontstaan bij een snelle opeenvolging van stimuli—korte ‘response-to-stimulus’ intervallen (RSI). Hier hebben repeterende vergeleken met alternerende stimulus-respons trials een voordeel (d.i. het eerste-orde repetitie-effect). De geheugensporen doen uit, maar bij een korte RSI zijn de sporen nog aanwezig bij volgende stimuli en accumuleren over opeenvolgende trials, wat hogere-effecten kan verklaren (d.i. het ‘benefit-only’ patroon). Subjectieve verwachting betreft een mechanisme dat zich eveneens manifesterd op eerste-orde (d.i. het alternatie effect) en hogere-orde niveau (d.i. het ‘cost-benefit’ patroon) en met name ontstaat bij een langzame opeenvolging van stimuli (lange RSI). Het alternatie effect wordt beschreven als de neiging om meer alternaties te verwachten, analoog aan het geloof in alternaties bij gokspellen. Het ‘cost-benefit’ patroon kan beschreven worden als de voorkeur voor een voortzetting van een...
Samenvatting

reeks van alternaties dan wel repetities. De experimenten in hoofdstuk 2 waren gericht op het vaststellen van ontwikkelingstrends van deze mechanismen. Dit werd bewerkstelligd door RSI en stimulus-respons compatibiliteit (SRC) te manipuleren. Deze laatste manipulatie bestond uit stimuli die op spatieel compatibele wijze werden toegewezen aan responsen (bijv. stimulus rechts, rechts reageren) en andersom (bijv. stimulus rechts, links reageren). Het hoofddoel van de experimenten in hoofdstuk 3 was om vast te stellen hoe de ontwikkeling in de temporele dynamiek van deze onderliggende mechanismen verloopt. Dit werd verwezenlijkt door RSI in kleine stapjes te verlengen en door proefpersonen veelvuldig te laten oefenen. In alle experimenten werd als basis gebruik gemaakt van een relatief eenvoudige tweeeuze reactietijdtaak (d.i. rode cirkel links of rechts van het midden op een computerscherm).

Onderzoek naar leeftijdsgerelateerde veranderingen van sequentiële effecten is schaars. Daarnaast waren eerder uitgevoerde studies voornamelijk gericht op eerste-orde sequentiële effecten. Deze studies lieten zien dat automatische facilitatie de prestaties van jonge kinderen domineert. Wij konden deze bevinding in onze studies repliceren. Wij hebben daarnaast ook analyses van hogere-orde effecten toegevoegd. Deze analyses toonden een ‘benefit-only’ patroon (automatische facilitatie) dat sterker was wanneer incompatibele reacties nodig waren. In overeenstemming met onze verwachtingen nam de sterkte van dit ‘benefit-only’ patroon af met het ouder worden van jonge kinderen. In tegenstelling tot onze verwachting had veelvuldig oefenen echter geen invloed op deze effecten. Bij jonge kinderen bleef het ‘benefit-only’ patroon domineren terwijl wij een graduele omslag naar een ‘cost-benefit’ patroon hadden verwacht. De omslag van het ‘benefit-only’ patroon (automatische facilitatie) naar een ‘cost-benefit’ patroon (subjectieve verwachting) werd wel gevonden voor volwassen proefpersonen wanneer het interval tussen de respons en de volgende stimulus werd verlengd.

We hebben onze bevindingen getracht te interpreteren met behulp van het DMC-model maar kwamen tot de conclusie dat de ontwikkeling van sequentiële effecten zich onttrekt aan dat model. Ook de literatuur op het gebied van simulatiestudies van sequentiële effecten boden geen uitkomst. We kwamen tot de conclusie dat de meeste interpretaties van sequentiële effecten gebaseerd zijn op patronen die verkregen zijn in experimenten of simulaties waarin het interval tussen respons en de volgende stimulus relatief lang is, terwijl de resultaten die wij hebben verkregen bij jonge kinderen gerealiseerd zijn aan patronen geassocieerd met korte intervallen. De voorlopige conclusie die we op grond van onze resultaten konden trekken gaat uit van de gedachte dat sequentiële effecten bij jonge kinderen gebaseerd zijn op automatisch gedreven verwachtingen, terwijl bij volwassenen verwachtingen over de volgende trial bewust zijn en moeite kosten.
Hoofdstuk 4 betrof onderzoek van leeftijdsgerelateerde verandering in post-error vertraging. In de literatuur bij volwassenen wordt in het algemeen gevonden dat, na het maken van een fout, de snelheid van reageren op de eerstvolgende trial afneemt. In het onderzoek bij kinderen is het beeld veel minder duidelijk. We hebben een literatuurstudie uitgevoerd waaruit bleek dat de aandacht van het onderzoek bij kinderen vooral gericht was op hersenpotentialen terwijl het gedrag goeddeels werd genegeerd. Daarbij werd in sommige studies de verwachte met leeftijd sterker wordende vertraging gevonden, terwijl in andere studies het omgekeerde werd geconstateerd. In hoofdstuk 4 hebben we een onderzoek uitgevoerd waarin we gebruik hebben gemaakt van een experimentele opzet die ook in de literatuur over de post-error vertraging veelvuldig is toegepast. De gebruikte basistaak was overeenkomstig met die in hoofdstukken 2 en 3. Onze resultaten lieten een robuuste ontwikkelingsstrend zien in de post-error vertraging—met het ouder worden neemt de sterkte van dit effect af. De conclusie die we uit dit resultaat trokken was tweeledig. Onze resultaten lieten zien dat ook jonge kinderen hun gedrag monitoren maar, in tegenstelling tot volwassenen, werd de reparatie na de fout (d.i., het opnieuw instellen van respons drempels) minder efficiënt uitgevoerd.

