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Young children's difficulties in switching from rhythm production to temporal interval production (> 1 s)

Anne Bobin-Bègue^{1*}, Sylvie Droit-Volet², Joëlle Provasi³

¹Laboratoire Éthologie Cognition Développement, Université Paris Ouest La Défense, Nanterre, France

²Laboratoire de Psychologie Sociale et Cognitive, CNRS, UMR 6024, Université Blaise Pascal, Clermont-Ferrand, France

³Laboratoire Cognition Humaine et Artificielle – École Pratique des Hautes Études, Paris, France

* **Correspondence:** Dr. Anne Bobin-Bègue, ¹Laboratoire Éthologie Cognition Développement, Université Paris Ouest La Défense, Nanterre, France.
abobinbe@u-paris10.fr

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Abstract

In order to efficiently perform audio–motor coordination children must process event duration. It has recently been shown that duration processing in adults involves two distinct, or at least hierarchically interrelated, processes. The processing of durations ranging from a hundred milliseconds to around one second is well accounted for by the Scalar Timing Theory. For duration above one second, temporal processing in adults appears to be task-dependent. Performances in the range of a hundred millisecond durations are usually studied with auditory tempo tasks. In this study, we examine timing performance in children for a large range of durations, from 400 ms to 4 seconds, using the same experimental design. The procedure consists in a motor synchronization task. Overall, our results show that 5 year olds perform better than 3 year olds. However, durations greater than, 1500 ms are difficult to process, leading to increasing variability in produced intervals. Moreover, only a few children are able to produce very long duration intervals. The main finding of this study confirms the existence of a break in the region of 1500 ms when a repeated synchronization task is tested. Consistently with the adult literature, this finding suggests the existence of two duration-dependent timing processes when children have to coordinate their motor behavior to external events.

1. Introduction

During childhood, one of the most important abilities is to efficiently coordinate actions with external events. This coordination requires timing abilities, i.e. estimating both event duration and the interval between two events, in order to produce actions at the right time, neither too late nor too early. The abilities involved in coordination of actions to external rhythms have been extensively studied in adults using a sensorimotor synchronization task (Repp & Su, 2013; Repp, 2005a). The procedure used with children involves 3 phases (Bobin-Bègue & Provasi, 2008; Bobin-Bègue, Provasi, Marks, & Pouthas, 2006; McAuley, Jones, Holub, Johnston, & Miller, 2006; Provasi & Bobin-Bègue, 2003). In the first phase (Spontaneous Motor Tempo phase, SMT), the participants are asked to tap with their finger on a button at their preferred rate, i.e., the most comfortable tapping rate (Drake, Jones, & Baruch, 2000; McAuley et al., 2006; Provasi & Bobin-Bègue, 2003). In the second phase (sensorimotor synchronization), they are asked to tap in synchrony with sounds displayed at a fixed inter-stimuli

41 interval (ISI), generally shorter than 800 ms. Then, in a third phase (continuation phase), the auditory
42 stimulus is removed and the participants are supposed to continue to tap at the same tempo. There are
43 very few studies in young children using this sensorimotor synchronization task. However, some
44 studies have found that the inter-tap interval (ITI) spontaneously produced by young children aged
45 from 2 to 7 years of age lies between 400 and 500 ms but slows down during childhood to
46 approximately 600 ms in early adulthood (Bobin-Bègue & Provasi, 2008; Drake et al., 2000; McAuley
47 et al., 2006; Provasi & Bobin-Bègue, 2003). More importantly, the variability (SD) of SMT decreases
48 with age. During the sensorimotor synchronization phase, the variability in ITI is also greater in
49 children than in adults (Repp, 2005b). In addition, adults anticipate the auditory stimulus, thus showing
50 a negative asynchrony between their finger tap and the beat of the metronome of about 10 ms (Miyake,
51 Onishi, & Pöppel, 2004). However, this negative asynchrony is rarely found in young children. In fact,
52 in the synchronization phase, very young children, aged from 1 to 3 years old, are able to synchronize
53 their taps to an external auditory tempo, but only when it is close to their own SMT. Furthermore, in
54 the continuation phase, they rapidly return to their initial SMT when the external auditory tempo is
55 farther away from their SMT (Bobin-Bègue & Provasi, 2008; Provasi & Bobin-Bègue, 2003). These
56 findings suggest that young children are able to synchronize their taps with external tempi but only
57 when these are close to their SMT, i.e., to what Jones and Boltz (1989) call the referent period. Unlike
58 children, adults succeed in producing longer ITI than their referent tempo up until a value of 1800 ms
59 (Repp & Su, 2013; Repp, 2005b). In sum, young children have a limited capacity for producing motor
60 tempo outside their referent periods. This contributes to explain why adults adapt their rhythmic
61 activities when interacting with infants (e.g., speaking more slowly) (Gratier & Trevarthen, 2008;
62 Gratier, 2003). However, it is possible that for children, tap synchronization with a dis-preferred tempo
63 requires a lengthy learning period. It might thus be observable only with a greater number of trials and
64 sessions than those used in previous studies. Consequently, the aim of the present study was to examine
65 young children's abilities to progressively learn to synchronize their motor tempo to external auditory
66 tempi with longer ITI than their SMT.

67 Moreover, according to Wing and Kristofferson's model (Wing & Kristofferson, 1973a, 1973b),
68 sensorimotor synchronization involves two separate components: a temporal and a motor component.
69 The temporal component determines when to initiate the response, and the motor component is
70 involved in the implementation of the motor response. Some authors (Ivry & Hazeltine, 1995; Keele,
71 Pokorny, Corcos, & Ivry, 1985) suggest that the temporal component involved in rhythmic activities
72 with ITI in the hundred milliseconds range is similar to that involved in the production of temporal
73 intervals in the few seconds range. They thus posit the existence of a central timekeeper (clock)
74 common to production of all temporal intervals regardless of their lengths. Whether or not there is a
75 common clock system for the processing of short and long durations, we may predict that children can
76 also learn, over several training sessions, to produce longer ITI lasting several seconds. However, in
77 this case, we would describe their behavior as temporal interval production rather than sensorimotor
78 synchronization because there is a duration limit beyond which sensorimotor synchronization no longer
79 occurs. This limit is around 1800 ms (Fraisse, 1948; Repp, 2006). Beyond this limit, auditory events
80 are perceived as being independent. When trying to synchronize taps to intervals longer than 1800 ms,
81 adults tap after the onset of the target sound, in reaction to them rather than anticipating them.

