Journal of Experimental Child Psychology 178 (2019) 137–154

Contents lists available at ScienceDirect

Journal of Experimental Child Psychology

journal homepage: www.elsevier.com/locate/jecp

A divergence of sub- and supra-second timing abilities in childhood and its relation to academic achievement

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ARTICLE INFO

Article history:
Received 13 February 2018
Revised 15 September 2018
Available online 28 October 2018

Keywords:
Math achievement
Reading ability
Sub-second timing
Supra-second timing
Interval timing
Academic achievement

ABSTRACT

Work with adult humans and nonhuman animals provides evidence that the processing of sub-second (<1 s) and supra-second (>1 s) durations are modulated via distinct cognitive and neural systems; however, few studies have explored the development of these separate systems. Moreover, recent research has identified a link between basic timing abilities and academic achievement, yet it is unclear whether sub-second and supra-second temporal processing may play independent roles in this relation. In the current study, we assessed the development of sub- and supra-second timing across middle childhood and examined how each ability may relate to academic achievement. Child participants (6- to 8-year-olds, $n = 111$) completed reading and math assessments and a temporal discrimination task that included comparisons in both the sub- and supra-second ranges. Results revealed that younger children performed comparably across the sub- and supra-second ranges, whereas 8-year-olds and adults ($n = 72$) were relatively better at discriminating durations in the supra-second range. Although discrimination performance in these distinct duration ranges did not uniquely predict math or reading achievement, overall timing abilities were related to math, but not reading, when controlling for age. Together, these data provide evidence for a divergence in timing abilities across sub- and supra-second durations emerging around 8 years of age; however, at least during this stage of development, the relation between children's timing and math achievement is unrelated to this divergence.

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https://doi.org/10.1016/j.jecp.2018.09.010

Introduction

Timing is critical for functioning in our everyday lives. Not only is timing important for engaging in recreational activities such as clapping to the beat at a concert and catching a baseball, it is crucial for basic learning (e.g., Gallistel & Gibbon, 2000; Mauk & Ruiz, 1992; Savastano & Miller, 1998). Given its fundamental nature, it is not surprising that human infants (e.g., Brannon, Suanda, & Libertus, 2007; Provasi, Rattat, & Droit-Volet, 2011), children (Droit-Volet, 2013; Droit-Volet, Delgado, & Rattat, 2006; Odic, 2018), and adults (e.g., Droit-Volet, Tourret, & Wearden, 2004; Fitzgibbons & Gordon-Salant, 1998; Rammsayer, Lima, & Vogel, 1993), as well as nonhuman animals (Boisvert & Sherry, 2006; Henderson, Hurly, Bateson, & Healy, 2006; Meck & Church, 1983; Reynolds & Catania, 1962; Stubbs, 1968), are well-tuned timers, tracking and discriminating temporal intervals across a variety of contexts and tasks. More recently, basic timing abilities have been found to predict both reading achievement (e.g., Casini, Pech-Georgel, & Ziegler, 2017; Hood & Conlon, 2004) and math achievement (Kramer, Bressan, & Grassi, 2011; Odic et al., 2016; Skagerlund & Traff, 2016) in childhood. These data highlight the pervasiveness of timing across nearly all aspects of everyday life while also emphasizing the importance of understanding the cognitive basis for timing abilities.

Although timing abilities have been well documented across both human and nonhuman populations, there is still much to be learned about how timing abilities change over the course of human development. Substantial research with adult humans and nonhuman animals points to the existence of two distinct timing systems for tracking sub-second durations (i.e., millisecond timing) and supra-second durations (i.e., "interval timing") (Buhusi & Cordes, 2011; Buhusi & Meck, 2005; Cordes & Meck, 2014; Gooch, Wiener, Hamilton, & Coslett, 2011; Koch et al., 2007; Lewis & Miall, 2003). For example, individuals with Parkinson's disease and Tourette syndrome have compromised supra-second timing but not sub-second timing (Koch et al., 2007; Smith, Harper, Gittings, & Abernethy, 2007; Vicario et al., 2010), suggesting that separate timing systems are employed when processing short and long durations. However, little is known regarding the developmental emergence of these distinct timing systems. Moreover, recent studies have pointed to a relation between timing abilities and academic achievement. Yet, it is unclear whether sub- and supra-second temporal processing may play distinct roles in the relation between timing and scholastic achievement. In the current study, we investigated sub- and supra-second timing precision of 6- to 8-year-old children in order to assess the likelihood of a two-system account of timing early in development. Then, we explored the relation between timing in these distinct ranges and academic achievement to determine whether academic success is uniquely related to these different timing processes.

