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Sequential effects on speeded information processing: A developmental study

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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 years) performed a spatially compatible choice task, with response-to-stimulus intervals (RSIs) of 50 and 500 ms varied between trial blocks. In Experiment 2, three age groups (7–9, 15–16, and 18–25 years) performed the task with spatial stimulus–response (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 responses than for 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

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pattern revealed an opposite trend, suggesting that the first-order and higher order indexes of subjective expectancy may relate to dissociable mechanisms.

Keywords: Sequential effects; Reaction time; Automatic facilitation; Subjective expectancy; Cognitive development; Cognitive flexibility

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, Braver, Barch, Carter, & Cohen, 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 & Phillips, 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 the conventional Wisconsin 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, Muller, Frye, & Marcovitch, 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, see 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, Chelune, Talley, Kay, & Curtis, 1993; Paniak, Miller, Murphy, Patterson, & Keizer, 1996; Rossellini & Ardila, 1993).

Recently, Crone and colleagues examined developmental change in the performance on an experimental analogue of the WCST (Crone, Ridderinkhof, Worm, Somsen, & van der Molen, 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) focused 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) improve 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*B* or B*A*) than on repeat trials (A*A* or B*B*) (Monsell, 2003). Only a few studies have 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, Kramer, & Gonzalez de Sather, 2001; Huizinga & van der Molen, 2004; Zelazo, Craik, & Booth, 2004; but see Kray, Eber, & Lindenberger, 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, Monsell, Sahakian, & Robbins, 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 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 stimulus–response (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 a few studies have examined developmental change in sequential effects, and the results that emerged from those studies reveal 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 responses to sequential dependencies in these 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).[1]

In an early study, Fairweather (1978) observed that the size of the repetition effect was smaller in 11-year-olds than in 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, Blanchard, & Miller, 1980; Kerr, Davidson, Nelson, & Haley, 1982). Consistent with the theoretical framework developed 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

[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.

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).

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, Deboeck, & Hueting, 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, Cho, Nystrom, Cohen, & Braver, 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 subjective 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 the 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 18 and 25 years of age ($M = 20.0$ years, 32 women 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 experiment 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 the 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 the left and right of the bottom row of a Querty 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 at either 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_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}. 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 code generated for each trial (R or A). The fourth

Table 1
Coding of trial sequences

Trial number T_{n-2}	Trial number T_{n-1}	Trial number T_n	First-order coding ($T_{n-1} > T_n$)	Second-order coding ($T_{n-2} > T_{n-1}$)	Trial sequence ($T_{n-2} > T_{n-1} > T_n$)
Left	Left	Left	R	R	RR
Right	Left	Left	R	A	AR
Left	Right	Left	A	A	AA
Right	Right	Left	A	R	RA
Left	Left	Right	A	R	RA
Right	Left	Right	A	A	AA
Left	Right	Right	R	A	AR
Right	Right	Right	R	R	RR

Note. R, repetition; A, alternation; T, trial; and *n*, trial number.

Table 2
Selection of trial sequences for statistical analysis

Trial	Response	First-order coding	Second-order coding	Trial sequence
1	Left	—	—	—
—	—	—	—	—
6	Left	—	—	—
7	Left	R	—	—
8	Right	A	R	RA
9	Right	R	A	AR
10	Right	R	R	RR
11	Right	R	R	RR
12	Left	A	R	RA
13	Left	R	A	AR
14	Error	—	R	—
15	Left	—	—	—
16	Right	A	—	—
17	Left	A	A	AA
18	Right	A	A	AA
19	Left	A	A	AA
20	Right	A	A	AA
21	Right	R	A	AR
22	Right	R	R	RR
23	Right	R	R	RR
—	—			
100	Left			
		Output		
		Median RT-R	Median RT R-	Median RT-RR
		Median RT-A	Median RT A-	Median RT-AR
				Median RT-RA
				Median RT-AA

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

column presents the second-order code (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 an 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). 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 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 errors 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 of 23.1 RTs for each combination of first- 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 children ($M = 433$ ms) and young children ($M = 481$ ms). Follow-up tests indicated that each age group differed significantly from the others (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 Fig. 1, with first-order effects shown in Fig. 1A and second-order effects shown in Fig. 1B. In Fig. 1A, it can be seen that the repetition effect decreases with age for the short RSI and that children show a repetition

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.

effect where adults demonstrate an alternation benefit for the long RSI. In Fig. 1B, 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 RSIs.

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 Fig. 1A, 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 ($p > .14$).