82 The existence of a common clock system for processing different temporal intervals is further
83 supported by evidence on the temporal scalar property of estimations (Gibbon, Church, & Meck, 1984;
84 Gibbon, 1977). Indeed, scalar timing is indexed by the increase in variability (SD) of temporal
85 estimates as the duration of intervals (D) increases while the coefficient of variation of the temporal

86 estimates (SD/D) remains constant for the different intervals values, as predicted by Weber's law.
87 However, an increasing number of studies suggest that the mechanisms underlying the processing of
88 short intervals in the sub-second range are different from those underlying the processing of longer
89 intervals. Neuroimaging studies for instance show that cerebral areas involved in the processing of
90 short durations (< 1 s) are different from those involved in the processing of long durations (Grimm,
91 Widmann, & Schröger, 2004; Lewis & Miall, 2003; Meck, 2005). In addition, several cases of violation
92 of the temporal scalar property have been found when comparing short and longer durations in temporal
93 reproduction tasks (Lejeune & Wearden, 2009). For instance, Bangert, Reuter-Lorenz and Seidler
94 (2011) showed a violation of the assumption of a single scalar timekeeper across millisecond and
95 second timescales using a reproduction task with intervals from 300 ms to 1700 ms. Their results indeed
96 suggest a shift in the region of 1 s for temporal reproduction. For tasks involving temporal production
97 or reproduction, both Fraise (1984) and Pöppel (1997) distinguish the perception of time for the
98 processing of durations shorter than 1 s and time estimation for durations greater than 3 seconds, the
99 latter requiring greater attention and different memory encoding. The *present*, according to Fraise
100 (1984) exists between both these two types of intervals. If there is a common mechanism for the
101 production of short and long durations, we expect children to succeed in learning to synchronize their
102 taps to longer ISI (> 1700 ms). We thus hypothesize that children are able to switch from rhythm
103 production to temporal interval production. Additionally, we expect children's performance to improve
104 with age. However, if the mechanisms for short and long intervals are entirely separate, we expect that
105 children would never succeed in producing long ITI despite the training sessions and regardless of their
106 ages. Their motor rhythm would remain closed to their preferred tempo at both ages.

107 The aim of this study was thus to examine whether 3 and 5-year-old children with similar SMT can
108 learn to increase the length of their ITI in a synchronization task. The children were asked to tap in
109 synchrony with a 200 ms auditory sound. The ISI value progressively increased from session to session
110 from 400 ms, close to children's referent period, to longer periods: 630 ms, 1000 ms, 1600 ms, 2500 ms
111 and 4000 ms. The motor tempo produced by the children without the auditory stimuli was also assessed
112 before and after this synchronization phase (respectively called pre-synchronization phase and post-
113 synchronization phase). In each synchronization phase, the children received reinforcement when their
114 taps occurred during the auditory stimulus or just before (15% of the ISI duration before). In addition,
115 a group of control children were given the synchronization task with longer durations of 4 s for all
116 sessions, in other to examine whether children directly succeed in learning to produce long ITI, without
117 a period of learning based on the gradual modification of their initial SMT.

118 **2. Materials and methods**119 **2.1. Participants**

120 Forty children took part in this experiment: Twenty 3-year-olds (10 girls and 10 boys; mean age = 3.33,
 121 $SD = 0.02$) and twenty 5-year-olds (10 girls and 10 boys; mean age = 5.42, $SD = 0.02$). These children
 122 were recruited in a nursery school in Paris, France.

123 **2.2. Apparatus**

124 Children were tested individually in a quiet room in their school. They were seated in front of an
 125 inclined 14-inch computer monitor covered by a transparent Plexiglas plate. Children were asked to
 126 produce taps on this plate with their preferred hand. A Computer recorded each tap via a high sensitive
 127 pressure transducer placed between the plate and the monitor. Each tap was recorded by the computer
 128 with a temporal precision of 1 ms. The pressure transducer sensitivity was very low in order to record
 129 both slight fingertip taps and strong taps. The auditory stimulus was an animal squeal produced by the
 130 computer speaker. The duration of the squeal was 200 ms. There were twelve different squeals (dog,
 131 cat, sparrow, duck, frog, monkey, bee, bear, hen, seal, pigeon, pup), all recorded with the same
 132 intensity. When the inter-tap interval (ITI) was “correct”, it was followed by a feedback presented in
 133 the center of the computer screen, in the form of the picture (10 cm x 15 cm) of the animal
 134 corresponding to the heard squeal. The animal squeal changed after every set of 20 taps (Table 1).

135 **Table 1: Procedure for the 0.4/4.0-s ISI group and the 4.0-s ISI group.**

136

	Pre-Synchronization	Synchronization	Post-Synchronization
	20 ITI	8 sets of 20 ISI	20 ITI
Session 1			
0.4/4.0-s group	Reinforced ITI at 4.0 s	0.4-s ISI	Reinforced ITI at 0.4 s
4.0-s group	Reinforced ITI at 4.0 s	4.0-s ISI	Reinforced ITI at 4.0 s
Session 2			
0.4/4.0-s group	Reinforced ITI at 0.4 s	0.63-s ISI	Reinforced ITI at 0.63 s
4.0-s group	Reinforced ITI at 4.0 s	4.0-s ISI	Reinforced ITI at 4.0 s
Session 3			
0.4/4.0-s group	Reinforced ITI at 0.63 s	1.0-s ISI	Reinforced ITI at 1.0 s
4.0-s group	Reinforced ITI at 4.0 s	4.0-s ISI	Reinforced ITI at 4.0 s
Session 4			
0.4/4.0-s group	Reinforced ITI at 1.0 s	1.6-s ISI	Reinforced ITI at 1.6 s
4.0-s group	Reinforced ITI at 4.0 s	4.0-s ISI	Reinforced ITI at 4.0 s
Session 5			
0.4/4.0-s group	Reinforced ITI at 1.6 s	2.5-s ISI	Reinforced ITI at 2.5 s
4.0-s group	Reinforced ITI at 4.0 s	4.0-s ISI	Reinforced ITI at 4.0 s
Session 6			
0.4/4.0-s group	Reinforced ITI at 2.5 s	4.0-s ISI	Reinforced ITI at 4.0 s
4.0-s group	Reinforced ITI at 4.0 s	4.0-s ISI	Reinforced ITI at 4.0 s

137 2.3. Procedure

138 The children were randomly assigned to a “4.0-s” and a “0.4/4.0-s” group. In each group, the children
139 were given 6 sessions of synchronization, one session per day. In the 4.0-s group, the Inter-Stimulus
140 Interval (ISI) was always 4.0 s (Table 1). In the 0.4/4.0-s group, the ISI progressively increased from
141 one session to the next: 0.4 s (session 1), 0.63 s (session 2), 1.0 s (session 3), 1.6 s (session 4), 2.5 s
142 (session 5), 4.0 s (session 6). Each session was composed of 3 successive phases: (1) a pre-
143 synchronization phase, (2) a synchronization phase, (3) and a post-synchronization phase. In the
144 synchronization phase, the children were given 8 successive sets of 20 auditory ISI. The children were
145 asked to tap at the same time as the auditory stimulus in order to activate the pictures (feedback). When
146 the child’s response occurred within a temporal window ranging from 15 % before the auditory
147 stimulus onset until the auditory stimulus offset, the ITI was considered “correct” and the visual
148 feedback is provided immediately. However, for the responses given in the period before the stimulus
149 onset, the visual feedback was delivered at the same time as the auditory stimulus. In addition, the
150 duration of the feedback presentation did not exceed that of the auditory stimulus. Its duration therefore
151 decreased with the increase of the delay between the child’s response and the auditory stimulus onset.
152 In both the pre-synchronization and the post-synchronization phase, 20 ITI were recorded. In these
153 phases, the procedure was similar to that used for the synchronization phase, except that the children
154 did not hear the auditory stimulus. The post-phase was quite similar to the continuation phase usually
155 used in rhythmic tasks (except that visual feedback was given, as explained previously). In contrast,
156 the pre-synchronization phase assessed the children’s SMT for the first session, and the capability of
157 recalling the ISI presented in the previous session. The children were thus told that they must try to get
158 pictures by tapping at the right rhythm. Children were offered a demonstration trial by the experimenter
159 prior to the synchronization phase of the first session.