In algemene zin werd de post-error vertraging geïnterpreteerd in termen van een dynamische wisselwerking tussen proactieve en reactieve controle processen. Vanuit de veronderstelling dat de ontwikkeling van proactieve controle bij (jonge) kinderen nog niet is voltooid, werd verondersteld dat hun sterkere post-error vertraging het gevolg is van minder proactieve ondersteuning bij de nodige reparaties na het maken van een fout. De disproportionele vertraging bij jonge kinderen wordt dan verklaard door aan te nemen dat zij nog moeite hebben met het afstellen van respons drempels. Dit is echter een zeer voorlopige conclusie die in toekomstige studies nog nader onderzocht dient te worden.

Hoofdstuk 5 betrof een studie over leeftijdsgerelateerde veranderingen in conflict-adaptatie. Conflict-adaptatie heeft betrekking op aanpassingen in het gedrag nadat de proefpersoon in een eerdere trial geconfronteerd werd met een conflict. Dit betekent dat, op een trial na een conflict, adequaat gereageerd kan worden wanneer de hierna volgende trial ook een conflict-trial is. Het nadeel is echter dat wanneer de volgende trial geen conflict-trial is er relatief traag wordt gereageerd. De ontwikkelingsliteratuur op dit gebied toonde wederom inconsistentie resultaten. We gebruikten verschillende conflict taken, maar met identiek gepresenteerde stimuli; een Simon taak, een SRC taak, en een keuze reactie/NoGo taak. In de Simon taak werden relevante (d.i. kleur op basis waarvan de proefpersoon beslist welke respons gemaakt moet worden) en irrelevante taakaspecten (d.i. richting van de stimulus, pijl links of rechts) gecombineerd, waardoor congruente en incongruente trials ontstaan. Bij congruente trials vielen de relevante
en irrelevante aspecten samen (geen conflict), bij incongruente trials niet (conflict). In de SRC taak bepaalde de kleur van de stimuli de wijze van reageren (overeenkomstig met de richting van de pijl of andersom), waardoor compatibele (geen conflict) en incompatibele stimulus-respons trials (conflict) ontstonden. In de keuze reactie/NoGo taak moesten sommige stimuli (bijv. rode pijlen naar rechts en blauwe pijlen naar links) worden beantwoord met een respons, respectievelijk rechts en links (geen conflict). Bij de presentatie van andere typen pijlen moesten proefpersonen zicht onttrekken van een reactie (NoGo, conflict). We gebruikten verschillende taken omdat de specifieke implementatie van conflict-adaptatie kan afhangen van het specifieke conflict dat uitgelokt wordt door een taak. De eerder gevonden inconsistenties kunnen dus het gevolg zijn geweest van de verschillende gebruikte taken. Onze resultaten lieten zien dat in alle taken conflict-adaptatie was en dat de sterkte van het effect verschilde tussen leeftijdsgroepen. In de Simon taak werd een leeftijdgebonden afname van het ‘trial-by-trial’ modulatie van het Simon effect gevonden. De SRC taak liet voor kinderen een veel sterkere omkering zien van het SRC-effect volgend op incompatibele trials. En tot slot werd, met toename van leeftijd, een afname gevonden in reactietijd op een keuzereactie trial na een NoGo trial. Hierbij moet worden aangemerkt dat de leeftijdgebonden veranderingen niet disproportioneel van aard waren.

