Developmental changes in cognitive control

Temporal dynamics of task performance across trial sequences

Smulders, S.F.A.

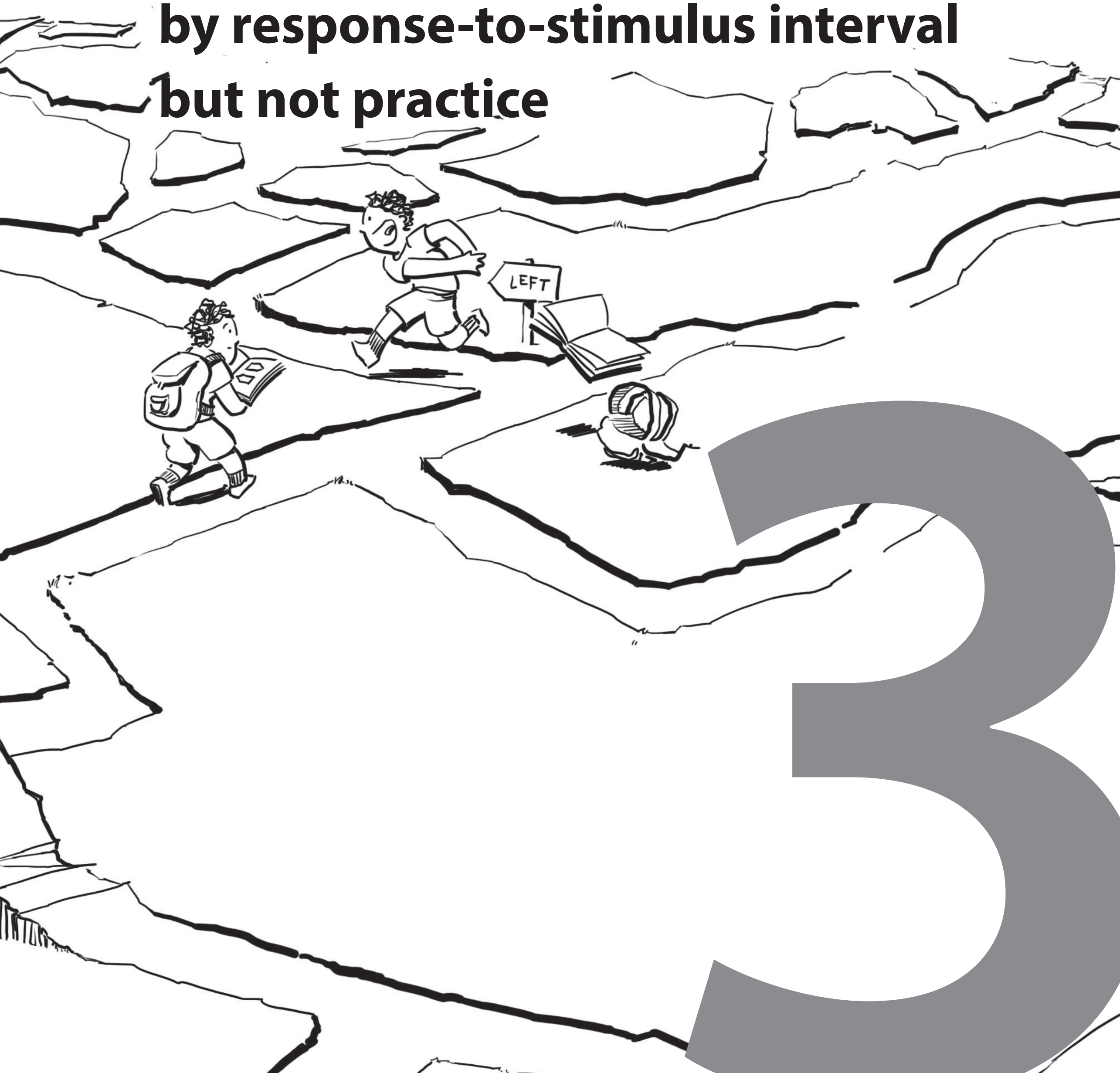
Publication date
2017

Document Version
Other version

License
Other

3

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 considerable 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 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. A white screen containing the vertical line initiated a new trial block. Before 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.

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.

3

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 3. 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.