160

161 3. Results

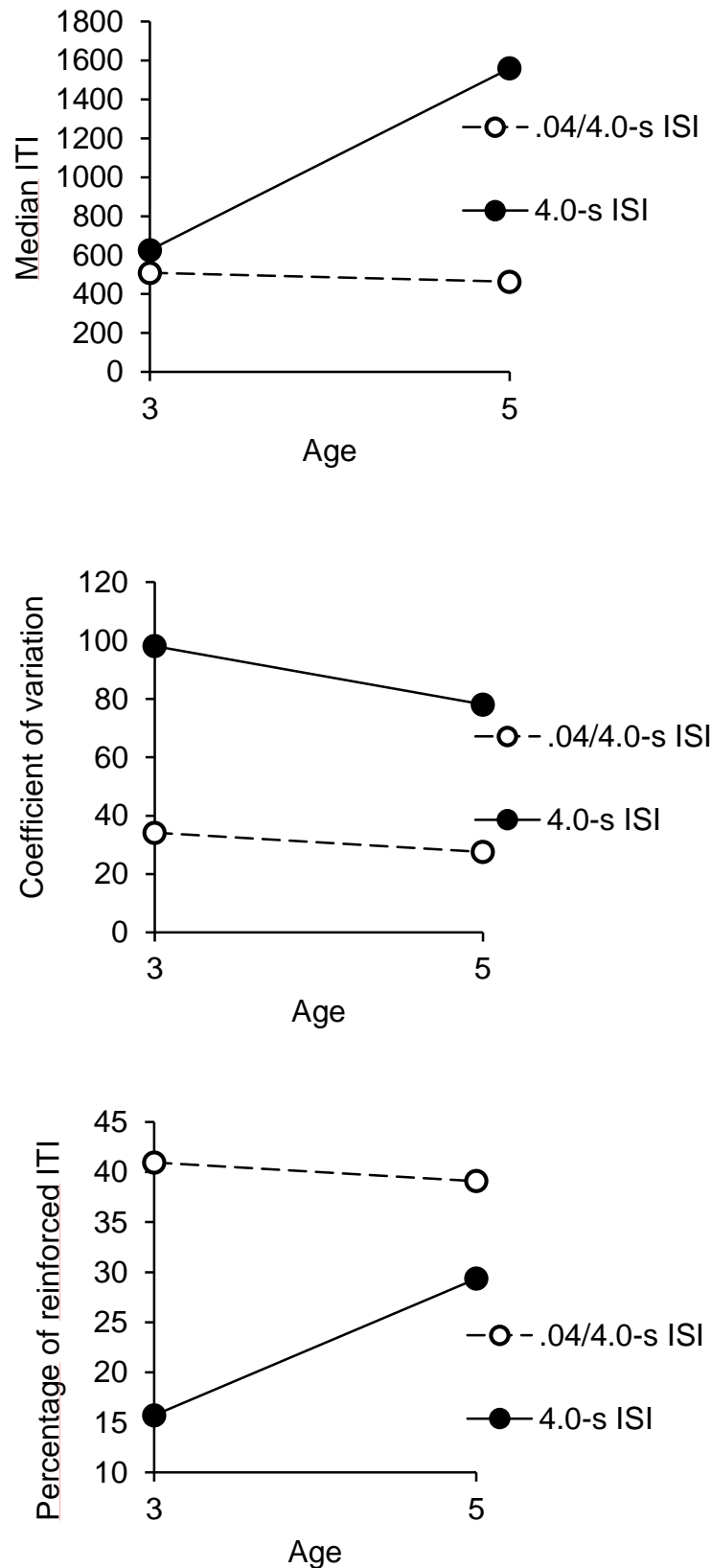
162 For the synchronization, pre-synchronization and post-synchronization phases, 3 indexes of
163 performance were measured: the median ITI, the coefficient of variation of ITI ($Q3-Q1/\text{median} \times 100$),
164 and the percentage of reinforced ITI, i.e., followed by a feedback.

165 3.1. Synchronization phase

166 For each index of performance, an analysis of variance (ANOVA) was conducted with 3 between-
167 subjects factors (age, group, sex) and 2 within-subjects factors (synchronization sets, session). When
168 Mauchly’s sphericity test indicated that the assumption of sphericity had been violated for stimulus
169 duration, the degrees of freedom were adjusted using the Greenhouse-Geisser correction in order to
170 take this violation into account in the statistical analysis.

171 *Median ITI.* The ANOVA showed a significant interaction between age and group, $F(1, 32) = 4.55, p$
172 $= .04, \eta^2_p = 0.12$, with a significant main effect of group, $F(1, 32) = 6.96, p = .01, \eta^2_p = 0.18$, while the
173 main effect of age failed to reach significance, $F(1, 32) = 3.73, p = .06$. Age did not interact with any
174 other factor. This significant interaction is illustrated in Figure 1. As shown in Figure 1 (upper panel),
175 the 5-year-olds succeeded in lengthening the median of their ITI in the 4.0-s ISI condition compared
176 to the 0.4/4.0-s ISI condition, $t(18) = 2.55, p = .02$, while the 3-year-old obtained the same median ITI
177 in these two temporal conditions, $t(18) = 1.60, p = .13$.

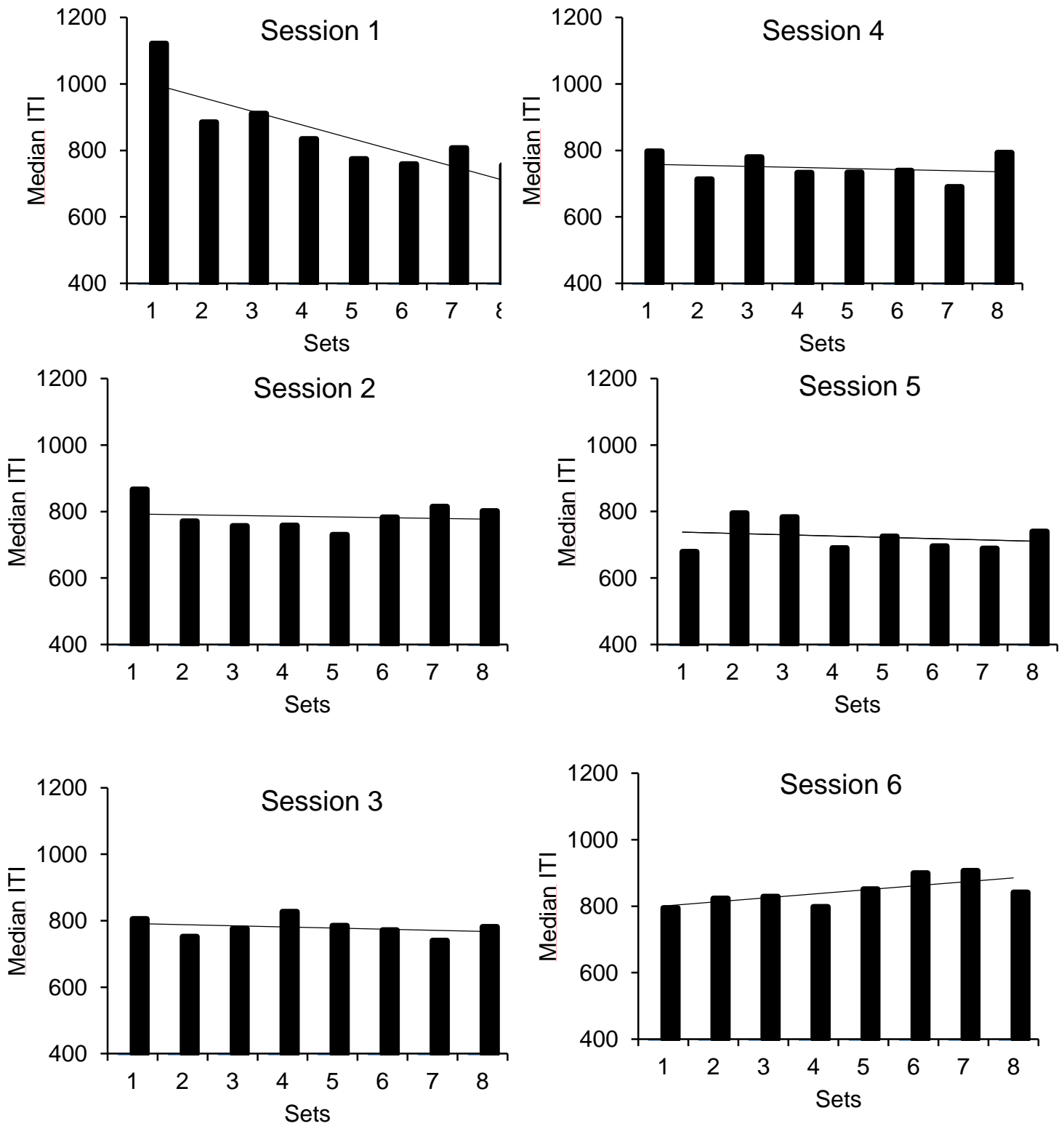
178 Figure 1 : Synchronization phase: Indexes of performances as a function of age and group.