Het overheersende idee binnen de ontwikkelingsliteratuur is dat conflict-adaptatie een manifestatie is van top-down controle, die sterker aanwezig is bij volwassenen vergeleken bij (jonge) kinderen. Op basis hiervan zou je verwachten dat kinderen geen conflict-adaptatie laten zien. Onze bevindingen zijn hiermee in tegenspraak en zijn niet goed te passen binnen het DMC-model. We beargumenteerden dat onze bevindingen verklaard kunnen worden door episodische ‘retrieval’. Binnen deze context wordt verondersteld dat conflict-adaptatie het resultaat is van geheugen gedreven effecten. Hierbij wordt verondersteld dat, zodra de taakconfiguratie betrokken bij het oplossen van conflict tot stand is gekomen, deze automatisch kan worden geactiveerd en geïmplementeerd met behulp van de juiste contextuele informatie. We suggereerden dat het proces van conflict-adaptatie efficiënter wordt met het ouder worden, vergelijkbaar met het efficiënter worden van het algemene informatieverwerkingsysteem.

In het laatste hoofdstuk werden de resultaten uit de voorgaande empirische hoofdstukken bediscussieerd. Het hoofdstuk beslaat globaal twee delen. In eerste instantie zijn de resultaten geïnterpreteerd in relatie tot de huidige theorievorming op het gebied van cognitieve controle. Daarnaast werd getracht om de bevindingen in verband te brengen met het DMC-model. Tot slot zijn enkele belangrijke conclusies en aanbevelingen geformuleerd.
Samenvattend presenteerde dit proefschrift een aantal studies gericht op de ontwikkeling van cognitieve flexibiliteit aan de hand van standaard reactietijdtaken waarin met behulp van relatief eenvoudige manipulaties (zoals het ‘response-to-stimulus’ interval of de relatie tussen stimulus en respons) ‘trial-by-trial’ aanpassingen in het gedrag werden bestudeerd. De verkregen resultaten bleken niet goed te passen in het DMC-model dat in de recente ontwikkelingspsychologie steeds meer opgeld doet. In algemene zin geven de resultaten van de studies in dit proefschrift aanleiding te veronderstellen dat leeftijdsgerelateerde veranderingen in cognitieve flexibiliteit (zoals onderzocht met ‘trial-by-trial’ manipulaties) goed te verklaren zijn zonder gebruik te maken van top-down controle mechanismen. Verder onderzoek is nodig om deze gedachte nauwkeuriger na te gaan en te bepalen hoe de verschillende factoren tezamen bijdragen aan de ontwikkeling van flexibel en adaptief gedrag. Het proefschrift biedt enkele suggesties om dit te bewerkstelligen.
DANKWOORD

Dit proefschrift is volbracht. Dat is een cruciaal verschil met de Sagrada Familia maar ik wil de vergelijking toch maken. Het werk leek in de loop der jaren veel trekken te vertonen vergelijkbaar met dat bouwwerk. Nou ja, de Sagrada wordt door velen gezien als het juweeltje van zijn meester en dat is hier natuurlijk nog maar de vraag. Enfin, er zijn nog wel wat andere verschillen… maar als een Barcelonees gevraagd wordt of hij/zij een idee heeft wanneer de basiliek gereed zal zijn, halen ze hun schouders op. Ze hebben geen idee en eigenlijk ook weinig vertrouwen dat het er ooit nog van zal komen. In de voorbije jaren een herkenbaar sentiment vermoedelijk voor mijn omgeving. En hoewel ik het vaak anders deed voorkomen, voelde ik me eerlijk gezegd vaak, boetserend aan mijn eigen ‘Sagrada’, ook zo’n Barcelonees.

Het was ook een lang pad; het begin gemakkelijk te bewandelen, later volgden onherbergzame etappes. Zo’n tocht, in mijn geval van aio, naar promovendus tot (parttime) buitenpromovendus, leg je onmogelijk alleen af. Veel mensen hebben direct, maar nog vaker indirect, bijgedragen aan de volbrenging van dit werk. Hier volgt een dappere poging ze te danken. Hierbij moet worden opgemerkt dat ik velen uit het oog ben verloren, echter niet uit het hart. En, ‘schrijven is schrappen’ zeggen ze. Dat heb ik dit keer verzuimd.