Dissociation between sub- and supra-second timing

Substantial neural, clinical, and behavioral evidence supports the presence of two separate cognitive systems for sub- and supra-second timing (Buhusi & Cordes, 2011; Buhusi & Meck, 2005; Gooch et al., 2011; Koch et al., 2007; Lewis & Miall, 2003). These data have revealed that patterns of neural activation vary as a function of the range of durations being processed. Sub-second timing is primarily localized in the cerebellum (De Zeeuw et al., 2011), whereas corticostriatal circuits appear to be active during supra-second timing (Hinton & Meck, 2004; Meck, Penney, & Pouthas, 2008; see also Gooch et al., 2011). In line with this work, the administration of transcranial magnetic stimulation (TMS, a process that temporarily renders brain areas inactive) to the adult cerebellum impairs sub-second timing but not supra-second timing (Koch et al., 2007). Moreover, clinical populations often experience timing deficits in one system but not both systems (see Koch et al., 2007; Smith et al., 2007; Vicario et al., 2010).

In addition to the neural and clinical data, behavioral evidence also supports the notion that sub- and supra-second timing may be modulated by two distinct cognitive systems. In adults, research points to differential precision of timing in the sub- and supra-second ranges (Grondin, 2010), and cognitive load affects supra-second timing but not sub-second timing (Rammsayer & Lima, 1991; Rammsayer & Ulrich, 2011; but see Rammsayer & Ulrich, 2005). Behavioral evidence from nonhuman animals also provides support for two timing systems; rats fail to spontaneously generalize an ordinal timing rule (i.e., indicating which of two durations is longer) learned in the supra-second range to durations in the sub-second range (Cordes & Meck, 2014).

These neural and behavioral differences in sub- and supra-second timing have led researchers to conclude that separate mechanisms underlie sub- and supra-second timing and that each system serves a unique purpose. Sub-second timing is considered automatic and critical for motor control, leading many to believe that the motor system is engaged during sub-second timing (Edwards, Alder, & Rose, 2002; Ivry, 1996; Lewis & Miall, 2003; Schubotz, Friederici, & Von Cramon, 2000). Supra-second timing (i.e., interval timing), on the other hand, involves more cognitive resources and is thought to underlie more deliberate timing and learning (see Buhusi & Meck, 2005, for a review).

Despite substantial evidence in support of two separate timing systems, many studies have largely ignored the possibility that distinct timing processes may underlie sub- and supra-second timing in childhood. The majority of timing studies in childhood typically present durations in the supra-second range (e.g., Droit-Volet, 1998; Droit-Volet, Clément, & Fayol, 2003; Droit-Volet, Clément, & Wearden, 2001; Droit-Volet, Meck, & Penney, 2007; Droit-Volet & Wearden, 2001; Skagerlund & Träff, 2016) and/or collapse across these ranges (e.g., Droit-Volet & Wearden, 2002; Odic, 2018). So far, only a few studies have performed a systematic exploration of sub- and supra-second timing in childhood to determine the relative precision of timing across these two ranges over development. Those studies, using temporal bisection tasks with 5-year-olds, 8-year-olds, and adults, have revealed comparable temporal sensitivity in both duration ranges in each age group (Droit-Volet, & Zélanti, 2013a, 2013b; Zélanti & Droit-Volet, 2011). However, importantly, temporal bisection tasks, which require participants to judge whether a duration is "more similar" to a learned short or learned long standard duration, allow for only an assessment of subjective timing midpoints and consistency in these midpoints, not temporal precision per se. These measures do not necessarily relate to the precision within the underlying temporal representation, which can be assessed only with a measure of accuracy. Thus, it remains unclear whether dissociations in the precision of sub- and supra-second timing, like those found in adults, are present early on or whether instead a temporal dissociation emerges over the course of development. If timing abilities in the sub- and supra-second ranges diverge over time, then the timing of this divergence may provide insight into the source, pointing to certain experiences and/or formal education that may shape temporal abilities.

In the current study, we performed an examination of sub- and supra-second timing abilities in children. Importantly, given that early–middle childhood is a period during which children acquire information about explicit temporal units of measurement (learn how to read a clock, learn how long a second or minute lasts, etc.), we chose to explore timing abilities in 6- to 8-year-olds. In particular, we hypothesized that the acquisition of temporal units of measurement during this period of development may result in significant changes in timing abilities; thus, we wanted to explore timing abilities during this developmental window.

Timing and academic achievement

A growing body of literature links timing abilities to academic success (e.g., Casini et al., 2017; Hood & Conlon, 2004; Kramer et al., 2011; Odic et al., 2016; Skagerlund & Träff, 2016). However, these studies have broadly overlooked the possibility that two distinct timing processes may underlie temporal abilities; thus, it is unknown whether each timing system contributes uniquely to academic achievement. In particular, the majority of studies exploring the relation between timing and reading abilities have focused on sub-second timing abilities; in contrast, work investigating how timing and math are related has been limited to supra-second timing. Although the source of the correlation between timing and achievement is not well understood, there are reasons to suspect that sub- and supra-second timing may be uniquely related to reading and math ability.

