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Developmental Dissociations of Preparation Over Time: Deconstructing the Variable Foreperiod Phenomena

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In a variable foreperiod (FP) paradigm, reaction times (RTs) decrease as a function of FP on trial n (FP effect) but increase with FP on trial $n - 1$ (sequential effects). These phenomena have traditionally been ascribed to different strategic preparation processes. According to an alternative explanation, common conditioning laws underlie both effects. The present study aims to disentangle these opposite views using a developmental perspective. In Experiment 1A, 4- to 11-year-old children and a control group of adults performed a simple RT task with variable FPs (1, 3, and 5 s). Furthermore, 12 4- to 5-year-old children were retested after 14 months (Experiment 1B). In Experiment 2, a narrower pool of participants (4, 5, and 6 years old) performed a variable FP paradigm with different FPs (1, 2, and 3 s). The results consistently suggest different ontogenetic time courses for the two effects: The sequential effects are already present in the youngest group (4–5 years old), whereas the FP effect appears gradually some years later. These findings are not fully compatible with previous views. A dual-process account is proposed to explain the data.

Keywords: developmental dissociation, foreperiod effect, nonspecific preparation, sequential effects, temporal processing

In cognitive research, neuropsychological dissociations can be useful in providing evidence on the functional architecture of normal cognition, given that the tasks involved do not differ in the quantitative levels of the cognitive resources employed (Shallice, 1988). An analogous logic could apply to dissociations observed in the developmental time course. In the present study, such a developmental perspective has been adopted in order to disentangle different accounts of the variable *foreperiod* (FP) *effect*, a well-known phenomenon that has traditionally been studied in adult participants.

Preparation is a ubiquitous and poorly understood aspect of human cognition (Sanders, 1998). The temporal aspects of nonspecific preparation can be well studied using the variable FP paradigm. The FP is the unfilled time interval between a warning stimulus and an imperative stimulus. In a typical variable FP paradigm, different FPs within a given range randomly occur over trials with the same a priori probability. Mean reaction time (RT) then decreases as a negatively accelerating function of FP (the variable FP effect; Woodrow, 1914). Traditionally, the FP effect has mainly been attributed to strategic processes (see Niemi & Näätänen, 1981, for a review). When no catch trials are used, as time elapses during the FP without the imperative stimulus occurring, the conditional probability of the imperative stimulus being presented in the next time interval increases. The cognitive system is believed to exploit this probability to endogenously increase response preparation (e.g., Näätänen, 1970).

However, despite its simplicity, this account has a major limitation in that it fails to explain another phenomenon occurring in a variable FP task: the sequential FP effects (Baumeister & Joubert, 1969; Karlin, 1959; Woodrow, 1914). RTs on the current trial (FP_n) are slower when preceded by a longer FP on the previous trial (FP_{n-1}) than when preceded by an equally long or shorter one. Such effects are asymmetric, as they are mainly present with the shortest FP_n in a block of trials. It should be noted that the asymmetry of the sequential effects contributes, at least to a certain extent, to the negatively accelerating shape of the FP effect. This should be taken into consideration as a constraint for any account of the FP phenomena.

To explain the sequential effects, traditional theories (e.g., Drazin, 1961; Karlin, 1959) assume that the participant expects a repetition of the previous FP_{n-1}, so that peak preparedness is reached at the same FP as that of the previous trial. If FP_n is shorter than FP_{n-1}, then peak preparedness will not have been reached when the imperative stimulus occurs, and a relatively slow RT will result. When instead the expectancy is disconfirmed because FP_n is longer than FP_{n-1}, it is assumed that participants can voluntarily

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extend the period of optimal preparation or cyclically reprepare, so accounting for the asymmetry in the sequential effects (e.g., Alegria, 1975; Thomas, 1967).

A difference between the conditional probability monitoring and the repreparation–maintenance hypothesis is that the former is a stand-alone process (which however does not account for sequential effects), whereas the latter can hold only if the FP repetition expectancy account also holds. At first glance, the traditional accounts of the FP effect seem in fact redundant, as the contribution of the repreparation–maintenance process to the FP_n–RT function is qualitatively similar to that derived from the process of monitoring the conditional probability. However, although the two processes have the same consequences on RTs if one considers only the effect of FP_n, the repreparation–maintenance account has the additional advantage of explaining the asymmetry of the sequential effects.

An apparent disadvantage of such traditional accounts of the sequential effects is that they propose two entirely different strategically mediated processes to explain different aspects of the results. As an alternative, Los and colleagues recently proposed a conditioning account (e.g., Los & van den Heuvel, 2001; Los, Knol, & Boers, 2001). They assumed that to each possible FP there corresponds a conditioned strength of activation, and that during a trial the participants' readiness to respond tracks these strengths. They further assumed that, on any trial, the conditioned strength corresponding to an FP is (a) increased if that FP occurs, (b) unchanged if a shorter FP occurs, and (c) decreased if a longer FP occurs. This final assumption is motivated by a supposed need to inhibit the tendency to respond ahead of time, which is held to be strong during the FP and to terminate with the presentation of the imperative stimulus (Los & van den Heuvel, 2001, p. 372; see also Ollman & Billington, 1972). Thus, Näätänen (1971, p. 324) argued that "to restrain the intensive cumulative tendency of motor readiness from flowing over into motor action, with a resulting relief from tension, is both exhaustive and provocative of aversion." It follows that the conditioned strength of activation corresponding to the longest FPs can never decrease because no longer FP can occur. Hence, the sequential effects, if present, should be asymmetrically biased toward the shortest FP. This single-process view has the advantage of making the FP effect a direct consequence of the sequential effects, because the change in RT with FP on trial n is a function of the conditioning influences produced on trial $n - 1$.

To summarize, two alternative views have been suggested in the literature to account for the FP phenomena: a dual-process strategic account and a single-process conditioning view. The present study uses developmental dissociations as a tool to disentangle these different cognitive accounts. Developmental dissociations occur when different effects produced in one or more tasks are shown to appear diachronically in cognitive development, as revealed either longitudinally in the same group of children or across different age groups. From a functional point of view, if the same process underlies two different behavioral effects, then they would be expected to show the same developmental trajectory. If instead two different processes underlie them, then there is no reason why they should develop in the same fashion.

More specifically, by exploring the ontogenetic development of the FP phenomena, the current study assesses the viability of the conditioning view as opposed to strategic models. The conditioning view of Los and van den Heuvel (2001), indeed, predicts a parallel ontogenetic development of the sequential effects with respect to the FP effect as, on this account, the FP effect occurs as a side effect of the interplay between reinforcement and extinction that gives rise to the asymmetric sequential effects. According to this view, therefore, if no FP effect is shown by the youngest children, no sequential effects should be observed either.