179 Consequently, the 5-year-olds produced longer ITI than did the 3-year-olds in the 4.0-s group, $t(18) =$
180 2.17, $p = .04$. However, in the 0.4/4.0-s ISI condition, when the initial rhythm was close to children's
181 spontaneous motor tempo, no difference was observed between the 3- ($M = 508$, $SE = 218$) and the 5-
182 year-olds ($M = 463$, $SE = 218$), $t(18) = .61$, $p = .55$, irrespective of the different synchronization
183 sessions. In this 0.4/4.0-s ISI condition, the mean of median ITI produced during the synchronization
184 phase of all the sessions was close to 0.5 s.

185 The ANOVA also showed a main effect of set, $F(7, 224) = 2.43$, $p = .02$, $\eta^2_p = 0.07$, as well as a
186 significant set x session interaction, $F(35, 1120) = 2.36$, $p = .0001$, $\eta^2_p = 0.07$, the main effect of session
187 being non significant, $F(5, 160) = 1.15$, $p = .34$. The set or the session factor did not interact with the
188 group factor. To analyze this significant interaction, we ran an ANOVA on the median ITI with 'set'
189 as within-subjects factor for each session taken separately (Figure 2, upper panel). The results showed
190 a significant effect of set only for the first session, $F(7, 273) = 6.14$, $p = .0001$. The effect of set did
191 not reach significance for any of the other sessions (all $p > .05$). As shown in Figure 2, for the first
192 session, there was a significant linear decrease in the median ITI from the first to the eighth set of the
193 synchronization phase, $F(1, 39) = 10.76$, $p = .002$, indicating that the children speeded up their motor
194 tapping under the effect of rhythmic auditory stimuli.

195 Figure 2 : Synchronization phase: Median ITI as a function of sessions and sets.



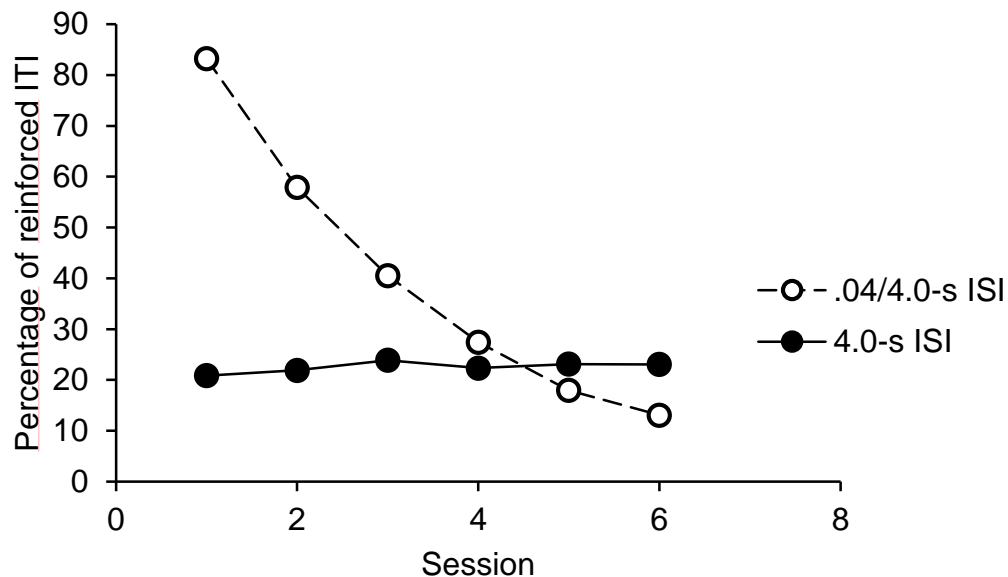
196 The overall ANOVA also showed a significant interaction between sex and session, $F(5, 160) = 3.37$,
197 $p = .006$, $\eta^2_p = 0.10$, with no main effect of sex, $F(1, 32) = 0.01$, $p = .91$. Indeed, the boys progressively
198 speeded up the rhythm of their tapping over sessions, as indicated by the significant linear session
199 effect, $F(5, 95) = 4.98$, $p = .03$, whereas the girls tended to maintain their tapping rhythm over sessions,
200 $F(5, 95) = 1.95$, $p = .09$.

201 *Coefficient of variation of ITI.* The ANOVA on the coefficient of variation showed a significant main
202 effect of group, $F(1, 32) = 17.16$, $p = .0001$, $\eta^2_p = 0.35$ though group did not interact with any other
203 factor (all $p > .05$). This indicated that the children produced more variable ITI in the 4.0-s group than
204 in the 0.4/4.0-s group, regardless of age and synchronization session (Figure 2, middle panel). The
205 variability of ITI was thus greater when the children tended to synchronize their taps to longer ISI. The
206 main effect of age was not significant, $F(1, 32) = 0.92$, $p = .34$, but age significantly interacted with
207 session, $F(5, 160) = 2.99$, $p = .01$, $\eta^2_p = 0.09$. Three and 5-year-olds thus produced or tended to produce
208 more variable ITI in the 4.0-s group than in the 0.4/4.0-s group ($t(18) = 5.26$, $p = .0001$, $t(18) = 1.98$,
209 $p = .06$, respectively), but the between-group difference was greater for the 3-year-olds than for the 5-
210 year-olds. There was also a significant sex x set interaction, $F(7, 224) = 2.84$, $p = .007$, $\eta^2_p = 0.08$. The
211 other main effect or interactions were not significant. Consequently, the boys, who tended to produce
212 shorter ITI than the girls (see above), obtained the same coefficient of variation of ITI over sessions,
213 $F(7, 133) = 1.65$, $p = .13$, whereas the variability of ITI tended to increase over sessions for the girls,
214 $F(7, 133) = 1.93$, $p = .07$, $\eta^2_p = 0.09$.