Timing and reading

Previous research has identified a link between sub-second timing and reading achievement. Phonological processing—the process of discriminating sounds in our language—is critical for comprehending written and spoken language (Wagner & Torgesen, 1987). Importantly, this process requires an ability to distinguish very quick acoustic differences or an ability to differentiate extremely brief (i.e., sub-second) time intervals. In line with this prediction, children's performance on temporal order judgment, gap detection, and interval discrimination tasks in the sub-second timing range has been shown to be correlated with reading abilities (Hood & Conlon, 2004; Plourde, Gamache, Laflamme, & Grondin, 2017). Moreover, an extant literature has shown that individuals with language disabilities have difficulty in processing rapidly (i.e., sub-second) presented auditory stimuli (Casini et al., 2017; Cohen-Mimran, & Sapir, 2007; Fostick, Bar-El, & Ram-Tsur, 2012; Rey, De Martino, Espesser, & Habib, 2002; see Farmer & Klein, 1995, for a review), again suggesting a link between sub-second temporal processing and language abilities.

Although a link exists between timing and reading abilities, these studies have largely focused on children's abilities to detect rapid changes, involving sub-second durations (<1 s; see Farmer & Klein, 1995, for a review), leaving it unclear whether supra-second timing may relate to reading abilities as well. Because phonological processing, which is critical for reading achievement, requires quick and automatic processing of temporal durations (Wagner & Torgesen, 1987), it is reasonable to expect a relation between sub-second timing and reading achievement. Although there are no clear expectations as to how supra-second timing may be important for reading, one study has found interval reproduction in the supra-second range to be correlated with first to sixth graders' reading abilities (Plourde et al., 2017). Given the importance of sub-second timing for reading, we predicted that sub-second timing, but not supra-second timing, may uniquely relate to reading abilities.

Timing and math

Recent studies have also reported correlations between timing abilities and mathematics achievement (Kramer et al., 2011; Odic et al., 2016; Skagerlund & Träff, 2016; see also Tobia, Rinaldi, & Marzocchi, 2018, for evidence of impaired timing in children at risk for math learning disabilities). This relation appears to be consistent in 6- to 10-year-olds and holds across various types of math tasks (including arithmetic fact retrieval, calculation, etc.). Exactly why math and timing are linked, however, is less clear. Some researchers have argued that the ability to order, process, and manipulate magnitudes (a key component of temporal processing) may underlie the relation between timing and mathematics (see Skagerlund & Träff, 2016). If so, then timing in both the sub- and supra-second ranges should equally predict math abilities because both ranges require an ability to order and process magnitudes. Another theory, however, posits that timing is important for mathematics inasmuch as time and number are part of a "common magnitude system" (e.g., Cantlon, Platt, & Brannon, 2009; Meck & Church, 1983; Walsh, 2003). A prominent theory in the field, the idea of a common magnitude system, was first proposed by Meck and Church (1983) to account for rat interval timing and counting data and has since been supported by numerous findings of commonalities across temporal and numerical representations in humans and nonhuman animals. The theory posits that supra-second timing and numerical processing are dictated by a single common neural locus. In line with this theory, timing should be related to math inasmuch as numerical abilities are related to math. Given the substantial literature identifying relations between numerical processing and mathematics (e.g., Halberda, Mazzocco, & Feigenson, 2008; Libertus, Feigenson, & Halberda, 2011; Mazzocco, Feigenson, & Halberda, 2011), the relation found between timing and math can be considered to be evidence for this common magnitude system.

Importantly, unlike the investigations of reading ability, work studying the relation between timing and math have exclusively focused on timing abilities in the supra-second range (e.g., Skagerlund & Träff, 2016), leaving the role of sub-second timing in math achievement unclear. Whether sub-second timing is related to math achievement may provide a hint at the mechanism responsible for the demonstrated link between supra-second timing and math. If the relation between timing and math hinges on the existence of a common magnitude system, then supra-second timing, but not sub-second timing, should predict math achievement. Alternatively, if timing and math are related inasmuch as both rely on an ability to order and manipulate magnitude information, then it is anticipated that sub- and supra-second timing abilities will equally predict math abilities. Given evidence that children diagnosed with dyscalculia—a learning disability characterized by math difficulties—have impaired sub-second timing abilities (Pellerone, 2013; Vicario, Rappo, Pepi, Pavan, & Martino, 2012; but see Cappelletti, Freeman, & Butterworth, 2011), it is possible that sub-second timing may also be important for math achievement. This study aimed to clarify whether such a relation exists in typically developing 6- to 8-year-old children.

In the current study, we investigated (a) sub- and supra-second timing abilities in 6- to 8-year-old children and adults and (b) how children's timing abilities in each of these distinct ranges relate to math and reading achievement in childhood. The 6- to 8-year-olds performed math and reading assessments and a temporal discrimination task in which they judged the relative duration of stimuli in the sub- and supra-second ranges. This age range was selected because it is the point during which children learn about temporal units of measurement, which may lead to dramatic changes in their timing ability. Moreover, children younger than this age are not reading yet and have very little formal arithmetic competence, making a true assessment of math and reading abilities difficult.