On the traditional strategic accounts, a different prediction can be made. If no FP effect is observed in a group of children, that might indicate that the repreparation–maintenance process (e.g., Alegria, 1975) does not fully operate. On such dual-process accounts, there is no need for the FP effect to follow the same developmental trajectory of the sequential effects, as they rely upon different processes. However, if the sequential effects are observed without the FP effect, the FP repetition expectancy account (e.g., Drazin, 1961) would predict faster RTs for short–short and long–long FP sequences rather than for long–short and even short–long ones, respectively (namely, a crossover $FP_n \times FP_{n-1}$ interaction).

A prediction can also be made about the developmental time course of the FP effect on the basis of recent neuropsychological (Stuss et al., 2005) and transcranial magnetic stimulation (TMS; Vallesi, Shallice, & Walsh, 2007) studies, which show that the FP effect depends upon the functioning of the right dorsolateral prefrontal cortex (rDLPFC). Hence, the FP effect might be expected to follow the neurodevelopmental curve of the rDLPFC. It is known that the pruning process subsequent to the early overproduction of synapses in the prefrontal cortex continues for a long period up to adolescence (Huttenlocher, 1979, 1990; Huttenlocher & Dabholkar, 1997). Moreover, the neurons within this region myelinate and develop in an accelerated fashion from 4–7 years of age (Delalle, Evers, Kostovic, & Uylings, 1997). In addition, a number of tasks which rely on frontally located processes, such as planning, flexibility, inhibition, and source memory, begin to be performed well at this age (Archibald & Kerns, 1999; Davidson, Amso, Anderson, & Diamond, 2006; Drummey & Newcombe, 2002; also see Zelazo, Carter, Resnick, & Frye, 1996, for a review). On the other hand, virtually nothing is known about the anatomical basis of the sequential effects that, however, do not seem to be linked to the functioning of the rDLPFC (Vallesi et al., 2007).

Experiment 1A

A few studies in the literature have examined the FP effect in children, who usually show a slightly smaller FP effect than that in adults (e.g., Adams & Lambos, 1986; Ozmun, Surburg, & Cleland, 1989). To our knowledge, the only study to investigate sequential effects in children is one by Elliott (1970). The results of that study failed to show any modulation of the FP phenomena as a function of age. However, the youngest group of children in that study was on average 6 years old. Therefore, studying the FP phenomena from a younger age could reveal more about their ontogenetic time courses. Experiment 1A was designed to investigate the ontogenetic time course of the FP effect and the sequential effects in young children from 4 years of age on. This was done by administering a variable FP paradigm to children from 4 to 11 years of age as well as to a control group of adults.

Method

Participants

Children (4–11 years of age) were mainly recruited in a summer camp and grouped into four age groups, with each group comprising 2 years (see Table 1). A control group of adults was also enrolled. A total of 106 participants took part in the experiment. Parents had previously signed informed consent for all the children participating in the study. The study was previously approved by the Scuola Internazionale Superiore di Studi Avanzati Ethical Committee.

Apparatus and Materials

Each participant was tested individually in a silent and dimly lit room. Participants viewed a 17 in. (43.2 cm) computer monitor at a distance of about 60 cm. The index finger of their writing hand rested on the keyboard space bar. At the beginning of each trial, an auditory warning stimulus (a 1,500 Hz pure tone) was presented for 50 ms through headphones. The visual stimuli were presented on a black background. A centrally presented cross (two yellow crossed bars: 1.0 × 0.5 cm), which appeared together with the warning sound, served as the fixation stimulus. The fixation lasted for the whole FP. Three FPs of 1, 3, and 5 s, respectively, occurred on an equal number of trials. The imperative stimulus was a downward-pointing white arrow (a 1.5- × 1-cm bar attached to a 0.5-cm arrowhead with a maximum width of 2 cm). The imperative stimulus replaced the fixation and disappeared after 500 ms. The time limit for response was 2,000 ms after the arrow's onset.

Procedure and Task

Each child (4–11 years of age) was individually introduced to the experiment through a short familiarization phase. When a friendly atmosphere had been established, the experimenter asked if the child would take part in the experiment. If the child agreed, the experimenter explained the task, which consisted of pressing the space bar when an arrow appeared. This task was presented as a "velocity game," but the need to avoid anticipations was also highlighted. Apart from this initial phase, the experimental conditions were completely comparable for children and adults. As no change in the FP phenomena was observed across blocks of 60 trials in two similar pilot experiments on adults (unpublished data from our lab), only a single block of 60 trials was used, in order to prevent the children from becoming tired or bored. Preceding the 60 test trials, 3 familiarization trials were run and repeated until the participant performed them without errors. No more than two to three familiarization cycles were necessary for any participant to reach this criterion.

Table 1
Main Demographic Characteristics of the Five Age Groups in Experiment 1A

		Gender[a]		Handedness		
Group[b]	Mean age (min–max)	Female	Male	Left	Right	*n*
4–5[c]	61 months (48–71)	11	10	1	20	21
6–7[d]	83 months (72–94)	10	12	2	20	22
8–9	107 months (96–119)	10	15	1	24	25
10–11	130 months (120–142)	5	12	1	16	17
Adults	25 years (19–30)	7	14	1	20	21

[a] Initial analyses of variance did not reveal any significant effect of gender. Therefore, the results were collapsed across gender. [b] Each age group, apart from adults, is defined by the range of years spanned. [c] Three children from this group refused to participate. [d] One child from this group refused to participate.

Data Analysis

The familiarization trials and the first test trial were not analyzed. Trials were treated as errors and discarded from the RT analyses if a response was made during the FP or the first 100 ms after imperative stimulus onset (premature responses), or if the RT was slower than 1,500 ms or no response was detected (delayed and null responses). For the RT analyses, the within-subjects independent variables included FP_n (1, 3, or 5 s) and FP_{n-1}. The between-subjects variable involved five age groups: 4–5 years, 6–7 years, 8–9 years, 10–11 years, and adults. The dependent variable chosen was the median RT. The RT data were normally distributed, but the analysis of variance (ANOVA) assumption of homoscedasticity was occasionally violated (significant Levene test). For that reason, a log transformation was applied to make the variances more homogeneous. After applying this transformation, the assumption of homoscedasticity was always achieved. Greenhouse–Geisser epsilon corrections were used when appropriate. Post-hoc Tukey's honestly significant difference comparisons were performed to evaluate pairwise differences among the means.

Results

Accuracy

The error percentages for each group are displayed in Figure 1 (see the middle and bottom panels). For the accuracy analysis, nonparametric tests were used because the distributions of most variables were non-Gaussian by the Kolmogorov–Smirnov test and because some participants did not make any errors.

Overall premature responses decreased as a function of age: Kruskal–Wallis test, $H(4, N = 106) = 17.8, p < .01$. Premature responses increased significantly as a function of FP_n in the 4- to 5-year-old children (Page's $L = 266, p < .05$) and, as a tendency, in the 6- to 7-year-old ones (Page's $L = 274.5$, critical L for $p < .05 = 275$). Premature responses decreased significantly as a function of the FP_{n-1} in 4- to 5-year-old children (Page's $L = 264$, $p < .05$) and also in 6- to 7- and 8- to 9-year-old ones (Page's $L =$ 280 and 319, respectively; $p < .01$ for both).