215 *Percentage of reinforced ITI.* As for the median ITI, the ANOVA run on the percentage of reinforced
216 ITI obtained during the synchronization phase showed a significant interaction between age and group,
217 $F(1, 32) = 6.27$, $p = .02$, $\eta^2_p = .16$, with a significant main effect of group, $F(1, 32) = 31.86$, $p = .0001$;
218 $\eta^2_p = 0.50$, and the main effect of age that tended toward significance, $F(1, 32) = 3.62$, $p = .07$, $\eta^2_p =$
219 0.10 (Figure 1). Consistently with the fact that the 5-year-olds produced longer ITI than did the 3-year-
220 olds, the older children obtained a greater percentage of reinforced ITI than the younger ones in the
221 4.0-s group, (20 vs. 16, $t(18) = 2.54$, $p = .02$) (, bottom panel). However, in the 0.4/4.0-s group, when
222 the children had to produce shorter ITI, the 5-year-olds obtained a percentage of reinforced ITI similar
223 to the 3-year-olds', $t(18) = 0.66$, $p = .52$.

224 The overall ANOVA also showed a significant main effect of session, $F(5, 160) = 129.61$, $p = .0001$;
225 $\eta^2_p = 0.80$, and a significant session x group interaction, $F(5, 160) = 146.36$, $p = .0001$, $\eta^2_p = 0.82$. No
226 other effect was significant. As illustrated in Figure 3, the percentage of reinforced ITI remained stable
227 over the sessions in the 4.0-s ISI condition, $F(5, 95) = 0.64$, $p = .67$, while it decreased in the 0.4-4.0-
228 s ISI condition, $F(5, 95) = 212.23$, $p = .0001$, $\eta^2_p = 0.92$, from one session to the next (for all sessions
229 comparisons with the Bonferroni test, $p < .05$).

230 Figure 3: Synchronization phase: Percentage of reinforced ITI as a function of sessions and groups.

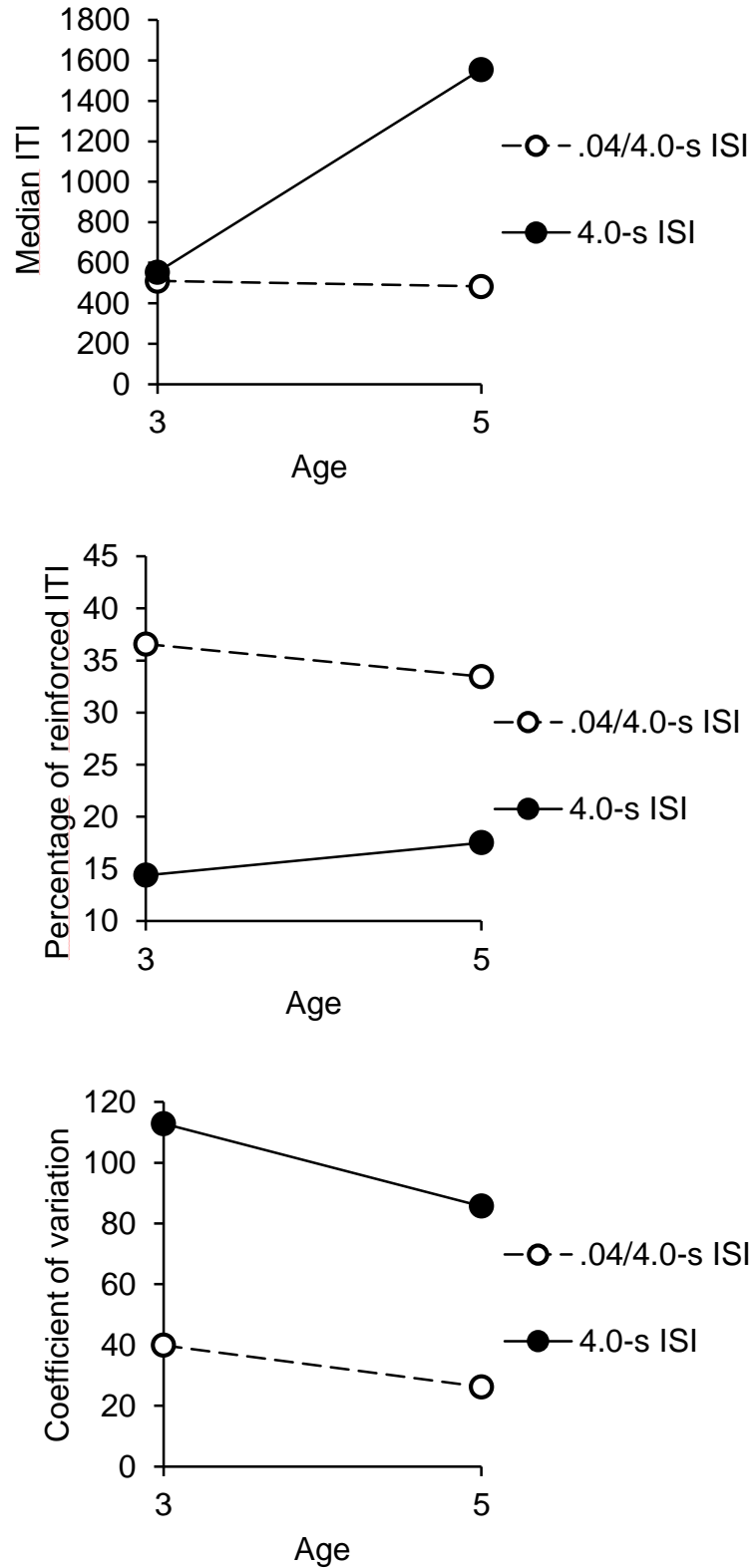
231 **3.2. Pre-synchronization and post-synchronization phase**

232 Using the same indexes as in the synchronization phase, an analysis of variance (ANOVA) was
 233 conducted with phase (pre-synchronization vs. post-synchronization phase) and session as within-
 234 subjects factors, and the same 3 between-subjects factors: age, group and sex. When Mauchly's
 235 sphericity test indicated that the assumption of sphericity had been violated for stimulus duration, the
 236 degrees of freedom were adjusted using the Greenhouse-Geisser correction.

237 *Median ITI.* As for the synchronization phase, there was a significant interaction between group and
 238 age, $F(1, 32) = 4.60$, $p = .04$, $\eta^2_p = 0.13$, with significant main effects of age, $F(1, 32) = 4.13$, $p = .05$,
 239 $\eta^2_p = 0.11$, and group, $F(1, 32) = 5.41$, $p = .03$, $\eta^2_p = 0.15$. As shown in Figure 4 (upper panel), the
 240 median ITI was longer in the 4.0-s group than in 0.4-/4.0-s group for the 5-year-olds, $t(18) = 2.38$,
 241 $p = .03$, while the median ITI value did not change between groups for the 3-year-olds, $t(18) = 0.62$,
 242 $p = .54$. Consequently, the ITI was longer in the 5- than in the 3-year-olds in the 4.0-s group,
 243 $t(18) = 2.22$, $p = .04$, while it remained similar between the two age groups in the 0.4/4.0-s group,
 244 $t(18) = 0.36$, $p = .72$. No other effect was significant, except the main effect of phase, $F(1, 32) = 5.24$,
 245 $p = .03$, $\eta^2_p = 0.14$, indicating that the median ITI was shorter in the post- than in the pre-
 246 synchronization phase (830 vs. 722), irrespective of age. In other words, the synchronization task
 247 tended to speed up the initial motor rhythm.