Age Group	5-6 yrs		7-9 yrs		10-12 yrs		13-14 yrs		15-17 yrs		18-25 yrs	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
50 ms RSI												
RR	558	82	419	76	436	104	343	47	361	99	322	54
AR	806	159	473	97	484	124	368	60	376	85	347	53
RA	843	153	552	125	484	116	371	61	366	77	324	55
AA	1041	260	597	152	530	138	401	89	400	100	348	52
First-order R	682	117	446	80	460	108	356	50	369	91	334	52
First-order A	942	204	574	131	507	120	386	73	383	87	336	51
150 ms RSI												
RR	448	36	386	86	402	121	298	30	326	81	281	33
AR	621	92	449	120	457	136	332	51	350	77	305	36
RA	778	140	581	191	460	111	349	71	352	68	313	38
AA	898	202	591	172	471	138	358	76	356	85	307	47
First-order R	534	61	418	100	430	125	315	39	338	78	293	33
First-order A	838	167	586	178	465	122	354	71	354	75	310	41
200 ms RSI												
RR	434	43	368	79	366	97	296	35	307	71	275	38
AR	594	72	417	79	405	98	336	37	337	67	302	36
RA	752	114	532	138	457	119	355	51	344	66	307	39
AA	766	153	538	144	445	138	347	62	331	82	290	49
First-order R	514	56	393	77	386	96	316	33	322	67	288	36
First-order A	759	127	535	138	451	127	351	55	337	73	299	42

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.

Age Group	**5-6 yrs**		**7-9 yrs**		**10-12 yrs**		**13-14 yrs**		**15-17 yrs**		**18-25 yrs**	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
250 ms RSI												
RR	463	76	402	116	383	134	289	28	304	62	265	30
AR	648	78	476	100	424	124	326	35	340	61	293	30
RA	859	224	596	221	489	143	340	28	341	59	306	39
AA	860	248	580	237	476	193	311	41	315	68	282	40
First-order R	556	63	439	102	403	126	308	29	322	60	279	29
First-order A	860	234	588	227	482	164	326	32	328	62	294	39
500 ms RSI												
RR	542	46	450	83	396	102	302	31	302	56	266	27
AR	687	95	519	85	447	118	340	41	332	58	288	29
RA	798	181	580	123	452	101	341	43	327	61	289	36
AA	744	188	510	122	396	144	298	48	302	69	255	26
First-order R	614	65	484	83	422	109	321	33	317	56	277	27
First-order A	771	182	545	121	424	120	320	42	314	63	272	31
1000 ms RSI												
RR	590	50	512	114	424	97	323	41	316	47	273	28
AR	729	60	583	135	462	89	351	52	334	47	294	30
RA	819	134	617	153	466	107	341	50	323	54	280	31
AA	705	96	528	125	388	89	300	49	298	56	257	23
First-order R	660	49	548	122	443	92	337	45	325	46	284	29
First-order A	762	102	572	138	427	97	320	48	311	54	269	27

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

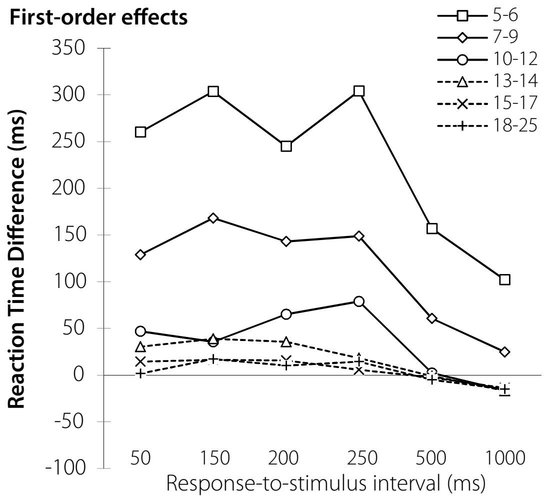


Figure 1. First-order sequential effects observed for each age group and RSI condition in Experiment 1. Reaction time (RT) differences between first-order alternations and repetitions are plotted. A positive difference indicates a first-order repetition effect and a negative difference indicates a first-order alternation effect.