Overall delayed and null responses decreased as a function of age: Kruskal–Wallis test, $H(4, N = 106) = 37.7, p < .001$. Delayed and null responses generally decreased as a function of FP_n and increased as a function of FP_{n-1}, but these tendencies, although constant, never reached significance for any group with Page's L test.

Reaction Times

A 3 × 3 × 5 mixed ANOVA was performed with FP_n and FP_{n-1} as the within-subjects variables and age as the between-subjects

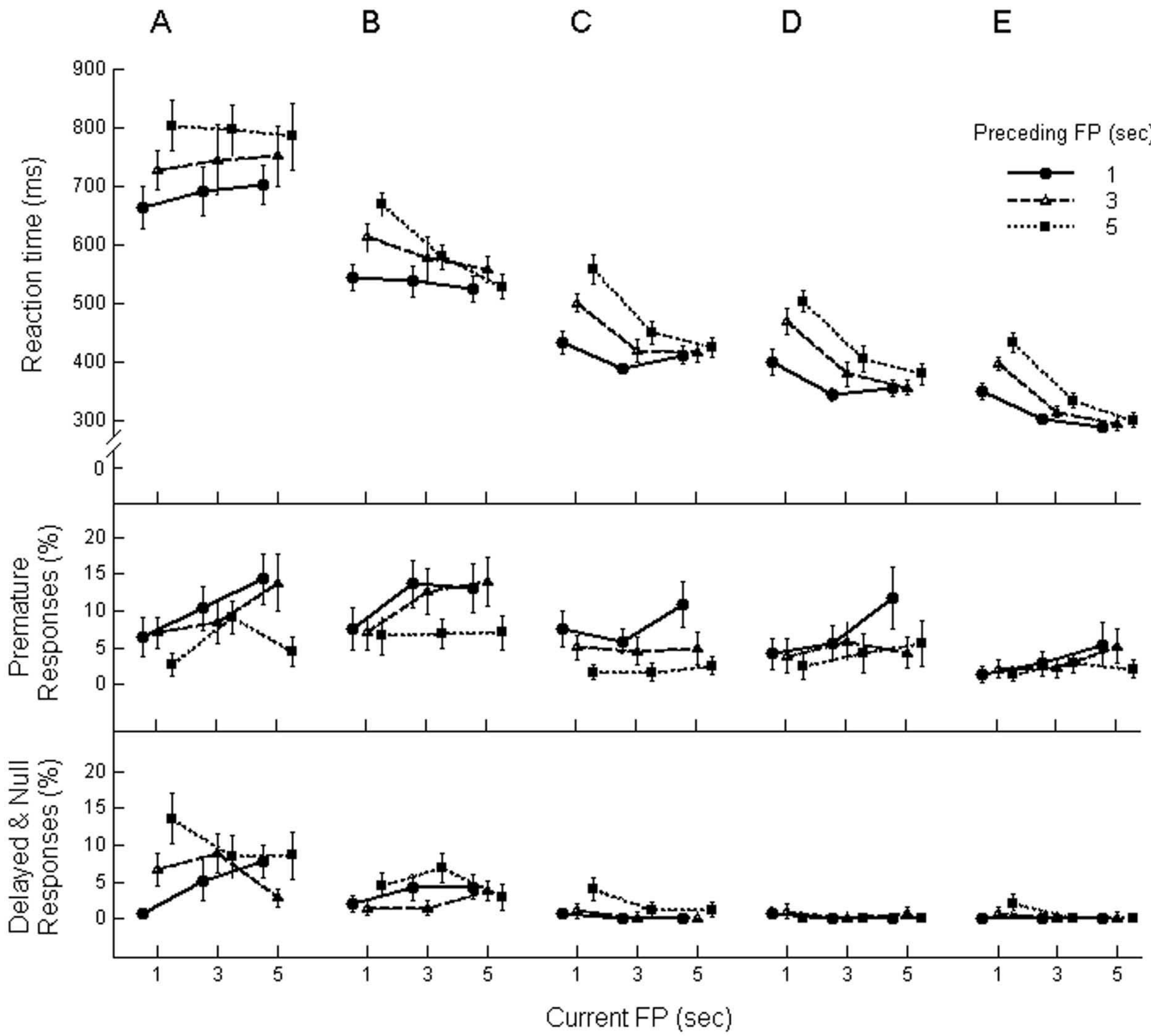

Figure 1. Median reaction times (top panel), percentage of premature responses (middle panel), and percentage of delayed and null responses (bottom panel), as a function of the current foreperiod (FP; *x* axis) and preceding FP (lines) in Experiment 1A. Error bars indicate standard errors of the mean. Columns A–E show the data separately for each age group: A = 4–5 years; B = 6–7 years; C = 8–9 years; D = 10–11 years; E = adults. Note that the analyses of variance reported in the text and in Table 2 were performed using log-transformed data whereas the top panel of the figure shows raw data for reasons of clarity.

variable (see Figure 1). This produced a significant main effect of age, $F(4, 101) = 83.7$, $p < .001$, indicating that RTs became faster with age.

FP effect. The main effect of FP_n was also significant, $F(1.7, 169.8) = 95.48$, corrected $p < .001$. Post-hoc comparisons showed that RTs were slowest for the shortest FP of 1 s compared to the medium and longest FPs (for both, $p < .001$). Critically, a reliable Age × FP interaction was present, $F(6.7, 169.8) = 9.67$, corrected $p < .001$: The FP effect (i.e., RTs slower for the shortest FP than for the longest one) was present in all groups apart from the 4- to 5-year-old one. For this group, the difference between the mean RT on shortest and longest FPs_n was nonsignificant (Tukey $p > .99$; for all other groups, $p < .01$).

To evaluate the difference in the magnitude of the FP effect across groups, *planned comparisons* were performed contrasting RTs on FPs of 1 s with those on FPs of 5 s for each age group and for each pair of age groups. The FP effect found in the 4- to 5-year-old children (−13 ms) was significantly smaller than in all the other groups (for all, $p < .001$). The 6- to 7-year-old group had a smaller FP effect compared with the 10- to 11-year-old group ($p < .05$) and the adults ($p < .001$). No other difference was found. Additionally, *polynomial contrasts* were used to obtain an overall picture after exclusion of the qualitatively different 4- to 5-year-old group: The linear model contrasting the RTs on FP_n of 1 s versus 5 s, for the other four groups, fitted the results well, $F(1, 81) = 17.87$, $p < .001$, indicating that the FP effect grows linearly as a function of age from 6–7 years through adulthood.

