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Age-related differences in predictive response timing in children: Evidence from regularly relative to irregularly paced reaction time performance

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ABSTRACT

Predictive timing refers to the anticipation and precise timing of planned motor responses. This study was performed to investigate children's predictive response timing abilities while accounting for confounding age-related effects of motor speed. Indices of predictive timing were evaluated for their contributions in motor skill proficiency as well. Eighty typically developing children in 4 age groups (5–6, 7–8, 9–10 and 11–12 years) performed a visuomotor reaction time (RT) test. Differences in speed and anticipatory responding at regularly relative to irregularly paced stimuli were evaluated as indices of predictive timing. Also, explicit timing and motor tests (M-ABC-2, VMI tracing, and KTK jumping) were administered. Significant faster responding for regularly versus irregularly paced stimuli was found from the ages of 9–10 years on. Better anticipatory responding behavior for regular in contrast with irregular stimuli was found to be present already at 7–8 years. Overall, predictive timing abilities increased across the 4 age groups. Also, inter-individual differences in the speed indices of predictive timing contributed to predicting VMI tracing and KTK jumping outcomes when controlling for age and overall motor response speed. In conclusion, predictive motor timing abilities increase during age 5 to 12 and correlate with motor skill performance.

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1. Introduction

The development of motor skills involves a movement repertoire that can be flexibly tailored to different and specific task demands (Clark, 2005). Typically, the acquisition of motor skills in children takes place through play and imitation. For instance, with repeated practice, children acquire accurate temporal predictions of motor actions (e.g., adopting a pace when running, rhythmic sequencing when typing or playing music). This learning of temporal sensorimotor information is necessary for adequate motor skill performance and thus might reflect one of the crucial processes underlying typical motor development (Salthouse & Davis, 2006). The present study investigated age-related differences in predictive response timing in typically developing children.

Accurate predictive response timing is reflected in speeded and anticipatory motor behavior due to temporal regularities in the occurrence of stimulus events. At regularly paced or rhythmic stimulus sequences, motor performance is considered to be predictive when RTs are faster relative to RTs at irregularly paced stimuli. In the latter case, RTs result from a passive feedback response mode (Pollok, Gross, Kamp, & Schnitzler, 2008; Sakai et al., 2000). Although predictive timing received a great deal of interest from adult literature (Dreher, Koechlin, Ali, & Grafman, 2002; Martin, Houck, Kicic, & Tesche, 2008; Piras & Coull, 2011; Pollok et al., 2008; Sakai et al., 2000), little is known about children's predictive response timing abilities.

When focusing on the development of children's simple RT performance, which is often used as a measure of response or processing speed, overall improvement (i.e., decrease) in RT performance throughout childhood is consistently reported (Iida, Miyazaki, & Uchida, 2010; McAuley & White, 2011). However, this age-related RT effect may also be determined in part by stimulus timing effects. Especially studies using a regularly paced task design may confound age-related changes in feedback based response effects with age-related changes in predictive response effects. To what extent children's RT performance at regularly paced stimuli benefits from temporal predictability and thus becomes predictive, is unclear. Other studies exclude all possible effects of predictive responding by using an irregularly paced RT task design (Kiselev, Espy, & Sheffield, 2009; McAuley & White, 2011). Consequently, knowledge on predictive response timing abilities in children is lacking in current developmental literature.

If predictive timing in children is age dependent, responding at temporally predictable events will result in speeding up effects in addition to general response speed effects across age. Indirect evidence for this hypothesis is drawn from developmental studies that investigated children's abilities to synchronize with rhythmic patterns (Mastrokalou & Hatziharistos, 2007; McAuley & White, 2011). Synchronizing involves temporal encoding abilities that might not have been fully developed yet in young children. Synchronizing at isochronously (fixed) visual or auditory stimulus rates around 800 to 1500 ms is found to be sensitive in identifying age-related differences in children samples of 3 to 12 years (Kumai & Sugai, 1997; Mastrokalou & Hatziharistos, 2007; McAuley, Jones, Holub, Johnston, & Miller, 2006; Sasaki, 1997). In these studies, time differences between a child's response and the onset of the rhythmic pulse were calculated with shorter differences indicating better synchronizing.