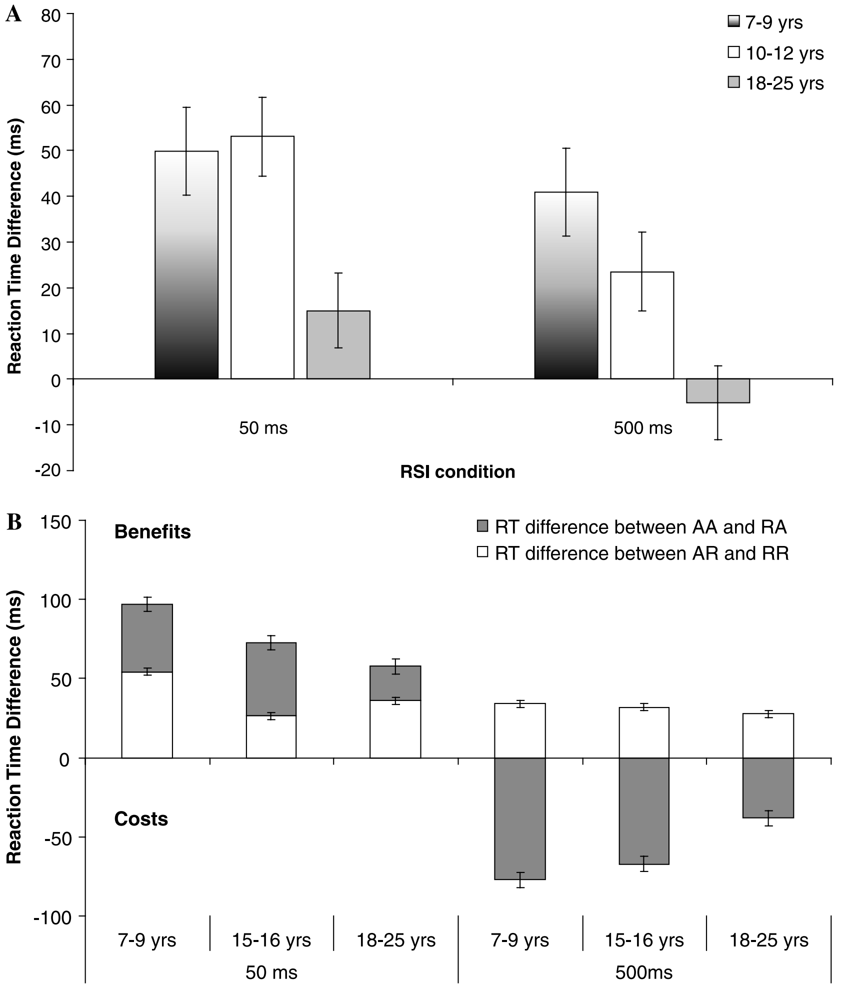

Fig. 1. (A) First-order sequential effects observed for each age group in both RSI conditions in Experiment 1. RT differences between first-order alternations and repetitions are plotted. A positive difference indicates a first-order repetition effect, whereas a negative difference indicates a first-order alternation effect. (B) Second-order sequential effects for each age group and RSI 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. yrs denotes years.

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 important, 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 (Fig. 1A) 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 also revealed 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, Boer, & Hueting, 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 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 adults, $F(1,33) = 9.27$, $p < .027$. 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 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 to peripheral stimulus identification and response execution processes. Indeed, several studies that complicated 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 shortcutting 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, Hasbroucq, & Osman, 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 spatially incompatible S–R mappings than for spatially 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 ages as in Experiment 1—8 years and between 18 and 25 years, respectively. But the intermediate group in Experiment 2 was older than that 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 18 and 25 years 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 of 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 Querty 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 at either 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 or the right stimulus mapped onto the right response) or to the incompatible task (i.e., the left stimulus mapped onto the right response or the right stimulus mapped 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 those in 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 errors 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 submitted to an ANOVA with age group (3) and task (2) as between-subjects factors and with 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 (*M*s = 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 Fig. 2A, showing a developmental decrease in the first-order repetition effect associated with the short RSI. The developmental decrease 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 Fig. 2B, showing a developmental decrease in the benefit-only pattern that seems more pronounced for the incompatible

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

	7–9 years				15–16 years				18–25 years			
	Compatible		Incompatible		Compatible		Incompatible		Compatible		Incompatible	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
50-ms RSI												
RR	417	56	404	61	324	44	291	41	265	50	276	50
AR	472	68	456	74	347	53	325	49	299	60	302	60
RA	526	76	578	83	365	60	364	55	296	67	331	67
AA	582	109	679	118	412	86	423	79	325	97	372	97
First-order repetition	444	61	430	66	335	48	308	44	282	54	289	54
First-order alternation	554	87	629	95	388	69	394	63	310	77	351	77
500-ms RSI												
RR	376	42	419	45	281	33	276	30	246	37	268	37
AR	444	54	471	59	305	42	313	39	273	48	303	48
RA	519	53	595	58	318	42	340	39	275	47	315	47
AA	436	69	561	75	273	54	308	50	236	61	287	61
First-order repetition	410	46	445	50	293	36	295	33	259	40	286	40
First-order alternation	478	57	578	62	296	45	324	41	256	50	301	50

Note. R, repetition; A, alternation.