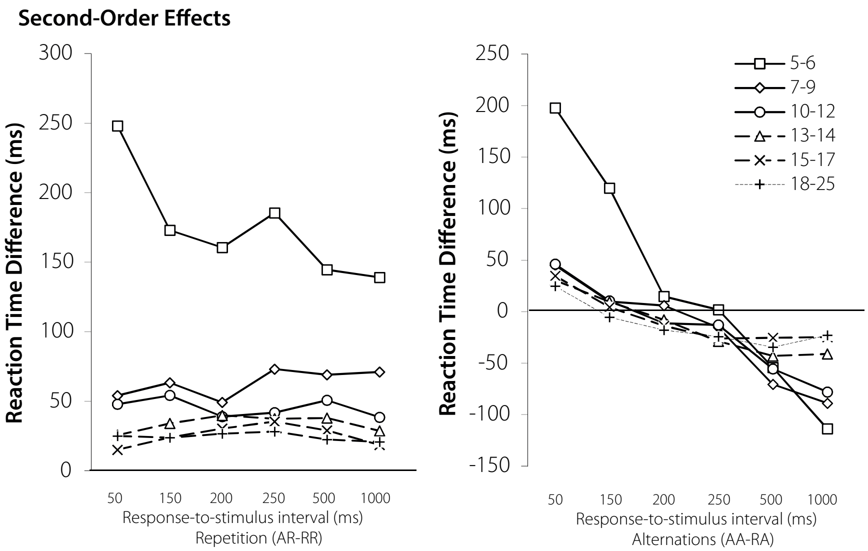


Figure 2. Second-order sequential effects for each age group and RSI condition in Experiment 1. RT differences between second-order AR vs. RR (*left* panel) and AA vs. RA sequences (right panel) are plotted. Two positive differences (left/right panels) indicate a higher order benefit-only pattern. A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

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.

First-order sequential effects (A-R)						
FO effects	50 ms	150 ms	200 ms	250 ms	500 ms	1000 ms
5-6 yrs	260.2	303.6	245	304	156.8	102.1
7-9 yrs	128.8	168.1	142.9	148.7	60.6	24.7*
10-12yrs	46.8	35.7	65.2	78.8	2.1*	**-16.5**
13-14 yrs	30.3	38.8	35.5	18.2	**-1***	**-16.8**
15-17 yrs	14.4	16.3	15.7	5.6*	**-2.7***	**-13.9**
18-25 yrs	1.7*	17.1	10.1*	14.5	**-5***	**-15.1**

Second-order sequential effects (AR-RR vs. AA-RA)						
SO effects	50 ms	150 ms	200 ms	250 ms	500 ms	1000 ms
5-6 yrs	248 vs. 198	173 vs. 120	160 vs. 14	185 vs. 1	**145 vs. -45**	**139 vs. -114**
7-9 yrs	54 vs. 45	63 vs. 16	49 vs. 6	**74 vs. –16***	**69 vs. -70**	**71 vs. -89**
10-12yrs	48 vs. 46	55 vs. 11	**39 vs. -12**	**41 vs. -13**	**51 vs. -56**	**38 vs. -78**
13-14 yrs	25 vs. 30	34 vs. 9	**40 vs. -8**	**37 vs. -29**	**38 vs. -43**	**28 vs. -41**
15-17 yrs	15 vs. 34	24 vs. 4	**30 vs. -13**	**36 vs. -26**	**30 vs. -25**	**18 vs. -25**
18-25 yrs	24 vs. 24	**24 vs. –6**	**27 vs. –17**	**28 vs. -24**	**22 vs. -34**	**21 vs. –23**

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.

	RSI 50								RSI 500							
Practice	**1**		**2**		**3**		**4**		**1**		**2**		**3**		**4**	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
7-9 yrs																
RR	447	96	475	140	438	111	414	101	433	78	494	129	502	112	519	98
AR	500	76	506	130	496	127	464	117	464	56	503	148	525	138	529	119
RA	508	63	535	116	507	101	472	63	529	71	562	147	563	138	579	128
AA	543	58	579	140	543	123	503	81	464	85	520	137	529	129	517	79
FO-R	473	85	491	134	467	115	439	107	448	64	495	136	513	121	524	106
FO-A	526	54	557	120	525	109	487	70	497	74	541	141	546	129	548	96
10-12 yrs																
RR	377	86	337	73	313	48	301	62	332	81	323	59	304	62	309	72
AR	410	102	362	78	344	68	336	80	361	72	347	60	332	65	333	68
RA	415	66	400	65	369	54	369	75	390	74	391	68	373	74	374	77
AA	478	86	447	83	408	59	384	78	325	71	351	69	328	63	326	70
FO-R	393	94	349	74	329	55	328	69	347	75	335	59	318	62	321	70
FO-A	447	72	424	70	388	53	376	74	357	70	371	67	351	66	350	72
18-25 yrs																
RR	335	68	308	44	298	49	280	33	308	46	283	35	266	31	266	29
AR	366	63	338	38	327	56	301	37	338	50	308	33	288	31	280	28
RA	362	65	347	41	333	46	311	41	339	46	326	43	309	39	295	37
AA	380	108	363	52	356	62	320	49	304	53	288	35	276	31	269	32
FO-R	350	63	323	38	312	51	291	34	323	46	295	33	277	30	273	28
FO-A	381	84	365	45	344	53	315	94	322	48	307	38	292	34	282	32