Method

Participants

A total of 111 6- to 8-year-old children (M_{age} = 88.34 months, *SD* = 10.19, 52 girls) participated in this study (6-year-olds: *n* = 39, M_{age} = 6.46 years, range = 6.00–6.92, 22 girls; 7-year-olds: *n* = 35, M_{age} = 7.46 years, range = 7.00–7.92, 18 girls; 8-year-olds: *n* = 37, M_{age} = 8.34 years, range = 8.00–8.83 years, 12 girls). Children were recruited from the Boston area in the northeastern United States and participated in the lab, at local parks, or at afterschool programs and received a toy for their participation. Written consent was obtained from participants' parents, and children over 7 years of age also provided their verbal and written assent to participate. An additional 5 children participated but were excluded from the analyses for being outside of the age range (*n* = 2), for having a learning disability (*n* = 1), or due to computer error (*n* = 2).

In addition, 72 adults (M_{age} = 18.92 years, 38 women) also participated. Adults provided oral and written consent and received course compensation for their participation. Data from an additional 8 adults were excluded due to computer error. All procedures were in accordance with the Boston College institutional review board.

Procedure

Child participants

Children completed the following tasks in a fixed order: Test of Word Reading Efficiency (TOWRE) assessment, Time Discrimination task, and Math Assessment (the Math Fluency subtest from the Woodcock–Johnson III).

After obtaining parental consent and child assent, child participants were brought into a quiet testing room, where they first completed the Sight Word Efficiency and Phonemic Decoding Efficiency subtests of the TOWRE (Torgesen, Wagner, & Rashotte, 1999). The experimenter instructed children to read lists of words as fast as possible without making mistakes. Following a brief practice list, children were given 45 s to read a longer list of words. The process was completed once with the Sight Word list (104 words) and again with the Phonemic Decoding list (63 nonsense words).

Next, a laptop was placed in front of children and the experimenter explained that two characters, a chicken on the left and a cow on the right, would appear on the computer screen and play a musical instrument. Children were told that the chicken and the cow would each take turns playing a musical instrument and that the children's job was to decide which animal played its instrument longer. No other instructions were given. The chicken always played first and the cow played second, with an interstimulus interval of 1500 ms. When each animal played its instrument, a trumpet appeared on top of the animal and a sound accompanied the presence of the trumpet stimulus (the chicken's trumpet sounded like a train, whereas the cow's trumpet sounded like a horn). Thus, children were given both auditory and visual information regarding the duration of each stimulus. Children were instructed to say out loud which animal played its instrument longer, and the experimenter pressed the appropriate keys on the computer to record their responses. Each animal was correct on 50% of the trials. Half of the trials involved durations exclusively in the sub-second range (<1 s; range = 200–800 ms) and half of the trials involved durations exclusively in the supra-second range (>1 s; range = 1000–4000 ms), with trials testing different ranges intermixed throughout the task. On every trial, one of the temporal stimuli (either the chicken or the cow) was a set standard duration (sub-second range = 400 ms; supra-second range = 2000 ms). The other temporal stimulus differed from that standard value by one of two ratios (1:2 or 3:4). On half of the trials the other temporal stimulus was longer than the standard duration, and on the other half of the trials it was shorter than the standard duration. After 8 initial practice trials (involving durations varying by a 5:16 ratio, 4 trials in each duration range), children completed 32 test trials (2 ratios (1:2 and 3:4) × 2 duration ranges (sub-second and supra-second) × 8 times each). Children were given positive reinforcement regardless of their responses ("You're doing a great job!") after every 8 trials—or four times throughout the experiment.

After the Time Discrimination task, children completed the Math Fluency subtest of the Woodcock–Johnson III (Woodcock, McGrew, & Mather, 2001), which involved a two-sided worksheet consisting of 160 addition, subtraction, and multiplication problems involving numbers 1–10. Children were given 3 min to complete as many math problems as possible. After completing the math assessment, children and their parents were debriefed.

Adult participants

All methods were identical for adult participants. Adults completed the TOWRE reading assessment and the Reading Fluency subtest from the Woodcock–Johnson III (Woodcock et al., 2001) prior to the Time Discrimination task. To increase accuracy of our timing measure, adults completed 96 trials in the Time Discrimination task involving 3 different ratios (1:2, 3:4, and 5:6) × 2 duration ranges (sub-second and supra-second) × 16 times each. This additional harder ratio (5:6) was included so as to ensure that adults did not perform at ceiling levels on the task. Adults also completed a math assessment after the Time Discrimination task. Because adult performance on the achievement tests revealed very little variability, only the Time Discrimination task is discussed. For additional information on methods and results from the achievement tasks with our adult sample, refer to the Appendix A.