Allereerst mijn hooggewaardeerde promotor, Maurits van der Molen. Dank voor jouw tomeloze inzet in de afgelopen jaren. Dankzij jouw sturing, vindingrijkheid, geduld en vertrouwen, is dit proefschrift tot een goed einde gebracht. Ik heb veel gehad en geleerd van jouw enorme kennis en talent op velerlei gebied. Het duurde lang (zelfs tot in het emeritaat), maar het is absoluut een eer geweest om onder jouw hoede te mogen werken en leren. Dank ook dat je me altijd weer tot geestdrift wist te brengen (“Het lijkt desastreus maar bij betere lezing valt het mee hoor.”) na het ontvangen van een stevige afwijzing van een editor of curieuze opmerking van een reviewer (“Frankly, in my view, it represents both the very best and the very worst in experimental child psychology.”). Je hebt je zelfs één keer, lang geleden, moeten opwerpen als hulpverlener om mijn ‘existentiële crisis’ tegemoet te treden: “SPORTEN IN DE BUITENLUCHT!!!!!!!!!!!!!!!!!!!!!!!!!!! Maar echt tot je erbij neerval want anders helpt het niet.” Door de hoeveelheid uitroeptekens verdween de lijdzaamheid stante pede. Het sporten kon ik gelukkig overslaan! Het project was voor mij uiteindelijk ook gewoon een oefening in geduld. Processen en procedures in de wetenschap lopen traag en noodzaakt lange en volgehouden inspanningen (aandacht en denkkracht). In de wetenschap word je geacht kritisch te zijn (ieder woord op de weegschaal, en ook “deep work” zoals Calvin Newport het noemt), in de praktijk ook, maar vooral niet te. Als deeltijd promovendus was dat soms echt een spagaat. De data
voor dit proefschrift bleken daarnaast ook van bijzonder weerbarstige aard, waardoor de puzzel alles behalve eenvoudig was en lastige keuzes gemaakt moesten worden. Zoals jij zei: “Het blijft een strijd (want het is lastige materie) maar deze moet wel gevoerd worden.” Gelukkig ging je altijd rustig om met mijn soms heetgebakerde reacties. Tot slot, lang geleden betrad ik als schuchtere eerstejaars het gebouw aan de Roetersstraat en zonk geregeld weg in de collegebanken van zaal A. Na een trimester inleiding in de psychologie door wijlen Christiaan Hamaker (die mij in zijn introductiecollege overhaalde psychologie te studeren), ontsluierde jij - beurtelings met Louis Oppenheimer - voor mij, en honderden andere studenten, de geheimen der ontwikkelingspsychologie. En nu, twee decennia later, dit dankwoord…

Copromotor Eric Soetens (inmiddels wat langer ‘in ruste’), kenner en één van de pioniers op het gebied van sequentiële effecten. In die zin had jij zelfs een deel van het pad al enigszins voor mij gebaand. Dank voor alle hulp en begeleiding vanuit het ‘verre’ België, vrijwel altijd via de elektronische weg. Jouw altijd snelle maar bijzonder kritische blik op de diverse manuscripten en het finale proefschrift is echt van wezenlijk belang geweest. Van één ding heb ik spijt: ik had je vaker moeten opzoeken in Brussel. Dat had eigenlijk sowieso gemoeten, want in het projectvoorstel uit 2000 stond: “Each year the AIO will visit Dr. Soetens (Brussels) for consultation and guidance.” Maar goed, de elektronische weg was wellicht toentertijd nog niet zo ingeburgerd.

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Dankwoord

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Zoals Géza Révész in zijn voorwoord van Inleiding tot de Muziekpsychologie (1944) het zo mooi formuleerde: “Aan de persoonlijke en daadwerkelijke belangstelling, die mijn werk van de zijde mijner collega’s heeft ondervonden, mag ik niet stilzwijgend voorbijgaan.” Dus daar gaan we…


_Mijn huidige collega’s te Den Haag (SBRM – De Haagse Hogeschool):_ Niek, Ronald V. (er staat koffie klaar na de verdediging!), Daphne, Eva, Sarah (dank voor wat taaltips), Albert K., Shashi, Miriam, Edwin, Sandy, Albert C., Johan, Herman, Ronald B., Michiel, Martijn, Rainer, Louise, Gerard, Marion, Anja, Irene, Bart, Ton, Joyce, Heleen, Jolien, Jeroen, Tosca, Hans, Philip, maar ook inmiddels oud-collega’s Frank, Michel, Poornima, Margo, Nan, Jeanette, Han en Luc. Ook aan alle collega’s van de ondersteunende diensten, uit verschillende commissies, gremia, verwante en minder verwante opleidingen met wie ik het zijdelings wel eens had over dit werk. Buurvrouw en HHS-collega Bianca wil ik hier speciaal ook graag noemen! Dank voor je betrokkenheid, bemoedigende woorden en presentjes als ik weer een klein stapje had gezet in de goede richting. Tot slot, in het bijzonder, Simone Fredriksz, Marc van Ee, Jos Kleijntjens, Marcel Veloo, Wim Schuller, Aad Otto (dank voor het zo nu en dan achter de vodden zitten), en mijn huidige kamer-
Dankwoord