Sequential effects. The main effect of FP_{n-1} was significant, $F(2, 202) = 103.86$, $p < .001$. Current RT was slower following a longest FP_{n-1} trial than a medium FP_{n-1} trial (post-hoc Tukey

Table 2
Outputs of the Separate Analyses of Variance (ANOVAs) for Each of the Five Age Groups of Experiment 1A

Group[a]	Effect	SS	*df*	*MSE*	*F*	*p* <
4–5	FP_n	0.001	2, 40	0	0.07	.93
	FP_{n-1}	0.124	1.5, 30.8	.062	13.46	Corrected .001
	$FP_n \times FP_{n-1}$	0.011	2.6, 52.5	.003	0.65	Corrected .57
6–7	FP_n	0.098	1.5, 32.4	.049	8.49	Corrected .01
	FP_{n-1}	0.072	2, 42	.036	16.97	.001
	$FP_n \times FP_{n-1}$	0.05	4, 84	.013	3.33	.05
8–9	FP_n	0.26	1.5, 35.3	.13	31.59	Corrected .001
	FP_{n-1}	0.137	2, 48	.068	38.85	.001
	$FP_n \times FP_{n-1}$	0.063	3, 72.5	.016	5.45	Corrected .01
10–11	FP_n	0.275	2, 32	.138	28.84	.001
	FP_{n-1}	0.109	2, 32	.054	29.54	.001
	$FP_n \times FP_{n-1}$	0.032	4, 64	.008	3.58	.01
Adults	FP_n	0.519	2, 40	.26	107.9	.001
	FP_{n-1}	0.079	2, 40	.04	21.7	.001
	$FP_n \times FP_{n-1}$	0.035	4, 80	.009	5.4	.001

Note. For each age group, a 3 (FP_n = foreperiod on Trial *n*) × 3 (FP_{n-1} = foreperiod on Trial $n - 1$) repeated-measures ANOVA was performed. Greenhouse–Geisser corrections were applied when appropriate. SS = sum of squares.
[a] Each age group, apart from adults, is defined by the range of years spanned.

test, $p < .001$). This, in turn, was slower than RT following a shortest FP_{n-1} trial ($p < .01$). There was also a reliable $FP_n \times FP_{n-1}$ interaction, $F(3.7, 371.5) = 13.88$, corrected $p < .001$. As shown by post-hoc tests, this interaction indicates that the effect of FP_{n-1} was greatest for the shortest FP_n and smallest for the longest FP_n, replicating results concerning the asymmetry of the sequential effects known from the literature. Most critically, no sequential effect involving the factor FP_{n-1} was significantly different between any of the groups (see Figure 1). Although the Age × FP_n × FP_{n-1} interaction was not significant, mean latencies (and visual inspection of Figure 1) suggest that the youngest children did not produce asymmetric sequential effects.

To statistically corroborate this observation, subsequent 3 × 3 repeated-measures ANOVAs were performed separately on each group, with FP_n and FP_{n-1} as the within-subjects variables. For all groups, apart from the 4- to 5-year-old one, these analyses confirmed results from the previous analysis, as all of them showed a significant main effect of FP_n, FP_{n-1}, and the $FP_n \times FP_{n-1}$ interaction (see Table 2). It is noteworthy that only the 4- to 5-year-old children failed to show the FP_n effect and the $FP_n \times FP_{n-1}$ interaction effect, but they did show a highly significant effect of FP_{n-1} (see Table 2). The lack of $FP_n \times FP_{n-1}$ interaction for this group was due to RTs being exclusively modulated by the previous FP_{n-1} with no effect of the current FP_n, even when the latter was the longest one (see Figure 1, Panel A).

Discussion

In the present experiment, a variable FP paradigm was administered to children of various ages with the aim of exploring the ontogenetic time course followed by the FP and the sequential effects. The results show a developmental dissociation between the two effects: Sequential effects are already present from at least 4–5 years of age, whereas the FP effect appears gradually from 6–7 years on. The different developmental trajectories followed by the two effects already provide evidence in favor of a dual-process account and are difficult to explain by a single-process account. A potentially useful additional result, in order to understand which mechanism underlies the sequential effects, is the observation that in the 4- to 5-year-old group, these effects were symmetrical[1] across all three current FPs_n. This pattern resembles that obtained for adults undergoing TMS of the rDLPFC (Vallesi et al., 2007). In the experimental block in which the inhibitory stimulation used in that study (i.e., theta burst) was expected to be stronger (second post-TMS block; see Experiment 2), a decrease in the FP effect was observed together with a pattern of sequential effects significantly more symmetrical with respect to the baseline. However, in the current study this observation is weakened by a lack of Age × $FP_n \times FP_{n-1}$ three-way interaction in the overall ANOVA.

Experiment 1B

A possible reason for the lack of the Age × $FP_n \times FP_{n-1}$ three-way interaction, which would demonstrate qualitative differences in the shape of the sequential effects in youngest children with respect to older, could be the variability across and within groups in Experiment 1A. A within-subjects approach would be of use in order to reduce the variability across groups. To that purpose, a follow-up approach was adopted in Experiment 1B. To our knowledge, no other developmental study has previously investigated the FP phenomena longitudinally.

[1] We use the expression *symmetrical sequential effects* here and hereafter, meaning that there is a symmetrical influence of the FP_{n-1} on the RTs whatever FP_n has occurred. This influence consists of RT being slower as the preceding FP_{n-1} gets longer. Strictly speaking, a crossover $FP_n \times FP_{n-1}$ interaction would also be symmetrical, but not in the sense explained above.

Method

Participants

Twelve participants from the 4- to 5-year-old group of Experiment 1A (9 girls, 3 boys; 1 left-handed, 11 right-handed) were retested 14 months after the first study. In the first session, children were on average 61 months old (range: 50–71).

Apparatus and Procedure

The apparatus and procedure of the second session were kept as similar as possible to those in the first session (see Method section of Experiment 1A), apart from the fact that in the second session children were tested in their homes instead of at the summer camp.

Data Analysis

The same criteria were adopted as in Experiment 1A for the accuracy and RTs here. For RT analyses, a 2 × 3 × 3 repeated-measures ANOVA was employed with test session (first vs. second session), FP_n (1, 3, or 5 s), and FP_{n-1} as the independent variables. The ANOVA assumption of normality was not violated by the median RT data, which were then used as the dependent variable.

Results

Accuracy

The accuracy results for Experiment 1B are presented in Figure 2 (see the middle and bottom panels). There was a tendency for a reduction of the overall percentage of anticipations from the first to the second session (Wilcoxon: $Z > 1.73$, $p = .08$). The rate of anticipations increased as a function of FP_n in both the first session (Page's $L = 154$, $p < .05$) and the second one (Page's $L = 157$, $p < .01$). The number of anticipations did not change significantly as a function of FP_{n-1} in either session. The rate of overall delayed and null responses decreased from the first to the second session (Wilcoxon: $Z > 2.49$, $p < .05$). The number of such responses did not vary significantly as a function of FP_n in either session. This type of error increased significantly as a function of FP_{n-1} in the first session only (Page's $L = 153.5$, $p < .05$).