In order to disentangle age-related RT effects adopted from a feedback based and predictive response mode, the present study compares RT performance respectively at irregularly and regularly paced visual stimuli. Since both interval types only differ in their temporal properties, predictive timing can be evaluated. To the best of our knowledge, this is the first developmental study using such design to study predictive response timing in an unconfounded way. Moreover, this kind of visuomotor RT task involves simple stimulus-response mappings and visuospatial processing; children are thus expected to rapidly learn to respond. Different response timing indices can be deduced from an analysis of resulting RT performances. RT reduction at regularly versus irregularly paced stimuli can be used as a behavioral index of predictive timing abilities, i.e., the greater the RT decrease, the more predictive the RT performance (Pollok et al., 2008; Takano & Miyake, 2007). In addition, the occurrence of anticipatory responses, typically defined as RT beneath 100 ms (Willingham, Nissen, & Bullemer, 1989), indicates that they are planned and initiated in advance of target appearance. The ability to produce anticipated responses serves as an index of the precision of voluntary motor responses initiated in omission of external sensory guidance. Furthermore, increasing effects across different runs of the task (i.e., learning rates) can be evaluated. Because explicit knowledge of timing manipulations employed in this paradigm may also influence the motor behavior of the child, the impact of explicit awareness is minimized by limiting deviance in random vs. regular time intervals. Furthermore, explicit awareness is assessed by evaluating possible effects of visual pacing differences in self-paced sequences and by asking the child whether she/he noticed any differences in stimulus timing during the visually paced RT task.

Although there is substantial evidence concerning the importance of motor timing abilities in diverse motor skills in children like drawing, balance and ball catching skills (Bo, Bastian, Contreras-Vidal, Kagerer, & Clark, 2008; Hatzitaki, Zisi, Kollias, & Kloumourtzoglou, 2002; Howe, Wang, Sheu, & Hsu, 2010), the exact nature of those mechanisms from the perspective of motor skill development is not properly explored yet. Dynamic balance control is found to be associated with motor response speed in 11–13 year old children, suggesting the importance of feedback control in responding to destabilizing hip abductions-adductions (Hatzitaki et al., 2002). To evaluate dynamic gross motor coordination and fine motor activity, respectively, the KTK sidewise jumping test (Kiphard & Schilling, 1974) and the VMI tracing test (Beery & Beery, 2004) were selected for this study. The KTK sidewise jumping task involves rhythmic and smooth coordination between flexor and extensor leg muscles in a regularly paced sequence (van Waelvelde et al., 2006). Given this rhythmic motor component, we expect indexed predictive response timing abilities to contribute in predicting children's KTK performance. VMI tracing requires the child to perform feedback based, discontinuous movements, i.e., to start and stop drawing movements at the right time, in order to trace within the trail. For that reason, overall motor response effects are expected to predict VMI tracing outcomes in children rather than indices of predictive timing.

In sum, the current study aimed to investigate children's predictive response timing abilities and assess age-related effects. To our knowledge no other developmental studies have attempted to behaviorally index predictive response timing while accounting for progress in overall response speed in children's RTs. Our indices of predictive response timing were evaluated on their contribution to interindividual differences in motor skill performance as well.

2. Methods

2.1. Participants

Eighty pupils (40 girls and 40 boys, all Caucasian) without diagnosed developmental motor or cognitive problems were randomly selected from two preschools and four primary schools in Flanders (Belgium). All children were tested on the Movement Assessment Battery for Children-2 (M-ABC-2) (Henderson, Sugden, & Barnett, 2007). The M-ABC-2 (Henderson et al., 2007) is a norm referenced motor test with eight items for assessing manual dexterity (three items), ball skills (two items) and balance (three items). Only children with a M-ABC-2 score higher than the 15th percentile were included. Among participating children, no motor problems or indications thereof were identified as none of the children's MABC-2 scores were below the 15th percentile. Additional information on age group and motor performance level is provided in Table 1. Permission was granted by the schools' principals and teachers and informed consent was obtained from the parents or legal guardians.

Table 1
Age group information, and mean (M) and standard deviation (SD) of M-ABC-2 percentiles, VMI tracing, KTK jumping raw scores within each age group.