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Muziek heeft altijd, met name in de periode voordat ik kinderen kreeg (zo’n 4 jaar geleden), een bijzonder belangrijke en nadrukkelijke plek in mijn leven gehad. Mijn muzikale en muziektheatrale avonturen zijn wellicht op veel momenten meer geweest dan een *welkome* afwisseling naast het schrijven van een proefschrift; het waren echter onmisbare belevenissen en uiteindelijk gewoon broodnodig. Ik heb veel mensen ontmoet, bij theatergezelschappen, in orkesten, bandjes, tijdens andere muzikale projecten of zijdelings. Dit werk was ook met grote regelmaat een gespreksonderwerp. Iedereen noemen in dit dankwoord is echt ondoenlijk. Maar uit de IMC-, RJT/NuRT-, PI/Musicalplay-, en Silly’s-periode, maar ook van Buitenkunst… allen enorm veel dank! In het bijzonder nog wel Loek Bosman, voor alle mooie theaterbelevenissen vanaf de late jaren negentig tot 2008. En Frank Heijman, voor het avontuur dat we in 2011 aangingen met FSS, na twintig jaar vol kleine en grote muzikale ontmoetingen. Het is nu allemaal anders maar er volgt in de toekomst zeker weer iets nieuws.


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Dankwoord

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Later werd ik ook nog eens parttime promovendus en kregen we, weer wat later, twee
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gelden kopte: “Promoveren naast je werk. Dan heb je maar tijdelijk geen leven.” Een bij-
zonder druk gezinsleven incluis, waren het eigenlijk soms best moeilijke tijden waarin
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data in om nieuwe analyses te draaien of het kritische commentaar van een reviewer
tegemoet te treden. En als ik niet concreet bezig was met dit werk, hing het toch altijd
boven het hoofd. Concreet betekende het gewoon dat jij het op sommige momenten
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Den Hoorn (ZH), september 2017
ABOUT THE AUTHOR

Silvan Smulders was born on November 8, 1977 in The Hague. After finishing his pre-university education at the Interconfessioneel Makeblijde College in Rijswijk, he started studying Applied Mathematics (Delft University of Technology) and Musicology (Utrecht University). After dabbling in technological sciences, humanities but also in non-scientific activities, he decided to make a switch to social and behavioral sciences in 1998. In 2002, after completing an internship at Rijndam Rehabilitation Centre Rotterdam (ABI clinic), and writing a thesis on the topic of neurocognitive aging in the domain of executive functions (supervised by Prof. dr. K. Richard Ridderinkhof) he obtained his Master’s degree in Psychology (with honors) at the University of Amsterdam (Psychonomics/Clinical Neuropsychology track). Subsequently, he started his PhD research at the developmental psychology department (University of Amsterdam) supported by a MaGW grant from the Netherlands Organisation for Scientific Research (NWO) and the Psychology Research Institute, supervised by Prof. dr. Maurits W. van der Molen (University of Amsterdam) and Prof. dr. Eric Soetens (Vrije Universiteit Brussel). During this period, the first chapters of his PhD thesis were finished and data was collected for the remaining chapters on which he continued to work over the following years while also undertaking other academic activities. In 2008, he was appointed lecturer of Applied Psychology at the University of Applied Sciences Leiden (cluster Social Work & Applied Psychology). He lectured, developed and coordinated courses in general psychology, psychology of learning, cognitive psychology, psychodiagnostics, research methods and statistics. Since 2012, the author works as a lecturer Research Methodology and Statistics at The Hague University of Applied Sciences at the Faculty of Business, Finance and Marketing (SBRM program), where he is also a member of the Examboard, Graduation Committee, and chairman of the Test Committee. During his lectureships he continued to work albeit intermittently on the completion of his PhD thesis.
Developmental studies of cognitive control indicated that control processes develop gradually during childhood through adulthood. The focus of this thesis is on developmental change in performance adjustments across trial sequences in relatively simple reaction time tasks. The results yielded robust developmental trends across an age range between 5 and 25 years. Collectively, however, the results question the idea that developmental change in trial-to-trial performance adaptation is guided by maturational changes in top-down cognitive control.