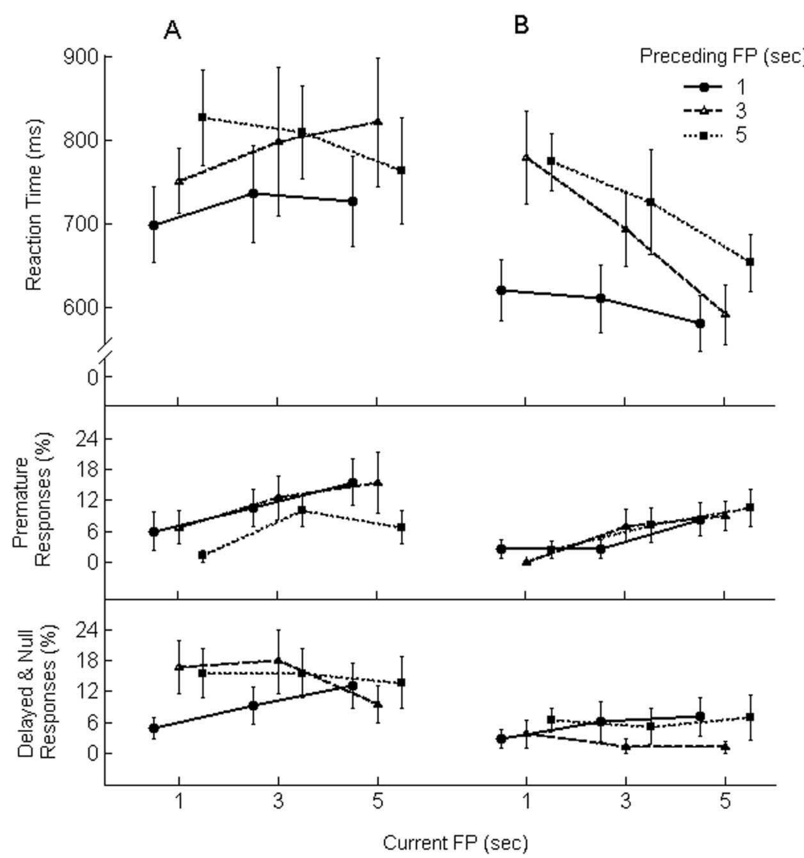

Figure 2. Median reaction times (top panel), percentage of premature responses (middle panel), and percentage of delayed and null responses (bottom panel), as a function of the current foreperiod (FP; *x* axis) and preceding FP (lines) in Experiment 1B. Error bars indicate standard errors of the mean. Columns A and B refer to the first and second sessions, respectively.

Reaction Times

The main effect of session, $F(1, 11) = 4.9$, $p < .05$, demonstrated that median RTs were slower in the first session than in the second one (770 vs. 670 ms).[2] There was a main effect of FP_n, $F(2, 22) = 3.5$, $p < .05$, but it was qualified by an $FP_n \times$ Session interaction, $F(2, 22) = 3.8$, $p < .05$. The latter was in accordance with the FP_n effect being present in the second session but absent in the first one, as confirmed by subsequent post-hoc comparisons. As far as sequential effects were concerned, the main effect of FP_{n-1} was significant, $F(2, 22) = 11.4$, $p < .001$, indicating that RT was faster as FP_{n-1} got shorter. No other effect reached significance. However, when data from the two testing sessions were analyzed separately, the $FP_n \times FP_{n-1}$ interaction showed a tendency toward significance in the second session only, $F(4, 44) = 2.3$, $p < .07$ (for the first session, $p = .46$), suggesting the presence of asymmetric sequential effects at 5–6 years of age.

Discussion

Experiment 1B confirmed results of Experiment 1A from a longitudinal point of view by demonstrating that a population of young children did not show the FP effect when they were 4–5 years old but showed the effect 14 months after the first test. Moreover, no difference was observed between sequential effects in the two sessions. Sequential effects were basically symmetrical in this population, as no $FP_n \times FP_{n-1}$ interaction was observed at either session. A limitation of Experiments 1A and 1B is that the difference between the symmetrical sequential effects in 4- to 5-year-old children and the asymmetric sequential effects in older children and adults was not statistically corroborated. This may be due to a lack of power in Experiment 1B, in which it was possible to retest only 12 participants in the second session. As far as Experiment 1A is concerned, detailed analyses of RT data performed on the 4- and 5-year-old children (ns = 8 and 13, respectively) as separate groups demonstrated that 4-year-olds showed symmetrical sequential effects whereas 5-year-olds did not: for the latter, Age $\times FP_n \times FP_{n-1}$ interaction, $F(4, 76) = 2.8$, $p < .05$.

In addition, within each age group of Experiment 1A, a Pearson correlation analysis was carried out between age in months and an index of the asymmetry of sequential effects. This index was obtained for each participant in the following fashion. First, sequential effects for the shortest FP_n were calculated through the RT difference between that FP_n given the longest FP_{n-1} and given the shortest FP_{n-1}. Then, sequential effects for the longest FP_n were calculated through the RT difference between that FP_n given the longest FP_{n-1} and given the shortest FP_{n-1}. To estimate the degree of asymmetry of the sequential effects, we calculated the difference between the two RT differences. A positive value would indicate asymmetry toward the shortest FP_n, and a negative one would indicate asymmetry toward the longest FP_n, with values close to 0 indicating symmetrical sequential effects. A positive correlation was obtained between the asymmetry index and months of age only in the 4- to 5-year-old children (Pearson's $r = .63$, $p < .05$), suggesting that sequential effects became gradually more asymmetric from 4 to 5 years of age. This suggested that the 4- to 5-year-old group consisted of two populations, which would be worthwhile to consider separately. However, given the small number of 4-year-old children ($n = 8$) in Experiment 1A, it was necessary to replicate the experiment with a new and larger sample size for each group, considering 4- and 5-year-old children as two separate groups (see Experiment 2).

Experiment 2

In Experiment 2, we concentrated on the most sensitive ages of 4, 5, and 6 years old, both because the main developmental changes in the FP effect found in previous experiments were observed during this critical period and because this permitted us to reduce the variability across ages in the magnitude of the absolute RTs that are observed when older groups are also included. In addition, a more fine-grained approach was adopted in this experiment, because 4- and 5-year-old children were treated as separate groups.

A limitation of Experiment 1 was the small number of trials used. The choice of 60 trials, although sufficiently small in number to avoid distraction and tiredness in children as young as 4 years old, was not optimal from a statistical point of view, given the high number of conditions involved in the analysis. For this reason, we doubled the number of trials in Experiment 2 (120 vs. 60). However, in order to run more trials roughly in the same amount of time, the range of FPs used was narrowed to 1, 2, and 3 s instead of 1, 3, and 5 s, a manipulation that, if one extrapolates from the literature on adults (e.g., Niemi & Näätänen, 1981), should not qualitatively affect the occurrence of the basic FP phenomena.