Age group	Girls	Boys	Age (years)		M-ABC-2		VMI tracing		KTK jumping	
	(*N*)	(*N*)	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
5–6	10	10	5.45	.44	46.80	5.47	18.05	2.90	24.85	6.53
7–8	10	9	7.39	.63	60.94	5.62	21.79	3.03	36.58	11.43
9–10	11	9	9.48	.57	54.0 5	5.47	25.00	3.15	55.80	8.37
11–12	9	12	11.52	.65	49.81	5.34	26.43	2.77	63.10	5.88

2.2. Materials and procedure

2.2.1. Visuomotor timing test

Commercial research software (E-Prime 2.0, Psychology Software Tools, Inc.) with timing accuracy to the millisecond precision level, was used to run the test and collect the behavioral data. Stimuli were displayed on a 15.4-inch LED screen located approximately 60 cm in front of the participant.

Responses were recorded by means of a response pad (CEDRUS RB-830) with functional (push) buttons corresponding with the right or left index finger. Participants rested the index finger of their dominant hand on the corresponding button and a foam pad was put under their forearm for comfort.

The visuomotor timing test consisted of two conditions within a blocked design: a *visually paced condition* including either regularly or irregularly paced stimuli to assess response timing and a *self paced condition* as an explicit timing control test. During the visually paced conditions, participants pressed a button as fast as possible in response to the stimulus, a red blowfish cartoon (2.6 × 1.8 cm; 2.48° × 1.72° of visual angle) that was centrally presented for 70 ms against a white background. In a regular visual pacing block, 20 stimuli with fixed inter stimulus interval (ISI) of 1200 ms were presented whereas in an irregular visual pacing block stimuli were presented, with random ISIs (900–1050–1200–1350–1500 ms). RTs at the visually paced stimuli were registered. The average pacing rate is identical in both visually paced blocks i.e., one stimulus every 1200 ms.

In the self paced condition, participants were instructed to reproduce the pacing of the preceding block by repeatedly pressing the response button for a period of 25.4 s (i.e., block duration of the visually paced blocks). As visual feedback, the blowfish stimulus was displayed in response to every button press. Inter response times (inter RTs) were registered, i.e., the time in between successive responses. The experiment comprised six runs in total. One run consisted of three blocks, including one of each condition (regular pacing, irregular pacing and self pacing). The two visual pacing blocks always preceded the self pacing block and were counterbalanced across runs and in between subjects. Between blocks, a countdown timer indicated a 4 s pause. A self pacing block was initiated by the appearance of a music note symbol (1.7 × 2.1 cm; 1.62° × 2.01°) for 1 s and a visually paced block (regular or irregular) by the appearance of an eye symbol (2.5 × 1.4 cm; 2.38° × 1.34°) (Fig. 1).

2.2.2. Jumping item of the Körper Koördination Test für Kinder (KTK)

The KTK (Kiphard & Schilling, 1974) is a norm referenced test for gross motor coordination. The ‘KTK jumping’ item of this test consists of two 15 s trials in which side to side jumps over a low beam

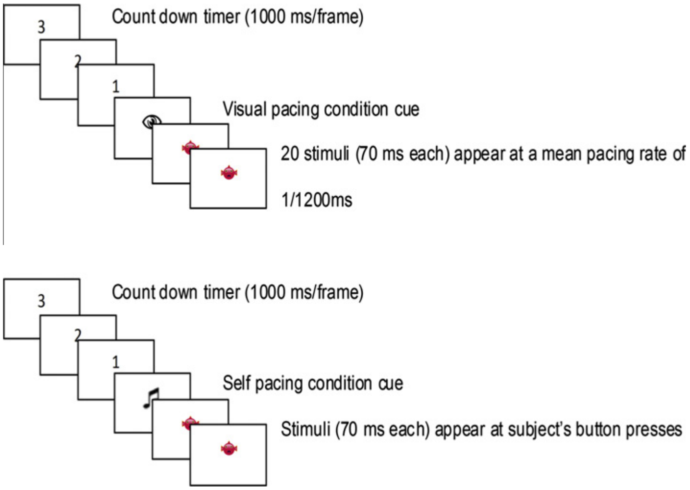

Fig. 1. Schematic representation of the implicit timing task, visually paced (top) and self paced conditions (bottom).

were performed, as many as possible while keeping both feet together. For scoring, the total number of correct jumps over both trials was used. The reliability of this KTK item is good with a test–retest correlation coefficient of .95 (Kiphard & Schilling, 1974).