248 *Coefficient of variation of ITI.* For the coefficient of variation, there was only a main effect of group,
 249 $F(1, 32) = 19.59$, $p = .0001$, $\eta^2_p = 0.38$, the main effect of age and the age x group interaction being
 250 non significant (both $p > .05$) (Figure 4, middle panel). Group did not significantly interact with other
 251 factors (all $p > .05$). The children thus produced more variable ITI in the 4.0-s ISI condition than in the
 252 0.4/4.0-s ISI condition (99 vs. 33).

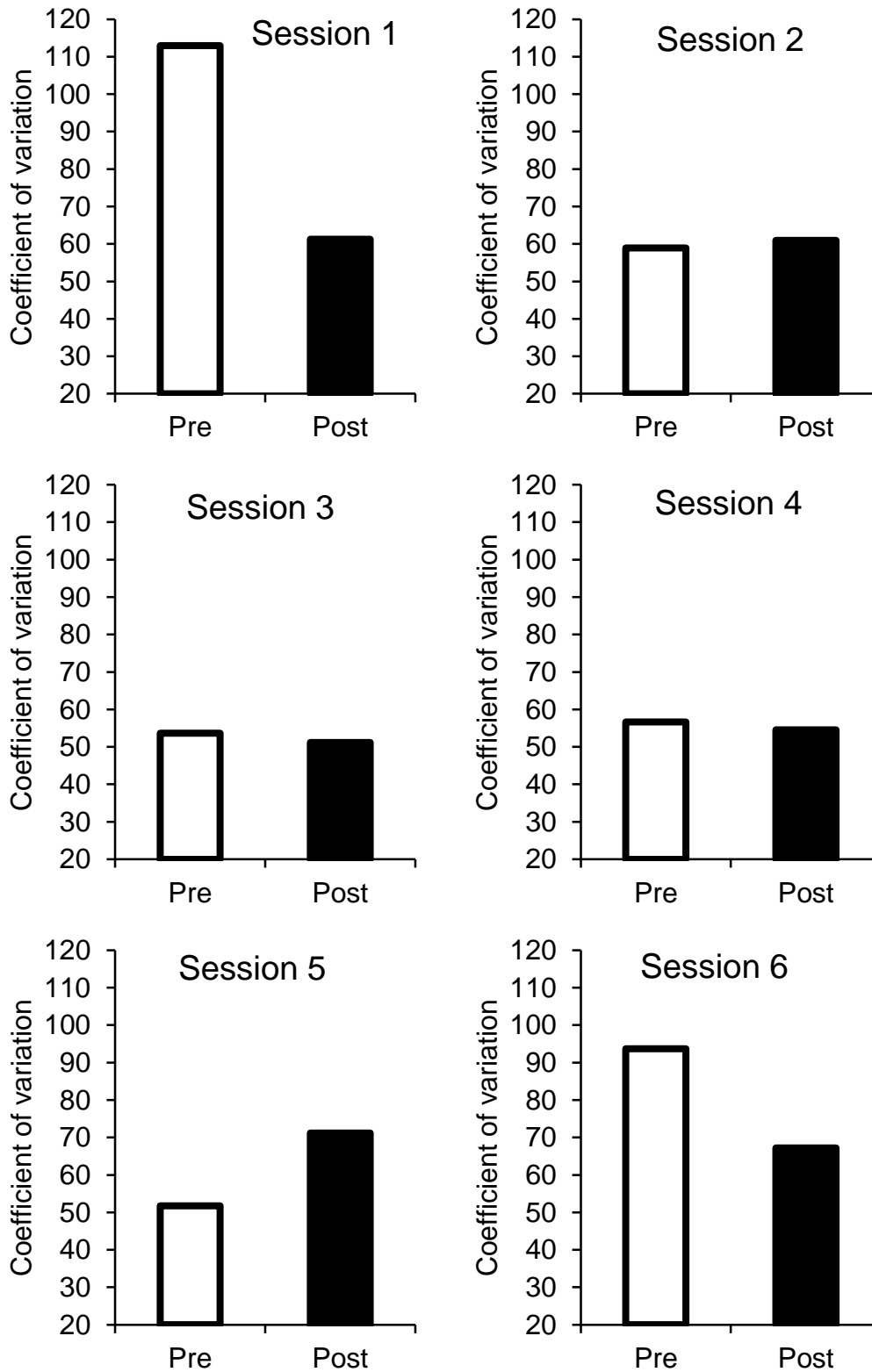
253 Figure 4: Pre- and post- synchronization phases: Indexes of performances as a function of age and
254 group.



255 There was also a significant main effect of phase (pre- vs. post- synchronization phase), $F(1, 32) =$
256 $5.86, p = .02, \eta^2_p = 0.16$, as well as a significant phase x session interaction, $F(5, 160) = 3.13, p = .01,$
257 $\eta^2_p = 0.09$, no other effect reached significance. The coefficient of variation of ITI (Figure 5)
258 significantly decreased after the synchronization phase (Bonferroni tests, $p < .05$), especially for the
259 latest session (session 6) with the longest ISI and for the first session, likely linked to the high level of
260 inter-individual variability in coefficient of variation of ITI for these sessions.