Results

Data coding

Age group

Child participants in our sample were grouped into one of three age groups: 6-year-olds (dummy coded as 1), 7-year-olds (dummy coded as 2), or 8-year-olds (dummy coded as 3). Adult data were analyzed separately and so were not assigned an age group.

Math performance

The dependent variable for the math task was number correct. Per Woodcock–Johnson guidelines, children who completed fewer than three arithmetic problems over the course of the 3 min were not included in the analyses including math performance ($n = 6$). Accuracy scores that were 3 standard deviations above or below the mean were replaced with the next highest or lowest value within 3 standard deviations ($n = 2$).

Reading performance

We report standard scores in our analyses of the TOWRE because they have been shown to provide the clearest indication of performance (Torgesen et al., 1999). Performances on both subtests of the TOWRE were combined to create a composite reading score. Performance on the TOWRE was voice recorded and subsequently coded by two independent coders (reliability: $r = 0.97$). In each instance where there was no voice recording ($n = 7$) or the participant spoke too softly to be heard on the audio recording ($n = 2$), the individual's performance on the reading assessments was taken from online coding only. Two participants did not have online coding and were not included in the reading analyses.

Time discrimination

Percentage correct was the dependent variable for the Time Discrimination task. Performance that was not within 3 standard deviations of the mean (for the overall performance or for each duration range separately) was adjusted to the next highest or lowest value within 3 standard deviations of the mean (children: $n_{\text{supra-second}} = 1$; adults: $n_{\text{overall timing}} = 1$; $n_{\text{sub-second}} = 1$; $n_{\text{supra-second}} = 1$).[1] We also ensured that each participant's performance on each ratio was within 3 standard deviations of the mean. Ratios above or below 3 standard deviations from the mean were replaced with the next highest or lowest score within the range (children: $n = 1$; adults: $n = 4$).

Overall performance

Gender did not interact with any of our variables of interest, and so we collapsed across this variable for all of the analyses. Children's average performance on each task is listed in Table 1, and the partial correlations between tasks, controlling for age group, are shown in Table 2. Both children and adults performed above chance on the timing task (children: $M = 81.64\%$; $t(103) = 24.88$, $p < .001$; adults: $M = 85.71\%$; $t(71) = 46.63$, $p < .001$).

Developmental trajectories for timing in each duration range

We conducted a 2 (Range: sub-second or supra-second) × 2 (Ratio: 1:2 or 3:4) × 3 (Age Group: 6-, 7-, or 8-year-olds) repeated-measures analysis of variance (ANOVA) on the child data. Not surprisingly, there was a main effect of ratio, $F(1, 101) = 51.059$, $p < .001$, $\eta_p^2 = 0.336$, such that children performed significantly better on the trials involving a 1:2 ratio change ($M = 85.3$, $SD = 14.53$) relative to those involving a 3:4 ratio ($M = 77.3$, $SD = 14.28$) (see Fig. 1, top), consistent with ratio-dependent responding. There was no main effect of age ($p = .660$), suggesting that children did not show significant improvements in their overall timing abilities with age. There was, however, a significant Range × Age Group interaction, $F(2, 101) = 5.461$, $p = .006$, $\eta_p^2 = 0.098$. Follow-up paired-samples t tests exploring performance on the sub- and supra-second ranges for each age group revealed that 6- and 7-year-olds performed comparably (if not slightly better) on trials involving sub-second durations compared with supra-second durations (6-year-olds: $M_{\text{sub}} = 81.93$, $SD = 15.29$, $M_{\text{supra}} = 78.72$, $SD = 15.83$, $t(36) = 1.328$, $p = .193$; 7-year-olds: $M_{\text{sub}} = 82.39$, $SD = 14.70$, $M_{\text{supra}} = 80.49$, $SD = 12.83$, $t(32) = 0.935$, $p = .357$). In contrast, 8-year-olds performed significantly better in the supra-second range ($M = 86.24$, $SD = 12.77$) than in the sub-second range ($M = 79.96$, $SD = 16.76$), $t(33) = -2.969$, $p = .006$ (see Fig. 2). No other main effects or interactions reached significance ($ps > .20$).

We performed a comparable 2 (Range: sub-second or supra-second) × 3 (Ratio: 1:2, 3:4, or 5:6) repeated-measures ANOVA on the adult temporal discrimination data. As with the children, there was a significant main effect of ratio, $F(2, 142) = 218.106$, $p < .001$, $\eta_p^2 = 0.754$, such that adults performed best on the 1:2 ratio ($M = 93.75$, $SD = 5.93$), followed by the 3:4 ratio ($M = 89.53$, $SD = 7.57$) and the 5:6 ratio ($M = 73.66$, $SD = 10.90$), all $ps < .001$ (see Fig. 1, bottom). Moreover, there was also a main effect of range, $F(1, 71) = 8.77$, $p = .004$, $\eta_p^2 = 0.110$. Like the 8-year-olds, adults performed significantly better in the supra-second range ($M = 86.95$, $SD = 7.31$) relative to the sub-second range ($M = 84.47$, $SD = 7.46$), $t(71) = -2.994$, $p = .004$ (see Fig. 2). Lastly, there was a Range × Ratio interaction, $F(2, 142) = 3.94$, $p = .025$, $\eta_p^2 = 0.053$. Although performance on trials involving stimuli in the supra-second range was better than performance on sub-second range trials at each ratio level, this difference was significant only for the easiest and hardest ratios [1:2 ratio: $t(71) = -2.002$, $p = .049$; 3:4 ratio: $t(71) = -0.350$, $p = .727$; 5:6 ratio: $t(71) = -3.232$, $p = .002$].