2.2.3. 'Motor Coordination' test of the Beery VMI tracing test

The Beery-Buktenica Developmental Test of Visual Motor Integration (VMI) (Beery & Beery, 2004) is a well-established normative test measuring the ability to copy geometric figures. In the supplemental test of Motor Coordination, the child traces 27 geometric forms with a pencil, without leaving the double-lined paths within a time frame of five minutes. For scoring the total number of correctly traced forms is used. This item will be referred to as the 'VMI Tracing Test' with an interscorer reliability of .93 and a test–retest reliability of .86 (Beery & Beery, 2004).

2.3. Procedure

All procedures were approved by the ethical commission of Ghent University. Children were tested separately and began with a short practice session (20 trials) of the visually paced RT condition with feedback on RT and accuracy (number of responses within ISI) for comprehension and familiarization with task demands. The visually paced RT task was instructed to the child as 'a fish catching task' with the preceding eye symbol hinting preparation for the appearing fishes to catch by pressing the response button as fast as possible. A music-note symbol signified self pacing or so called 'tempo task' in which participants attempted to imitate/simulate the pacing of the previously appearing fish cartoon by pressing a button. After the experiment, children were asked whether they had been aware of any temporal differences during the visual pacing conditions. Next, they were told about regular and irregular pacing blocks in the fish catching task and asked again if they had noticed this. Subsequently, children were evaluated with the M-ABC-2 (Henderson et al., 2007), the Motor Coordination of the Beery-Buktenica Developmental Test of Visual-Motor Integration – Tracing test (Beery & Beery, 2004), and the jumping item of the KTK (Kiphard & Schilling, 1974).

3. Results

3.1. Visuomotor timing

The performance of the visually paced RT condition resulted in anticipatory responses (AR; $RT < 100$ ms), visually guided responses and missed responses. No significant age group differences were found on the number of missed responses within regular and irregular pacing stimuli blocks. For further RT analyses, missed responses were excluded.

3.2. Response speed

A repeated measures ANOVA to examine effects of age group (4 levels), condition (2 levels: regular and irregular pacing) and run (6 levels) revealed a main effect of age, $F(3, 76) = 46.503$, $p < .0001$, designating general faster responding with increasing age (Fig. 2). Also the condition, $F(1, 78) = 34.847$, $p < .0001$, and Condition × Age interaction, $F(3, 76) = 11.553$, $p < .0001$, were significant, signifying differences in RT mean (M) between both pacing conditions which differed across ages. No other effects reached any significance. The Condition × Age interaction was further analyzed by testing the condition effect within age groups. At 5–6 years, no significant difference occurred between RTs at regular ($M = 490$ ms) and irregular ($M = 491$ ms) visual pacing, $t(1,19) = -.061$, $p = .952$. Subsequent age groups showed increasingly greater RT differences (7–8 years; regular: $M = 374$ ms, irregular: $M = 377$ ms, $t(1,18) = -.126$, $p = .901$, 9–10 years; regular: $M = 284$ ms, irregular: $M = 340$ ms [$t(1,19) = -5.488$, $p < .0001$] and 11–12 years; regular: $M = 223$ ms, irregular: $M = 297$ ms, $t(1,20) = -5.456$, $p < .0001$). Regression analysis to describe the Condition × Age interaction showed significant linear, $F(1, 78) = 30.170$, $p < .0001$, as well as quadratic functions, $F(2,77) = 15.271$,

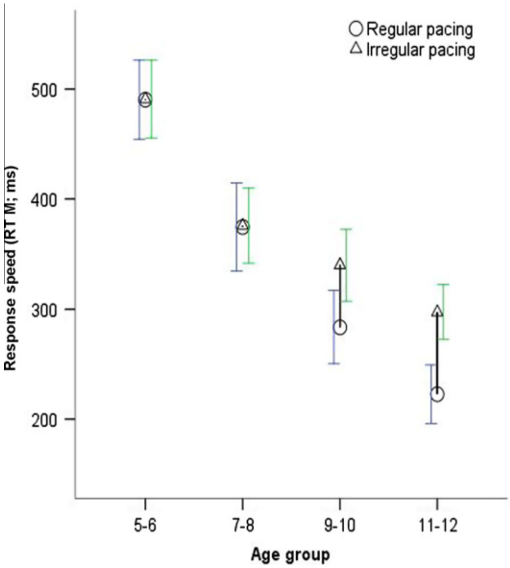

Fig. 2. Response speed (RT Mean; ms) at regularly and irregularly paced stimuli averaged across runs in children of different age groups. Error bars represent 95% confidence intervals.