261

262 Figure 5: Pre- and post- synchronization phases: Coefficient of variation as a function of sessions.



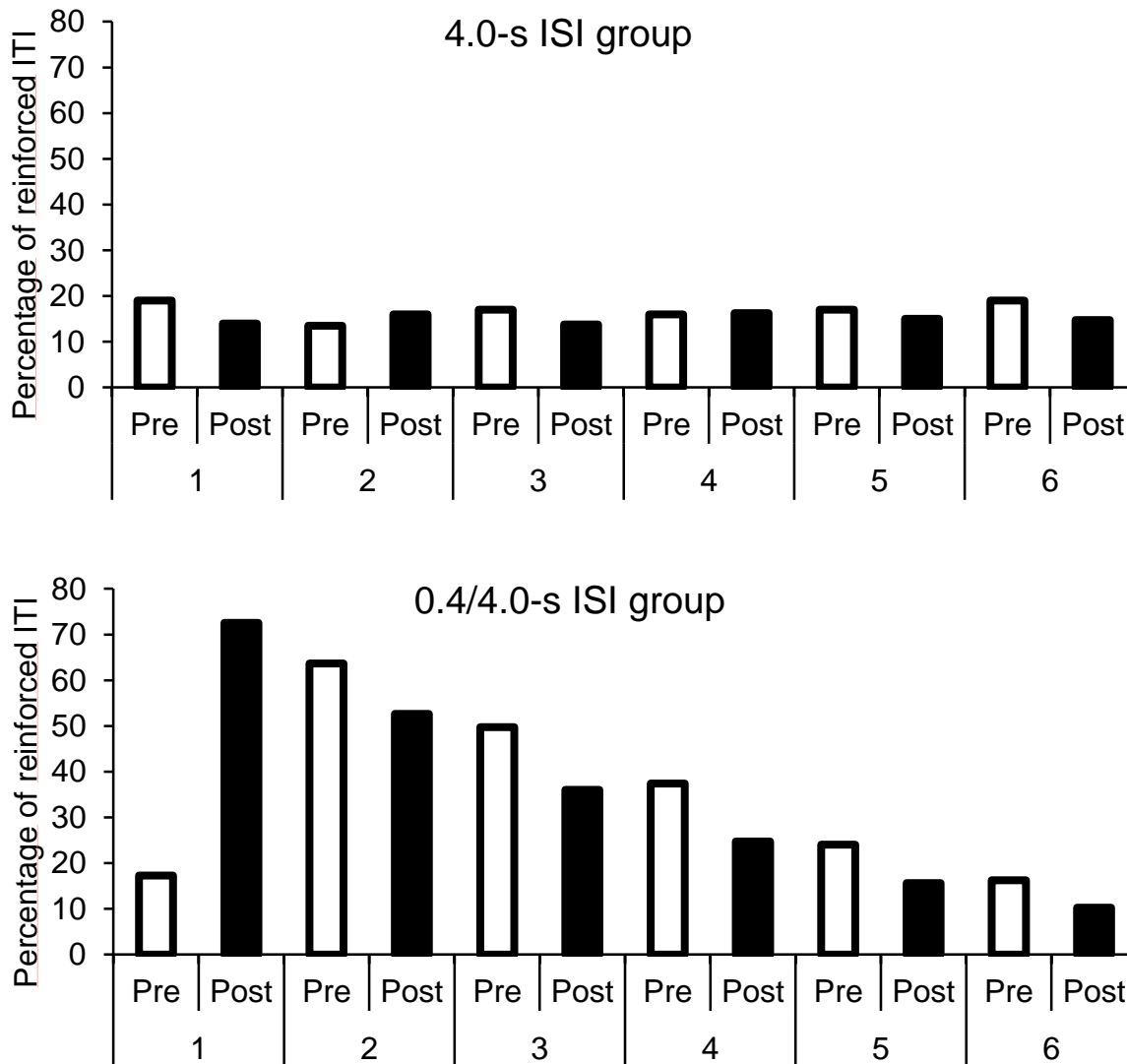
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264

265

266 *Percentage of reinforced ITI during pre- and post-synchronization phase.* The overall ANOVA again
267 showed a significant interaction between group and age, $F(1, 32) = 4.22, p = .048, \eta^2_p = 0.117$, with a
268 significant main effect of group, $F(1, 32) = 157.30, p = .0001, \eta^2_p = 0.83$, but without significant main
269 effect of age, $F(1, 32) = 0.01, p = 1.0$. Concerning phase (pre- vs. post- synchronization phase), the
270 participants thus obtained a greater percentage of reinforced ITI in the 0.4/4.0-s than in the 4.0-s group,
271 but the magnitude of the between-group difference was lower for the 5-year-olds than for the 3-year-
272 olds, this difference was due to the older children who tended to increase the length of their ITI. There
273 was also a 3-way interaction between session, phase (pre- vs. post- synchronization phase) and group,
274 $F(5, 160) = 61.13, p = .0001, \eta^2_p = 0.66$, with a significant session effect, $F(5, 160) = 75.12, p = .0001,$
275 $\eta^2_p = 0.70$, session x group, $F(5, 160) = 86.13, p = .0001, \eta^2_p = 0.73$, phase x group, $F(1, 32) = 5.18, p$
276 $= .03, \eta^2_p = 0.14$, and session x phase interaction, $F(5, 160) = 48.40, p = .0001, \eta^2_p = 0.60$. For each
277 group taken separately (0.4/4.0-s and 4.0-s group), the ANOVA showed a significant phase (pre- vs.
278 post- synchronization phase) x session interaction ($F(5, 95) = 76.08, p = .0001, \eta^2_p = 0.80, F(5, 95) =$
279 $2.40, p = .04, \eta^2_p = 0.11$, respectively). As shown in Figure 6, in the 0.4/4.0-s group, participants
280 obtained more reinforced ITI after (72 %) than before (17 %) the synchronization phase in the first
281 session with the 0.4-s ISI (Bonferroni, $p < .05$). However, after this first session, the percentage of
282 reinforced ITI systematically decreased after the synchronization phase whatever the values of ISI (for
283 all sessions, $p < .05$), in such a way that the percentage of reinforced ITI for the post-synchronization
284 phase in session 5 and 6 returned to the percentage obtained in the pre-synchronization phase for the
285 first session ($p > .05$).
286

287 Figure 6: Pre- and post- synchronization phases: Comparison of the percentage of reinforced ITI as a
 288 function of groups and sessions.



289 Nevertheless, the percentage of ITI obtained in the post-synchronization phase for the sessions before
 290 the fifth session was always greater than that obtained in the pre-synchronization phase of the first
 291 session (all $p > .05$), thereby suggesting a sort of temporal learning in children. For the 4.0-s group, the
 292 percentage of reinforced ITI remained low and did not significantly change between the post- and the
 293 pre-synchronization phase for all sessions (all $p > .05$), except for the first and the last session, for
 294 which a lower percentage of reinforced ITI for the post- than for the pre-synchronization phase was
 295 observed ($p < .05$). This attests to children's difficulty in learning to produce long ITI in a
 296 synchronization task.

297 The overall ANOVA also revealed a significant sex x age x synchronization phase interaction, $F(1,$
 298 $32) = 4.37, p = .045, \eta^2_p = 0.12$, with no other significant effect. This significant interaction indicated
 299 that, regardless of session, the percentage of reinforced ITI was lower in the post- than in the pre-
 300 synchronization for 5-year-old boys (25 vs. 23, Bonferroni test, $p < .05$), but not girls (.26 vs. .27,

301 $p > .05$). At 3 children showed, no significant between-phase difference in the percentage of reinforced
302 ITI was as a function of sex (all $p > .05$).

303

304 4. Discussion

305 The purpose of this study was to further examine the characteristics of auditory-motor coordination
306 during early childhood. Specifically we investigated whether, in a synchronization task, 3 and 5-year-
307 old children can learn to change their preferred tempo to produce ITI longer than 1 s, in other words to
308 switch between rhythm production and temporal interval production.

309 Our results revealed that children succeed in synchronizing their taps with an external tempo when it
310 is close to their own SMT, as indicated by the high percentage of reinforced ITI, as well as the median
311 ITI (close to 400-ms) in the synchronization phase of the first session of the 0.4/4.0-s group.
312 Consequently, children succeed in speeding up their tempo under the effect of an external rhythm with
313 a 0.4-s ISI, as suggested by the progressive decrease of median ITI from an ITI set to another rhythm
314 in the synchronization phase of the first session (). However, once this motor rhythm was initiated, the
315 children were not successful in changing it, i.e., in slowing down their motor rhythm in the
316 synchronization sessions with longer ITI. In the 0.4/4.0-s condition, the percentage of reinforced ITI
317 indeed decreased across sessions as the length of ITI increased (Figure 3), while the median ITI did
318 not vary. In addition, beyond a threshold of 1.0-s (session 3), when ISI was too far away from their
319 own SMT, the percentage of reinforced ITI fell below 50%. This means that less than one tap out of
320 two was reinforced. Further experiments are required to examine whether the children could learn to
321 progressively produce longer ITI in a synchronization task with more training sessions and smaller ISI
322 differences between sessions that those used in our study. Nevertheless, our data suggest a lack of
323 flexibility in sensory-motor synchronization in young children, at least in children aged 3 and 5 years
324 old. This is consistent with the results of studies using short ITIs (< 900-ms), reported in the
325 introduction, showing that young children are able to synchronize their taps to an external auditory
326 tempo but only when it was close to their own tempo (Bobin-Bègue & Provasi, 2008; Provasi & Bobin-
327 Bègue, 2003). For instance, Provasi and Bobin-Bègue (2003) showed that the 2½ - and 4-year-old
328 children, who had to synchronize their tapping rhythm to an 800 ms auditory tempo, maintained a
329 spontaneous tapping rhythm of around 400 ms.