Method

Participants

Sixty-eight children were recruited for Experiment 2, mostly from a kindergarten. They belonged to three age groups: 4 years old ($n = 26$; 9 girls, 17 boys; 1 left-handed, 25 right-handed; mean age: 55 months), 5 years old ($n = 24$; 12 girls, 12 boys; 1 left-handed, 23 right-handed; mean age: 65 months), and 6 years old ($n = 18$; 7 girls, 11 boys; 2 left-handed, 16 right-handed; mean age: 76 months). Parents had previously signed informed consent for all the children participating in the study. Two other 4-year-old children refused to participate. One further 4-year-old child refused to complete the test.

Apparatus and Materials

The apparatus and materials were the same as in Experiment 1. Children were tested in a quiet room at a kindergarten rather than at a summer camp. The FPs employed were 1, 2, and 3 s instead of 1, 3, and 5 s.

Procedure and Task

The procedure and the task were the same as in Experiment 1, except that 120 test trials were administered to each participant

[2] In order to control for possible learning effects, the results from the 12 children of the second session of the longitudinal study (5–6 years old) were compared with those of the 5- and 6-year-old children of Experiment 1A not tested in Experiment 1B ($n = 21$). A $2 \times 3 \times 3$ mixed ANOVA was performed with group, FP_n, and FP_{n-1}. This analysis did not show any significant effect relating to the group factor, suggesting that no reliable learning effects had occurred for the children retested in the second session of Experiment 1B.

instead of 60. A short rest was given after the first block of 60 trials.

Data Analysis

The same criteria were adopted to analyze data in Experiment 2 as in Experiment 1. For the RT analyses, a 3 × 3 × 3 mixed-design ANOVA was used, with FP_n (1, 2, 3 s) and FP_{n-1} as the within-subjects independent variables and age group (4, 5, and 6 years of age) as the between-subjects variable. No assumptions underlying ANOVAs were violated. This permitted the use of median RTs as the dependent variable.

Results

Accuracy

The percentage of errors in Experiment 2 is shown in Figure 3 (see the middle and bottom panels). The rate of overall premature responses was comparable across age groups, Kruskal–Wallis test: $H(2, N = 68) = 4.1$, $p = .13$. The rate of premature responses increased significantly as a function of the FP_n for the 4- and 5-year-old groups (Page's $L = 386.5$ and 348.5, respectively; for both, $p < .001$), but this tendency was not significant for the 6-year-old group. Premature responses decreased significantly as a function of the FP_{n-1} in the 4- and 5-year-old groups (Page's $L = 332$, $p < .01$, and Page's $L = 350$, $p < .001$, respectively), and there was a similar tendency in the 6-year-old group (Page's $L = 226.5$, critical L for $p < .05 = 227$).

The rate of overall delayed and null responses decreased as a function of age, Kruskal–Wallis test: $H(2, N = 68) > 15.8$, $p < .001$. Delayed and null responses decreased significantly as a function of FP_n in the 4- and 5-year-old groups (Page's $L = 392$, $p < .001$, and Page's $L = 305$, $p = .01$, respectively), and there was a similar tendency among the 6-year-olds (Page's $L = 225.5$, critical L for $p < .05 = 227$). Delayed and null responses increased reliably as a function of FP_{n-1} in the 4- and 5-year-old groups (Page's $L = 336.5$, $p < .001$, and Page's $L = 302$, $p < .05$, respectively), but this tendency was not significant in the 6-year-old group.

Reaction Times

The median RTs in Experiment 2 are shown in Figure 3 (see the top panel). A significant main effect of age was obtained, $F(2, 65) = 17.4$, $p < .001$. Post-hoc comparisons demonstrated that, for any two groups, responding was faster in the older group (for all comparisons, $p < .01$).

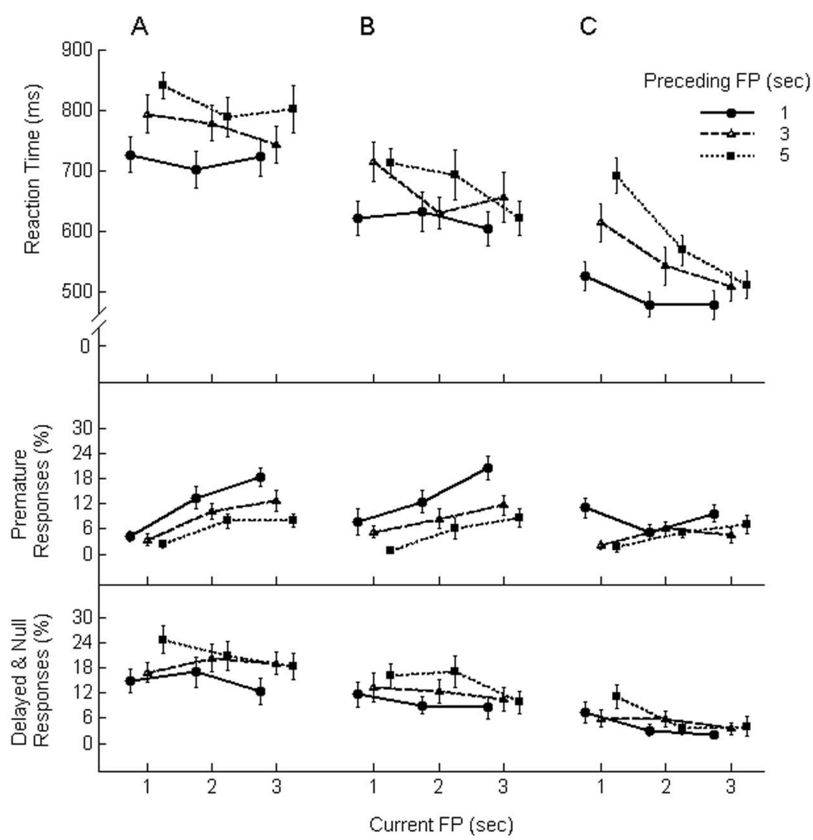

Figure 3. Median reaction times (top panel), percentage of premature responses (middle panel), and percentage of delayed and null responses (bottom panel), as a function of the current foreperiod (FP; *x* axis) and preceding FP (lines) in Experiment 2. Error bars indicate standard errors of the mean. Columns A–C show data for the 4-, 5-, and 6-year-old groups, respectively.

FP effect. The main effect of FP_n was significant, $F(1.9, 124.3) = 24.1$, corrected $p < .001$. Critically, a significant Age × FP interaction was also present, $F(3.8, 124.3) = 3$, $p < .05$. Post-hoc comparisons demonstrated that the FP effect (i.e., RTs slower for the 1-s FP than for the 3-s FP) was present only in the 5- and 6-year-old group (for both, $p < .01$).