$p < .0001$, indicating that RT M differences (i.e., speeding in RT at regular relative to irregular pacing) increased with age and starts leveling off before the ages of 11–12 years.

3.3. Anticipatory responses

A 4 (Age Group) × 2 (Condition: regular and irregular pacing) × 6 (Runs) repeated measures ANOVA on the percentage of anticipatory responses revealed a main effect of age, $F(3, 76) = 8.198$, $p < .0001$, reflecting more AR with increasing age (Fig. 3). A main effect of condition, $F(1, 78) = 51.588$, $p < .0001$, and also the Condition × Age interaction, $F(3, 76) = 10.978$, $p < .0001$, were significant, indicating differences in AR between regular and irregular pacing conditions which differed between age groups. No other effects reached significance. To test at what ages a condition effect was manifest, within age group analysis showed that aniticipatory responding at visual pacing already occurred at 7–8 years (regular: $M = 7.18\%$, irregular: $M = 4.04\%$) [$t(1, 18) = 2.856$, $p < .05$]) and likewise for the subsequent age groups of 9–10 (regular: $M = 8.56\%$, irregular: $M = 3.39\%$ [$t(1, 19) = 3.526$, $p < .01$]) and 11–12 (regular: $M = 18.34\%$ and irregular: $M = 6.61\%$ [$t(1, 20) = 5.745$, $p < .0001$]), whereas the youngest age group did not show a condition effect (5–6 years; regular: $M = 4.87\%$ and irregular: $M = 4.14\%$ [$t(1, 19) = 1.025$, $p = 318$]). Regression analysis denoted both significant linear [$F(1, 78) = 30.010$, $p < .0001$] as well as quadratic [$F(2, 77) = 16.279$, $p < .0001$] functions describing a progressive increase of AR with age.

3.4. Explicit visuomotor timing control

Inter RT (i.e., time between subsequent responses) M in the self paced condition was examined using a repeated measures ANOVA to test effects of age (4 levels), run (6 levels) and preceding visual pacing condition (regular, irregular). This analysis did not show a significant main effect of the preceding visual pacing condition, $F(1, 78) = .037$, $p = .847$, or Condition × Age interaction, $F(3, 76) = .331$, $p = .803$. Other effects involving run were also not significant either.

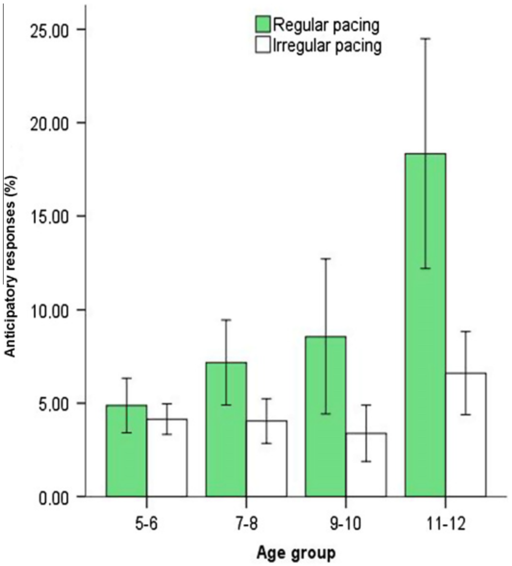

Fig. 3. Percentage (%) anticipatory responses at regularly and irregularly paced stimuli averaged across runs in children of different age categories. Error bars represent 95% confidence intervals.

Table 2
The unstandardized and standardized regression coefficients in the predictive models for motor performance in VMI tracing and KTK jumping.

	VMI tracing task			KTK jumping		
	B	SEB	*β*	*B*	SEB	*β*
Age group	.56	.23	.29*	4.88	.68	.64**
ARTM	.02	.01	.30*	.06	.02	.20*
RT M irregular	−.02	.01	−.41**	−.03	.01	−.18*

[*] $p < .05$.
[**] $p < .0001$.