[1] Because below-chance performance (<50%) on the Time Discrimination task is not particularly informative, we conducted a separate set of analyses in which below-chance performance (overall, in either duration range, or on any ratio) was replaced with chance level (50%). All analyses remained consistent with this transformation.

Table 1
Children's average performance on each task.

Age group	TOWRE	Overall timing (%)	Sub-second timing (%)	Supra-second timing (%)	Arithmetic
6-year olds	108.03 (13.21)	80.32 (13.70)	81.93 (15.29)	78.72 (15.83)	23.03 (14.48)
7-year olds	107.81 (14.12)	81.44 (12.28)	82.39 (14.70)	80.49 (12.38)	33.03 (15.28)
8-year olds	108.49 (15.13)	83.27 (13.05)	79.96 (16.76)	86.24 (12.77)	46.51 (14.79)

Note. Standard deviations are in parentheses.

Table 2
Correlations between tasks in the child sample (controlling for age group).

	1	2	3	4	5
1. Reading					
2. Arithmetic	0.561**				
3. Sub-second timing	0.121	0.254*			
4. Supra-second timing	−0.002	0.207*	0.635**		
5. Overall timing	0.075	0.262*	0.925**	0.878**	

* $p < .05$.
** $p < .01$.

Given the dissociation of timing sub- and supra-seconds throughout development, we then conducted two separate one-way ANOVAs to explore the effect of age group (6-, 7-, or 8-year-olds) on sub-second timing, and separately on supra-second timing, to determine whether timing in either duration range improves with age. The ANOVA testing sub-second timing did not reach significance, $F(2, 101) = 0.231$, $p = .794$, suggesting that sub-second timing abilities remain consistent in middle childhood. The ANOVA testing supra-second timing was marginally significant, $F(2, 101) = 2.822$, $p = .064$, indicating that there was no significant age difference in supra-second timing abilities.

Relation to academic achievement

Effects of age

A one-way ANOVA revealed no effect of age on TOWRE performance, $F(2, 102) = 0.020$, $p = .980$.[2] A comparable one-way ANOVA, however, revealed a significant effect of age group on arithmetic performance, $F(2, 98) = 21.141$, $p < .001$, such that older children performed better on the arithmetic task.

To investigate the relationship between each timing system and academic achievement in childhood, we performed linear regressions, entering age group in the first step and timing performance (sub- and supra-second performance separately) in the second step as predictors of reading and math performance. When predicting reading, the first model including only age group did not reach significance, $F(1, 96) = 0.004$, $p = .949$. Adding timing performance in the second step did not contribute any additional variance to the model (R^2 change = 0.022, $p = .351$), and so the second model remained insignificant, $F(3, 94) = 0.708$, $p = .550$. Thus, neither age nor timing performance significantly predicted reading ability (see Table 3A).

When predicting math, the first model was significant, $F(1, 96) = 40.284$, $p < .001$, such that age group (β = 11.74, $p < .001$) significantly predicted math performance. Importantly, the second model was also significant, $F(3, 94) = 17.298$, $p < .001$. Including sub- and supra-second timing performance explained additional unique variance (R^2 change = 0.060, $p = .015$). Although age group (β = 11.398, $p < .001$) continued to predict math performance, neither sub-second timing performance (β = 18.554, $p = .121$) nor supra-second timing performance (β = 14.809, $p = .287$) independently

[2] It is important to note that standard scores on the TOWRE assessment are normed across ages. Thus, standard scores are not expected to correlate with age. Children's raw scores on the TOWRE assessment, however, did correlate with age ($p < .001$), as predicted.