330 The question raised here is: what factor explains this lack of flexibility in sensory-motor
331 synchronization in young children. Are factors related to the development of motor and cognitive
332 capacities during childhood or factors related to the specificity of temporal mechanisms underlying
333 rhythmical activities, which would radically differ from those involved in the production of temporal
334 interval, or both? Some results in our study suggest that developmental factors account in part of this
335 lack of flexibility in children's synchronization behavior. Indeed, in the 4.0-s condition, when the
336 children must directly learn to synchronize their taps to a 4.0-s ISI, the 5-year-old children succeeded
337 in lengthening their ITI compared to the younger children. In the different synchronization phases (pre-
338 synchronization and post-synchronization phases and synchronization phase per se), the 5-year-olds
339 indeed obtained longer median ITI than did the 3-year-olds and the percentage of reinforced ITI was
340 higher for the 5-year-olds than for the 3-year-olds. The difference in the coefficient of variation of ITI
341 between the groups was also more important for the 3-year-olds than for the 5-year-olds. The ITI were
342 thus more variable in the 4.0-s condition than in the 0.4/4.0-s group, especially for the 3-year-olds. In

343 summary, this confirmed our hypothesis that with as they develop, children learn to produce long
344 intervals in a synchronization task.

345 The developmental sources of this age-related change in performance in a synchronization task are far
346 from being clear. In a recent study however, Provasi et al. (2014) used neuropsychological tests to
347 assess the cognitive and fine motor skills of children aged between 5 and 14 performing a
348 synchronization task with ITI of 400-ms and 600-ms. They found that age-related increase in both fine
349 motor skills and speed of processing were the best predictors of individual variance in children's
350 synchronization performance. Synchronization performance thus improves with the development of
351 abilities involved in the rapid production of motor acts under temporal constraints. In addition, in our
352 study, the children were required to inhibit a spontaneous motor behavior to produce longer intervals.
353 It has been clearly demonstrated that it is particularly difficult for children to slow down their own
354 tapping rhythm and/or to inhibit the triggering of a tap (Condon & Sanders, 1974; Hulsebus, 1973).
355 This is explained by the limited inhibitory capacities in young children related to the slow maturation
356 of the prefrontal cortex involved in attention capacities (see e.g., Bjorklund, & Harnishfeger, 1995). In
357 the same way, Bobin-Bègue & Provasi (2008) found that the 3-years-old children were able to
358 accelerate their tapping rhythm during a synchronization task but they did not slow down their tapping
359 rhythm when the auditory tempo was slower than their own spontaneous motor tempo. Consequently,
360 the development of cognitive capacities (attention, information processing speed) and fine motor skills
361 could explain the age-related improvement in performance in a sensorimotor synchronization task.

362 However, in our study, even in the 4.0-s group, when the 5-year-olds succeeded in lengthening their
363 ITI, the value of their ITI did not exceed 1500 ms. The mean of their median ITI was indeed 1559 ms
364 for the different synchronization sessions. This ITI value is remarkable because it is very close to the
365 temporal limit in the production of rhythms pointed out in various studies (Bangert et al., 2011; Fraise,
366 1984; Repp, 2006). As explained by Repp (2006), when a tempo is longer than 1800 ms, adults perceive
367 auditory events as independent events, and their responses occur after the beginning of the auditory
368 event, rather than before the auditory events as an anticipation. Our results thus suggest that specific
369 mechanisms underlying the production of rhythm also explain the lack of flexibility of sensorimotor
370 synchronization behaviors observed in children. Our result point to children's difficulty, even
371 impossibility, in switching from rhythmic production to interval production with long interval (> 1.5
372 s) in a synchronization task. This does not mean that children are unable to produce long intervals.
373 Several studies using a fixed interval schedule of reinforcement (FI) have demonstrated that young
374 children can learn to produce long intervals between two reinforced responses (for a review see Droit-
375 Volet, Provasi, Delgado, & Clément, 2005; Droit-Volet, 2011). Our study suggests rather that rhythmic
376 activities involve different mechanisms for the production of ITI shorter and longer than 1-2 s. This is
377 consistent with recent data from adults suggesting there are two processes within this range of durations
378 (Rammsayer & Troche, 2014). This is also consistent with results from neuroimaging studies
379 suggesting that the activation of the cerebellum would be restricted to timing of action in the range of
380 temporal intervals shorter than 1 s (Ivry, Spencer, Zelaznik, & Diedrichsen, 2002; Wiener, Turkeltaub,
381 & Coslett, 2010). In summary, our study provides empirical data confirming a border around 1 and 2
382 s between different temporal processes in a synchronization task, beyond which rhythm is lost.

383 Furthermore, although there is no main effect of sex on synchronization performance in our study, our
384 results indicate that boys progressively speed up their tapping rhythm through sessions in the
385 synchronization phase whereas girls maintain their tapping rhythm. Indeed, the percentage of
386 reinforced ITI was lower in the post-synchronization phase than in the pre-synchronization phase for

387 boys, but not for girls. However, this sex difference in synchronization performance was only observed
388 at the age of 5 years. This suggests that, at that age, when children begun to succeed in changing their
389 tapping rhythm, boys had more difficulties to do so than girls. However a previous study conducted by
390 Provasi and Bobin-Bègue (2003) showed that boys aged 4 years performed better than girls whatever
391 the ISI (0.4, 0.6 and 0.8 s). We find no clear interpretation of the opposite effect found in this study,
392 except that the interval used in our study was longer than those used by Provasi & Bobin-Bègue (2003),
393 thus requiring more attention to be processed. However, to better examine this sex effect further
394 analyses are required involving more participants.

395 In conclusion, the present study demonstrates that young children do not easily learn to produce
396 intervals longer than 1.5 s in a sensorimotor synchronization task, even with a procedure using visual
397 feedback and several training sessions. Indeed, our results show that children do not succeed in
398 switching from the production of rhythm to the production of temporal interval. The processing of
399 short (< 1.5 s) and long (> 1.5 s) intervals would thus involve different mechanisms even in a same
400 sensorimotor synchronization task. Nevertheless, 5-year-olds perform better than 3-year-olds revealing
401 an age-related improvement in the flexibility of synchronization behavior. Further experiments are
402 required with older children to better describe the development of this synchronization ability.

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484 **7. Figure legends**

485 Figure 1: Synchronization phase: Indexes of performances as a function of age and group.

486 Figure 2: Synchronization phase: Median ITI as a function of sessions and sets.

487 Figure 3: Synchronization phase: Percentage of reinforced ITI as a function of sessions and groups.

488 Figure 4: Pre- and post- synchronization phases: Indexes of performances as a function of age and
489 group.

490 Figure 5: Pre- and post- synchronization phases: Coefficient of variation as a function of sessions.

491 Figure 6: Pre- and post- synchronization phases: Comparison of the percentage of reinforced ITI as a
492 function of groups and sessions.

493