3.5. Predictive models for individual motor skill performance

Stepwise multiple linear regression analyses assessed which response timing indices in addition to age to enter in a regression equation for predicting motor skill performance. Two indices of predictive timing were calculated as follows: Difference scores of RT *M* at irregularly and regularly paced stimuli resulted in the respective index ΔRT *M* and differences in percentage (%) AR at regularly versus irregularly paced stimuli resulted in the index ΔAR% with scores >0 indicating predictive timing. RT *M* at irregular stimulus pacing was also entered as an index of response speed. The initial model included predictive timing indices (ΔRT *M*, ΔAR%*)*, motor response speed (RT *M* irregular) and age group as predictor variables and KTK jumping and VMI tracing scores as dependent variables. Predictors were eliminated from the model with a backwards selection procedure to achieve at the most sparing model. The resulting models consisted of ΔRT *M* and RT *M* irregular as significant predictors contributing unique variance to the KTK jumping as well as VMI tracing performance, even when controlling for age (Table 2). The model for predicting KTK jumping scores, *F*(3, 76) = 97.895, *p* < .0001, explained 79% of the variance and the VMI tracing model, *F*(3, 77) = 45.550, *p* < .0001, explained 64% of the variance.

4. Discussion

This study was performed to investigate predictive timing abilities in children's simple visual RT performance. Differences in speed and anticipatory responding at regularly relative to irregularly paced visual stimuli were evaluated as indices of predictive timing. Overall, predictive response timing abilities were found to increase during the ages of 5 to 12 years. Significantly faster responding for the regular versus irregular paced stimuli was found from the ages of 9 to 10 years on. Better anticipatory responding behavior (i.e., voluntary motor responses initiated in omission of external sensory guidance) was already present at the ages of 7 to 8 years. With consecutive runs of the task, 5 and 6 year old children did not exhibit predictive responses at an average pacing rate of 1200 ms. Their RT at regular and irregular paced stimuli was not significantly different which indicates a merely passive feedback based response mode instead of active anticipation of the next stimulus. These results add to the current developmental literature on synchronizing skills in children as our study induced synchronizing-like behavior in speeded responding at regularly paced stimuli. Less fine-tuned synchronizing noted in this youngest age group in, e.g., Sasaki (1997), seems to involve a failure to perform predictive responses. Our data do not comprise information on possible extra responses within one ISI, so-called disinhibitory responses because only the first response within one ISI was registered. Although younger children's responses are slower and disinhibitory responses might have occurred, these overall response effects could not have confounded our results since RT statistics were used at regularly relative to irregularly paced stimuli. Previous studies estimated a preferred pacing rate at around 500 ms based on spontaneous self pacing rates in children aged 3 to 12 years (McAuley et al., 2006; Sasaki, 1997). Given the evidence of a preferred pacing rate, perhaps a degree of predictive responding is inducible also in 5 to 6 year old children when using 500 ms pacing rates in an analogous task design. Also, we cannot exclude that training across different test sessions or longer pacing blocks might result in improved predictive response timing across age groups.

Concerning motor skill development, children's speed index of predictive timing as well as motor response speed (i.e., feedback based RT performance at irregularly paced stimuli) significantly contributed to the prediction of performance outcomes on a sidewise jumping task, even when controlling for age. Sidewise jumping to and fro entails a definite rhythmic component and henceforth the expected contribution of predictive response timing was confirmed. The additional significant correlation of feedback based motor response speed is not surprising. Precise feedback based response abilities are a necessary prerequisite to perform subsequent predictive responding. Predictive response timing uses feedback information from previous reactive responses: the timing between movements (inter response interval) as well as information on the timing error (response latency) (Joiner & Shelhamer, 2009). Unlike sidewise jumping, tracing does not involve rhythmic movements and therefore hypothesized to entail less predictive timing requirements. Tracing implicates the child to perform feedback based movements, i.e., to start and stop drawing movements at the right time. Accordingly, our data denoted a substantial correlation with feedback based motor response speed relative to predictive timing and age effects. The differential contributions of predictive timing abilities as indicated with differences in beta regression coefficients are in line with VMI tracing and KTK sidewise jumping that clearly differ in their temporal requirements.