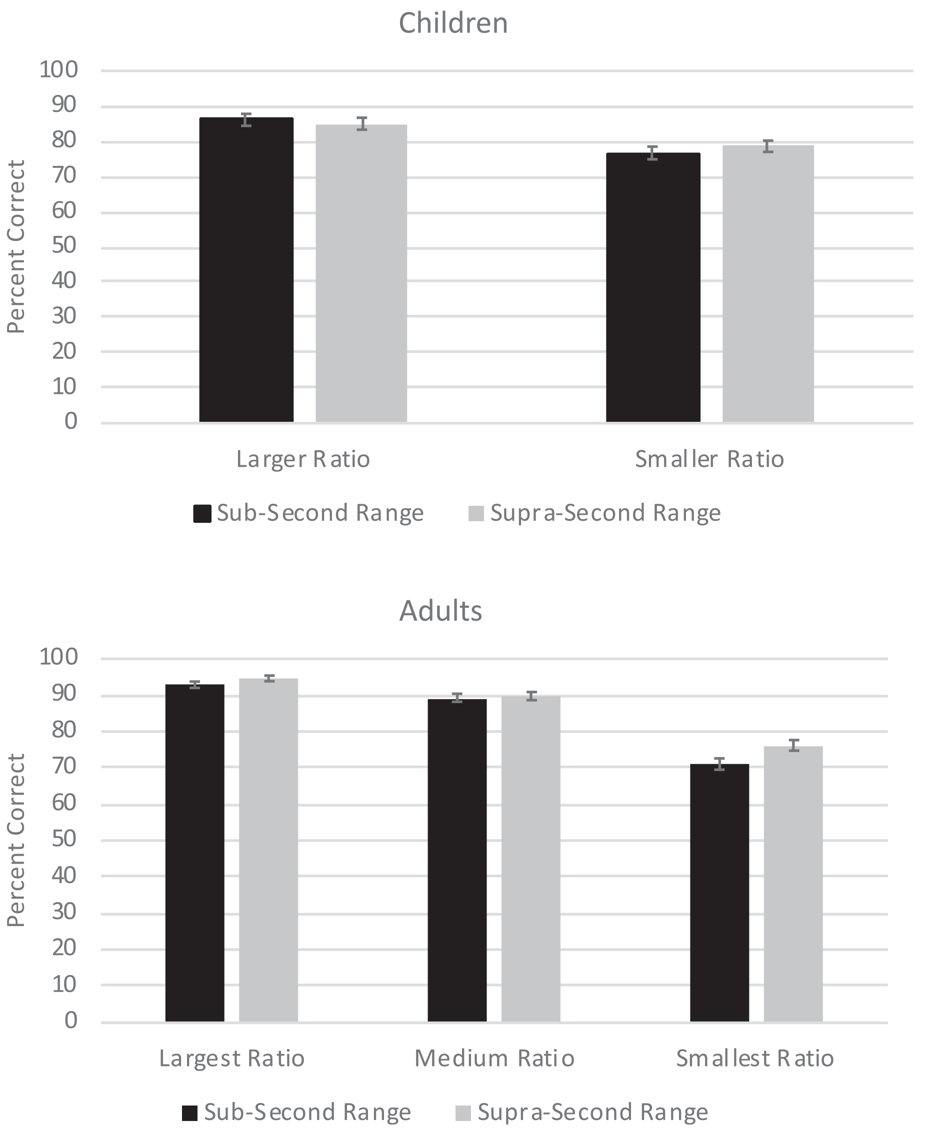

Fig. 1. Ratio effects were present in both the sub- and supra-second ranges for both children (top) and adults (bottom). * indicates $p < .05$.

significantly predicted math performance. Thus, age and *overall* timing performance (across both duration ranges) significantly predicted math ability (see Table 3B).

In a second set of regression analyses, we entered age group in the first step and academic ability (math or reading) as predictors of sub- and supra-second timing (performed separately) to determine whether academic abilities predict timing abilities in either duration range. In particular, we were interested in whether the link between math and timing would hold when controlling for reading abilities. When predicting sub-second timing, the first model including age group did not reach significance, $F(1, 90) = 0.123$, $p = .726$. Adding reading and math ability only marginally contributed to the

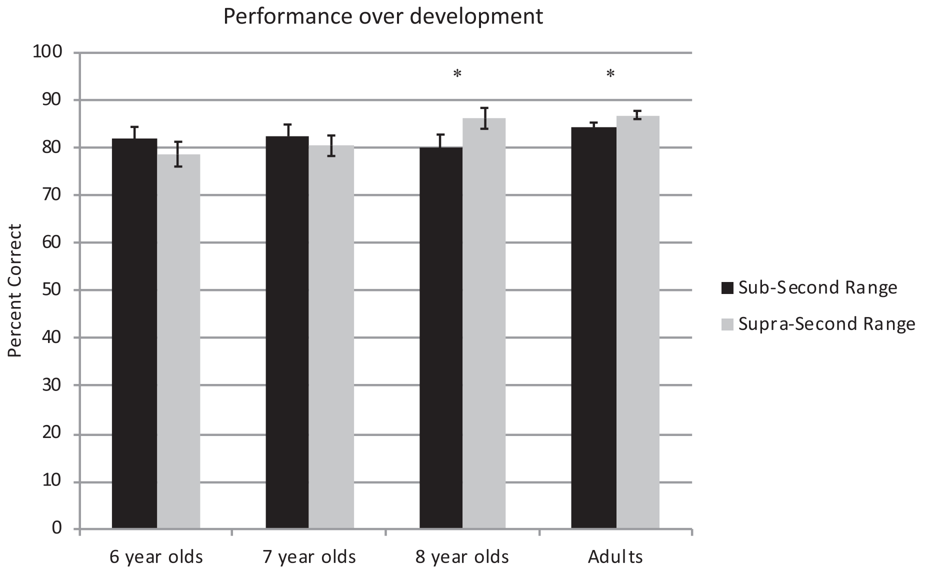

Fig. 2. Sub- and supra-second timing across all age groups.