Sequential effects. The main effect of FP_{n-1} was significant, $F(1.8, 119.3) = 46.6$, corrected $p < .001$. RTs were slower following a longest FP_{n-1} or a medium FP_{n-1} than a shortest FP_{n-1} (for both, $p < .01$). The $FP_n \times FP_{n-1}$ interaction was also significant, $F(3.6, 231.8) = 4.1$, $p < .01$, indicating that the effect of FP_{n-1} was greatest for the shortest FP_n and smallest for the longest FP_n. However, this interaction was qualified by an Age × $FP_n \times FP_{n-1}$ interaction, $F(8, 260) = 2$, $p < .05$. This latter finding indicates that sequential effects were symmetrical for the 4-year-old children and asymmetric for the older groups. This was supported by subsequent ANOVAs (3 FP_n × 3 FP_{n-1}) that were performed separately on each group. The 4-year-old children did not show a significant $FP_n \times FP_{n-1}$ interaction ($p = .49$), whereas this interaction was significant in older children: for the 5-year-olds, $F(3.5, 81.6) = 3.7$, corrected $p < .01$; for the 6-year-olds, $F(4, 68) = 6.3$, $p < .001$.

We wanted to check further if the performance of 4-year-old children, who made more errors than the other two groups, could be explained by a form of speed–accuracy trade-off. Due to the relatively high number of errors made by the youngest children (normally distributed), it was possible to perform two 3 FP_n × 3 FP_{n-1} full factorial ANOVAs on the percentage of their anticipations and delayed and null responses, respectively. These ANOVAs did not show any $FP_n \times FP_{n-1}$ interaction—premature responses, $F(4, 100) = 1.3$, $p = .26$; delayed and null responses, $F(4, 100) = 2.1$, $p = .09$—a finding which mirrors the results of the RT analysis. This result does not fit with the idea that the symmetrical sequential effects found in the RT data of the youngest children are an artifact of errors, as their pattern of performance cannot be attributed to a speed–accuracy trade-off.

Discussion

The results of Experiment 2 basically confirm those of Experiments 1A and 1B with respect to the developmental curve shown by the FP effect. The 4-year-old children again do not show the FP effect, whereas this effect is fully present in the 6-year-old group, with the 5-year-old one in between. More interestingly, the picture of the sequential effects obtained in this experiment is clearer than that obtained in Experiment 1A, as the significant Age × FP_n × FP_{n-1} three-way interaction obtained here reveals that sequential effects change qualitatively with age. The sequential effects are symmetrically present across all three FPs_n in the 4-year-old children, whereas they decrease toward the longest FP_n in 5- and 6-year-old children. This could explain the lack of three-way interaction when 4- and 5-year-old children are considered as a single group, as the critical processes underlying the FP phenomena seem to develop gradually from 4 to 5 years of age.

General Discussion

The present study reveals a dissociation in the variable FP paradigm between the FP effect and the sequential effects from an ontogenetic perspective. As shown consistently in all three experiments of the study, the ontogenetic time course of the FP effect gradually develops as one goes from 4 or 4–5 years of age to older ages, whereas the sequential effects are already present in their typical magnitude even in the youngest children considered here.

In the literature, a study by Elliott (1970) already investigated the sequential effects together with the FP effect in children. The results of that study showed the presence of sequential effects in children, but unlike our study, there was only a slight and nonsignificant modulation of the FP effect as a function of age. The difference in results between the two studies can be attributed to the different ages of the youngest groups of children tested (5–7 years old in Elliott's study vs. 4–5 years old here). However, even when comparable age groups are considered, the results still remain partially incongruent. It is possible that the differences in a number of experimental details could explain the remaining differences across studies. These include the use of different stimulus modalities (auditory in Elliott's study vs. visual here), different social backgrounds (upper-middle-class children with parents in academic and medical occupations in Elliott's study vs. children chosen randomly from a wider range of social contexts here), and probably most important, the different ranges of FPs used (1–16 s, with an exponential distribution, in Elliott's case vs. 1–5 s and 1–3 s, with an arithmetic distribution, here). In particular, a possible influence of different FP ranges and distributions on the developmental time course of the FP phenomena needs further investigation. Thus, if a larger range of FP values was used, then young children might also be able to show a normal-sized FP effect, possibly because the processes underlying it are not fully mature in young children and require a more sensitive design to appear.

A closer examination of the sequential effects shown by the youngest children in the current study can help to further clarify their nature and to discriminate between different accounts of these phenomena. Despite the usual pattern of asymmetric sequential effects found in adults, sequential effects were symmetrical for the youngest children in all three experiments of this study. In other words, RTs become slower when FP_{n-1} is increasingly long, regardless of FP_n. However, the pattern of sequential effects observed in the youngest children was significantly different from that found in older children only in Experiment 2, when the 4-year-old children were considered separately from the 5-year-old ones. The change found in Experiment 2 suggests that the mechanism responsible for an *asymmetrization* of the sequential effects, whatever it is, begins to mature between 4 and 5 years of age. As a further support for this hypothesis, when the performance of 4-year-old children was compared to that of 5-year-old children in Experiment 1A, a significant difference in the pattern of sequential effects (i.e., Age × $FP_n \times FP_{n-1}$ interaction) was obtained (see the Discussion section of Experiment 1B).

In the traditional view (e.g., Drazin, 1961), the sequential effects per se are due to an expectation of FP repetition being carried over from one trial to the next. Their asymmetry is due to a complementary repreparation–maintenance mechanism operating when this expected repetition does not occur for short FP_{n-1}–long FP_n sequences (e.g., Alegria, 1975). It follows that if this repreparation–maintenance mechanism does not work, no FP_n effect should occur, whereas an $FP_n \times FP_{n-1}$ crossover interaction should emerge. That is, RTs should be faster when FP_n is the same as FP_{n-1} than when it is longer or shorter, according to the repetition expectation hypothesis. Contrary to this prediction, although the youngest children did not show an FP_n effect, they did not show any interaction either—only a significant main effect of FP_{n-1}.

Symmetrical sequential effects are also not predicted by the conditioning view (Los & van den Heuvel, 2001). On this single-process account, the FP effect should have occurred together with the sequential effects in ontogenetic development, as both are held to originate from common conditioning mechanisms. In other words, if no FP_n effect occurs, neither an FP_{n-1} effect nor an $FP_{n-1} \times FP_n$ interaction is to be expected. No interaction was actually obtained, but the FP_{n-1} did modulate RTs even in the youngest children considered here. The presence of sequential effects without an FP effect, however, suggests that they have at least partially different functional origins. This also makes it unlikely that conditioning mechanisms alone could explain the empirical results of the present study.

There is recent evidence in support of a dual-process interpretation of the FP phenomena. Los and Agter (2005), for instance, obtained changes in the slope of the FP–RT function by contrasting different distributions of FPs within blocks of trials (i.e., uniform, exponential, and peaked). According to a pure conditioning model, the shape of the FP–RT function, obtained under a given distribution of FPs, might be predicted by reweighting sequential effects as a function of the different frequency of occurrence of the various FP sequences under the other distributions. However, this was shown not to be a critical factor, as reweighting sequential effects accounted for little of the variance in the difference between the FP–RT functions obtained in the three distributions, suggesting that processes other than conditioning ones could account for the effect of FP distribution. These critical processes are likely to be intentional ones.