Several runs of the task were administered in order to investigate possible learning effects in predictive response timing abilities within one test session. In agreement with findings in adult samples, no evidence was found of any learning effect across runs (Piras & Coull, 2011). Apparently, a fast learning effect of predictive responding is present in children within the first run, which is maintained throughout the task in children of 7 years on. Because motor tasks often differ in temporal as well as action sequencing demands, the underlying accounting processes in developing motor skills are not yet well distinguished. By reducing action sequencing and explicit demands, the simplicity of this predictive response timing task may place less demand on prefrontally mediated skills, such as maintaining an action sequence or temporal pattern in working memory during the learning process. As a result, this task can easily be evaluated and trained in young children.

The improvement in RT performance gained from a predictable, temporally regular task structure has been assigned to optimized motor processing (Tandonnet, Burle, Vidal, & Hasbroucq, 2003), but may also be mediated by premotoric stages of processing, such as response selection (Muller-Gethmann, Ulrich, & Rinkenauer, 2003) or sensorimotor association (Joiner & Shelhamer, 2009). Evidence from typically developing adult samples suggests that predictive timing in motor responding is regulated by internal chronometric, neural timekeeping systems that entail well-defined frontostriatal and frontocerebellar circuits (Martin et al., 2008). Maturational changes in the brain have been demonstrated to coincide with motor developmental progress. Structural as well as functional age-related changes of striatal and cerebellar systems have been shown in pediatric neuroimaging and motivate further investigation of possible neurodevelopmental changes underlying predictive response timing processes (Sowell et al., 2004; Thomas et al., 2004). Possibly neural development during childhood underlies the use of adaptive strategies to enable predictive response timing. For further research it would be interesting to test this visuomotor RT paradigm using fMRI in a developmental study. Also, timing deficits have been previously reported in children with ADHD and Developmental Coordination Disorder (DCD) (Durston et al., 2007; Nicolson & Fawcett, 2007). Future studies could investigate development of predictive response timing abilities through adolescence and determine adult levels, or compare test results in samples of atypically developing children with their peers.

Taken together, our results identify age-related differences in an important component of motor functioning, coding temporal information for anticipatory behavior. Also, interindividual differences correlate with sidewise jumping and tracing performance. Consequently, predictive response timing abilities might yield developmental significance in the acquisition of diverse motor skills.

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References

Beery, K. E., & Beery, N. A. (2004). *Beery-Buktenica developmental test of visual motor integration*. Minneapolis: NCS Pearson Inc.

Bo, J., Bastian, A. J., Contreras-Vidal, J. L., Kagerer, F. A., & Clark, J. E. (2008). Continuous and discontinuous drawing: High temporal variability exists only in discontinuous circling in young children. *Journal of Motor Behavior, 40*, 391–399.

Clark, J. E. (2005). From the beginning: A developmental perspective on movement and mobility. *Quest, 57*, 37–45.

Dreher, J. C., Koechlin, E., Ali, S. O., & Grafman, J. (2002). The roles of timing and task order during task switching. *Neuroimage, 17*, 95–109.

Durston, S., Davidson, M. C., Mulder, M. J., Spicer, J. A., Galvan, A., Tottenham, N., et al. (2007). Neural and behavioral correlates of expectancy violations in attention-deficit hyperactivity disorder. *Journal of Child Psychology and Psychiatry, 48*, 881–889.

Hatzitaki, V., Zisi, V., Kollias, I., & Kloumourtzoglou, E. (2002). Perceptual-motor contributions to static and dynamic balance control in children. *Journal of Motor Behavior, 34*, 161–170.

Henderson, S., Sugden, D., & Barnett, A. (2007). *Movement assessment battery for children-2 second edition [Movement ABC-2]*. London: The Psychological Corporation.

Howe, T. H., Wang, T. N., Sheu, C. F., & Hsu, Y. W. (2010). Ball catching skills of 5-to 11-year-old typically developing children in real and virtual environments. *American Journal of Physical Medicine & Rehabilitation, 89*, 523–529.

Iida, Y., Miyazaki, M., & Uchida, S. (2010). Developmental changes in cognitive reaction time of children aged 6–12 years. *European Journal of Sport Science, 10*, 151–158.