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, $F(1,19) = 6.76$,

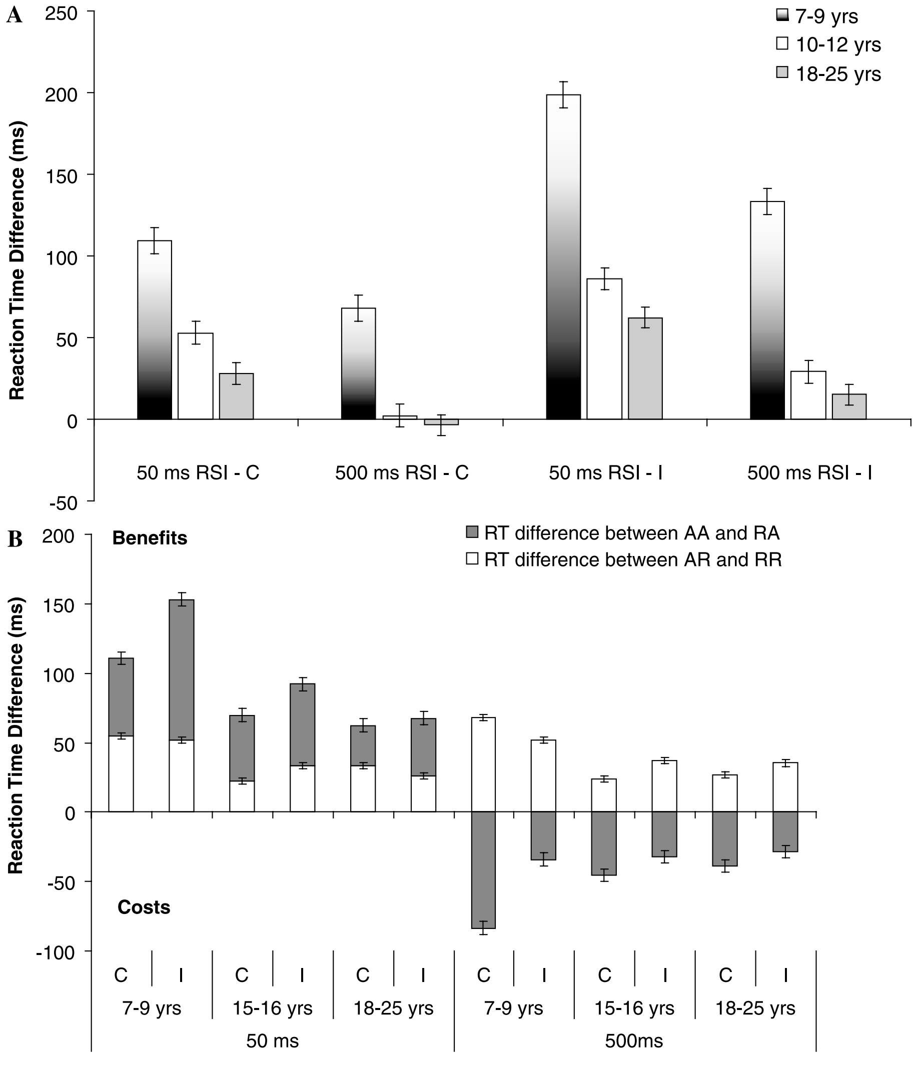

Fig. 2. (A) First-order sequential effects observed for each age group in both RSI and S–R compatibility conditions in Experiment 2. RT differences between first-order alternations and repetitions are plotted. A positive difference indicates a repetition effect, whereas a negative difference indicates an alternation effect. (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.

$p < .014$, $F(1,27) = 5.37$, $p < .032$, and $F(1,30) = 4.59$, $p < .041$, for children, adolescents, and adults, respectively. In Fig. 2B, 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, $F(1,48) = 4.70$, $p < .035$. Adolescents and adults did not differ in this respect ($p > .19$). Most important, 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.[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 mappings 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.

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 was 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, $F(1,76) = 0.52$, $p = .47$, 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

[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 failed to produce a significant first-order alternation effect in adults.

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)

	7–9 years A	10–12 years B	15–16 years C	18–25 years D
50-ms RSI				
First-order effect (A-R)	$79.7^{C/D}$	53.1^{D}	53.0^{A}	21.6^{A}
Second-order effect (AR-RR/AA-RA)	$56.6/49.3^{C/D}$	26.4/46.3	$22.3/47.5^{A}$	$34.7/25.3^{A}$
500-ms RSI				
First-order effect (A-R)	$54.4^{C/D}$	23.2^{D}	2.3^{A}	-4.3^{A}
Second-order effect (AR-RR/AA-RA)	$51.1/-80.3^{C/D}$	$32.0/-66.6^{D}$	$24.1/-45.5^{A}$	$27.3/-38.5^{A}$

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 the adults (Group D). This is indicated by the C/D superscript following the value of the repetition effect observed for the youngest children.

between-subjects 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 versus 277 ms), $F(1,49) = 24.75$, $p < .001$. 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 are 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.

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 toward 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 mappings 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 spatially 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, 1998; Soetens et al., 1985).

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 current 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 has received considerable support in 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 for 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 & Paclisanu, 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 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 in adults (van den Wildenberg & van der Molen, 2004; Williams, Ponesse, Schacher, Logan, & Tannock, 1999) and that the activation of the alternate response is particularly time-consuming in children relative to adults (Band, van der Molen, Overtoom, & Verbaten, 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 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 reexamine developmental change in the cost–benefit pattern using electrophysiological measures of expectancy [e.g., P300 component of the event-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).

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