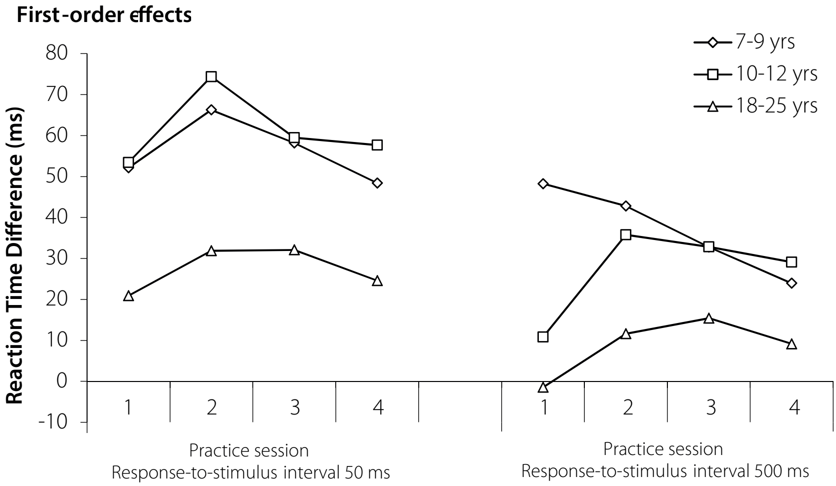


Figure 3. First-order sequential effects observed for each age group in function of practice blocks for both RSI conditions (left and right panel) in Experiment 2. Reaction time (RT) differences between first-order alternations and repetitions are plotted. A positive difference indicates a repetition effect; a negative difference indicates an alternation effect.

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,

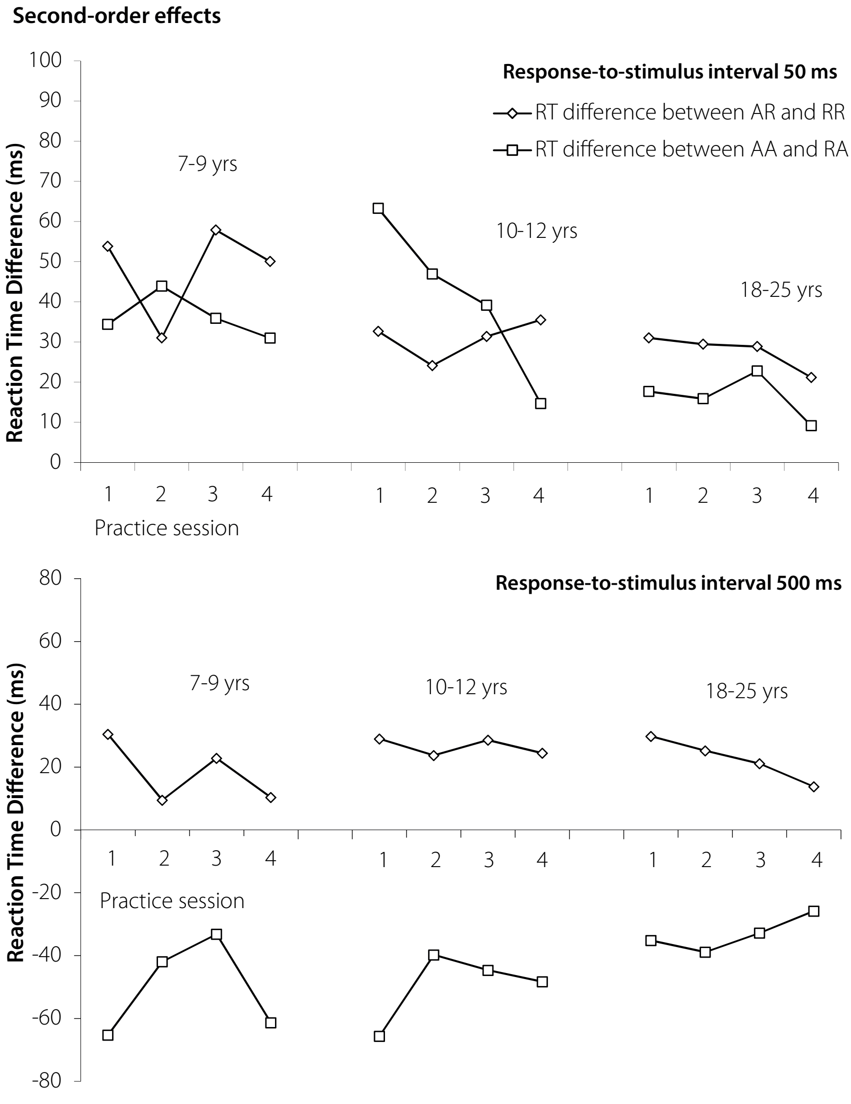


Figure 4. Second-order sequential effects for each age group in function of practice for 50 ms (upper) and 500 ms RSI (lower) in Experiment 2. RT differences between second-order AR vs. RR and AA vs. RA sequences are plotted. Two positive differences indicate a higher order benefit-only pattern. A positive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

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 suggests 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.