Joiner, W. M., & Shelhamer, M. (2009). A model of time estimation and error feedback in predictive timing behavior. *Journal of Computational Neuroscience, 26*, 119–138.

Kiphard, B. J., & Schilling, F. (1974). *Körperkoördinationtest für Kinder*. Weinheim: Beltz Test GmbH.

Kiselev, S., Espy, K. A., & Sheffield, T. (2009). Age-related differences in reaction time task performance in young children. *Journal of Experimental Child Psychology, 102*, 150–166.

Kumai, M., & Sugai, K. (1997). Relation between synchronized and self-paced response in preschoolers' rhythmic movement. *Perceptual and Motor Skills, 85*, 1327–1337.

Martin, T., Houck, J. M., Kicic, D., & Tesche, C. D. (2008). Interval timers and coupled oscillators both mediate the effect of temporally structured cueing. *Neuroimage, 40*, 1798–1806.

Mastrokalou, N., & Hatziharistos, D. (2007). Rhythmic ability in children and the effects of age, sex, and tempo. *Perceptual and Motor Skills, 104*, 901–912.

McAuley, J. D., Jones, M. R., Holub, S., Johnston, H. M., & Miller, N. S. (2006). The time of our lives: Life span development of timing and event tracking. *Journal of Experimental Psychology-General, 135*, 348–367.

McAuley, T., & White, D. A. (2011). A latent variables examination of processing speed, response inhibition, and working memory during typical development. *Journal of Experimental Child Psychology, 108*, 453–468.

Muller-Gethmann, H., Ulrich, R., & Rinkenauer, G. (2003). Locus of the effect of temporal preparation: Evidence from the lateralized readiness potential. *Psychophysiology, 40*, 597–611.

Nicolson, R. I., & Fawcett, A. J. (2007). Procedural learning difficulties: Reuniting the developmental disorders? *Trends in Neurosciences, 30*, 135–141.

Piras, F., & Coull, J. T. (2011). Implicit, predictive timing draws upon the same scalar representation of time as explicit timing. *Plos One, 6*, e18203.

Pollok, B., Gross, J., Kamp, D., & Schnitzler, A. (2008). Evidence for anticipatory motor control within a cerebello-diencephalic-parietal network. *Journal of Cognitive Neuroscience, 20*, 828–840.

Sakai, K., Hikosaka, O., Takino, R., Miyauchi, S., Nielsen, M., & Tamada, T. (2000). What and when: Parallel and convergent processing in motor control. *Journal of Neuroscience, 20*, 2691–2700.

Salthouse, T. A., & Davis, H. P. (2006). Organization of cognitive abilities and neuropsychological variables across the lifespan. *Developmental Review, 26*, 31–54.

Sasaki, R. (1997). Developmental characteristics of temporal control of movement in preschool and school children of different ages. *Perceptual and Motor Skills, 85*, 1455–1467.

Sowell, E. R., Thompson, P. M., Leonard, C. M., Welcome, S. E., Kan, E., & Toga, A. W. (2004). Longitudinal mapping of cortical thickness and brain growth in normal children. *Journal of Neuroscience, 24*, 8223–8231.

Takano, K., & Miyake, Y. (2007). Two types of phase correction mechanism involved in synchronized tapping. *Neuroscience Letters, 417*, 196–200.

Tandonnet, C., Burle, B., Vidal, F., & Hasbroucq, T. (2003). The influence of time preparation on motor processes assessed by surface Laplacian estimation. *Clinical Neurophysiology, 114*, 2376–2384.

Thomas, K. M., Hunt, R. H., Vizueta, N., Sommer, T., Durston, S., Yang, Y. H., et al (2004). Evidence of developmental differences in implicit sequence learning: An fMRI study of children and adults. *Journal of Cognitive Neuroscience, 16*, 1339–1351.

van Waelvelde, H., de Weerdt, W., de Cock, P., Janssens, L., Feys, H., & Engelsman, B. (2006). Parameterization of movement execution in children with developmental coordination disorder. *Brain and Cognition, 60*, 20–31.

Willingham, D. B., Nissen, M. J., & Bullemer, P. (1989). On the development of procedural knowledge. *Journal of Experimental Psychology-Learning Memory and Cognition, 15*, 1047–1060.