Therefore, the sequential effects found in the youngest children are theoretically relevant. As an alternative to the previous accounts, they can be better explained by assuming an enhancement in arousal (defined here as the readiness to respond) following a short FP_{n-1} and a decrease in arousal following a long FP_{n-1}, regardless of the current FP_n. It is as if the preparation process benefits if the previous preparation has been maintained for only a short interval but becomes refractory when preparation has previously been maintained over a long interval. This may be because to remain prepared for a long interval is cognitively expensive and exhausts processing resources (see Näätänen, 1971). This account is also supported by the accuracy data of Experiment 2. In that experiment, children (especially 4- and 5-year-old ones) were more likely to give a very slow response (i.e., $> 1,500$ ms), or even not to respond, as the FP_{n-1} got longer, suggesting a long-lasting inhibitory effect of long FPs_{n-1} on the preparation level during the current trial. The fact that a similar pattern of errors was not statistically corroborated in older children and adults may well be attributed to ceiling effects derived from the ease of the task. Moreover, all children performing Experiment 2 (i.e., those 4–6 years old) were more likely to give premature responses as the FP_{n-1} got shorter, suggesting a facilitation of their preparation level after a short FP_{n-1}. It is notable that the trend in the accuracy data for the youngest groups in Experiments 1A and 1B (and sometimes even for older children) goes in the same direction (see Figures 1 and 2), even if this is not always statistically detectable.

There is recent electrophysiological evidence that may be interpreted in favor of this hypothesis of preparation modulation by the previous FP. Using temporal cueing paradigms with variable FPs on adults, Los and Heslenfeld (2005) found symmetrical sequential effects in the contingent negative variation (CNV), a negative event-related potential component whose amplitude is considered a marker of nonspecific preparation and is known to be modulated by arousal level (e.g., Kamijo et al., 2004). Specifically, when the FP_{n-1} was short, the CNV amplitude was tonically greater throughout the FP_n than when the FP_{n-1} was long. Moreover, the effect of FP_{n-1} did not interact with the effect of cueing. In other words, the effect of FP_{n-1} on the CNV was additive with effects of the status of the cue (valid vs. neutral) and of the information provided by a valid cue (short vs. long). Moreover, at least one electrophysiological effect found by Los and Heslenfeld (2005) does not fit the conditioning model of the sequential effects in its first version (Los et al., 2001; Los & van den Heuvel, 2001). According to the conditioning model, there is no reason for the preparation to be lower when a long FP_n follows an equally long FP_{n-1}. In this case reinforcement should enhance, rather than tonically diminish, the nonspecific preparation reflected by the CNV amplitude. This should especially be the case with a neutral cue condition when the effect of conditioning mechanisms, if present, should be observed more clearly without the interfering effects of informative cueing.

The pattern of asymmetric sequential effects observed in older children and adults in the present study and in the literature would seem to require an additional process of endogenous preparation, analogous to that already described by some traditional accounts (e.g., Coull & Nobre, 1998; Miniussi, Wilding, Coull, & Nobre, 1999; Niemi & Näätänen, 1981). In a variable FP task, this process checks for the nonoccurrence of the imperative stimulus; in this case it uses the increasing conditional probability of the imperative stimulus occurring as time elapses to enhance preparation (Näätänen, 1970). In this way, it would partially compensate for and attenuate the process of tonic arousal modulation producing the sequential effects at longer FPs, thus generating sequential effects asymmetrically biased toward the shortest FPs. With respect to the previous versions of the conditional probability checking account, this explanation emphasizes more the role of this process by relating it with the sequential effects. On this account, indeed, the conditional probability monitoring not only determines the FP effect but also does it by countering the negative influence of a previous long FP on RTs.

In an analogous fashion to findings in neurological patients after lesions to the rDLPFC (Stuss et al., 2005) and in healthy adults after TMS on the same area (Vallesi et al., 2007), this checking process would be assumed not to work in the youngest children. The reason would be that the rDLPFC region controlling such a process is permanently damaged in right frontal patients, transiently inhibited after TMS, and not yet adequately mature in 4-year-old children.

However, the occurrence of this endogenous process, although it may attenuate the influence of FP_{n-1} at longer $FPs_{n,}$ does not eliminate such influence. Indeed, in studies employing variable FP paradigms with catch trials (i.e., when no imperative stimulus appears across the trial), RTs at the longest FP_n are slower after a catch trial than after a respond trial (e.g., Correa, Lupiáñez, Milliken, & Tudela, 2004; Correa, Lupiáñez, & Tudela, 2006; Los &

Agter, 2005), demonstrating an effect of the events occurring during the preceding trial.

From a broader point of view, the results of the current study may be interpreted in the context of other studies of executive functioning in childhood. There is evidence showing that the executive processes supposed to underlie the tasks at study, and not task difficulty or complexity per se, may explain the developmental dissociations found in children (e.g., Davidson et al., 2006). A prediction derived from the supervisory attention system model (Norman & Shallice, 1986) is that known as the age-of-acquisition principle, according to which processes involved in lower-level systems, such as automatic processes (i.e., contention scheduling, in Norman & Shallice's terminology), are acquired before processes belonging to the higher-level supervisory system (e.g., Shallice, 2004; see also Karmiloff-Smith, 1994; Zelazo et al., 1996), as the latter are mainly localized in the prefrontal cortex, which is known to mature at a slower rate compared with other portions of the brain (e.g., Delalle et al., 1997; Huttenlocher & Dabholkar, 1997). On this view, the fact that sequential effects are acquired before the FP effect suggests that underlying processes are more automatic than those involved in the FP effect (see Houdé, Angard, Pillon, & Dubois, 2001, for a similar approach). This interpretation supports the position that preparation is a multicomponential cognitive capacity, consisting of central, supervisory processes on the one side and more peripheral, automatic factors on the other side. These two kinds of processes, and their psychophysiological correlates, have been shown to poorly correlate with each other (see Jennings & van der Molen, 2005, for a recent review).

A possible limitation of the present study is the small number of trials used, which were 6–7 per condition in Experiments 1A and 1B and 12–13 per condition in Experiment 2. The use of such a small number of trials was necessary because the variable FP paradigm is quite a boring task for children. However, longer and possibly multisession studies are desirable, possibly using a more interesting experimental procedure in order to retain the children's attention longer. It would be theoretically relevant to test whether the FP effect remains absent in the 4-year-old children even after long practice (if so, supporting the view that maturational factors account for its absence) or whether it appears gradually with practice (if so, suggesting a role of more strategic factors, such as poor task-setting capacity in young children).

In conclusion, the present results suggest that the process of endogenous preparation, thought to produce the FP effect, appears later in cognitive development than the processes underlying the sequential effects. The observation that FP and sequential effects can be dissociated across different ages, both between- and within-subjects, demonstrates that at least partially different processes underlie the two FP phenomena. This study shows that developmental dissociations are a valuable method to infer cognitive processes underlying performance in adults.

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