Table 3A
Regression: Timing abilities predicting reading.

	B	*SE B*	*β*	*p* value
Model 1				
Age	0.109	1.689	0.007	.949
Model 2				
Age	0.404	1.772	0.024	.820
Sub-second	15.675	11.774	0.177	.186
Supra-second	−5.477	13.689	−0.054	.690

Note. R^2 change = 0.022, $p = .351$.

Table 3B
Regression: Timing abilities predicting math.

	B	*SE B*	*β*	*p* value
Model 1				
Age	11.735**	1.849	0.544	<.001
Model 2				
Age	11.398**	1.879	0.528	<.001
Sub-second	18.554	11.843	0.162	.121
Supra-second	14.809	13.839	0.113	.287

Note. R^2 change = 0.060, $p = .015$.
** $p < .01$.

model (R^2 change = 0.065, $p = .051$), preventing the second model from reaching significance, $F(3, 88) = 2.095$, $p = .107$ (see Table 4A).

An identical regression was performed including age group and academic ability as predictors of supra-second timing. The first model including only age group reached significance, $F(1, 90) = 4.219$, $p = .043$, suggesting that age group ($\beta = 0.034$, $p = .043$) predicted supra-second timing. Adding

Table 4A
Regression: Academic abilities predicting sub-second timing.

	B	*SE B*	β	*p* value
Model 1				
Age	−0.007	0.02	−0.037	.726
Model 2				
Age	−0.042	0.026	−0.224	.102
Reading	0.000	0.001	−0.032	.797
Math	0.003*	0.001	0.330	.031

Note. R^2 change = 0.065, $p = .051$.
* $p < .05$.

academic ability marginally contributed to the model (R^2 change = 0.060, $p = .057$), and the second model remained significant, $F(3, 88) = 3.438$, $p = .020$. In the second model, only math ($\beta = 0.003$, $p = .017$) predicted supra-second timing. Age ($\beta = 0.000$, $p = .991$) and reading ($\beta = -.002$, $p = .172$) did not (see Table 4B).

Discussion

Despite prior evidence for two unique timing systems responsible for sub- and supra-second timing, little is known about the developmental origins of these systems. Moreover, it is unclear whether temporal processing in the sub- and supra-second ranges may hold unique relations with separate aspects of academic achievement. The current study addressed these questions by assessing math, reading, and sub- and supra-second timing abilities in 6- to 8-year-olds. Our data suggest that (a) sub- and supra-second timing abilities dissociate over the course of middle childhood and (b) despite this developmental divergence, timing accuracy across these two ranges does not offer uniquely greater predictive power to academic success.

Developmental divergence of sub- and supra-second timing abilities

The first aim of our study was to investigate the developmental trajectory of each timing system. Our findings provide evidence of a developmental divergence between sub- and supra-second timing abilities. Younger children (6- and 7-year-olds) performed comparably on both duration ranges, whereas 8-year-olds, like adults, performed significantly better when discriminating durations in the supra-second range. In fact, younger children showed an opposite (although nonsignificant) pattern, such that sub-second timing was slightly more accurate than supra-second timing. Thus, although timing in the sub-second range and that in the supra-second range appear to have similar developmental origins, temporal precision in these distinct ranges follows a unique developmental trajectory, diverging at around 8 years of age.

Although our findings vary from previous reports (e.g., Droit-Volet, & Zélanti, 2013a, 2013b; Zélanti & Droit-Volet, 2011) in which it was found that subjective temporal judgments were comparable across duration ranges, our experimental design differed from this work in several significant ways. In the current study, participants were presented with a temporal discrimination task in which there was a single correct response, allowing us to assess accuracy in the two duration ranges. Past research investigating similar research questions, however, employed a bisection task in which participants were asked to determine whether a duration (e.g., 750 ms) was closer to one of two learned standard durations (e.g., short standard = 500 ms, long standard = 1000 ms). Although a bisection task can assess consistency in temporal responding as well as subjective estimates of time, it is impossible to ascertain a measure of timing accuracy. Moreover, in the current study, trials involving sub- and supra-second comparisons were intermixed within a single block, whereas past research separated the different comparisons into blocks. Participants in our study may have been more likely to employ a similar strategy for sub- and supra-second timing given that the sub- and supra-second trials were intermixed and likely hard to distinguish. Thus, these important differences in design may account for the different patterns of results.

Table 4B
Regression: Academic abilities predicting supra-second timing.

	B	*SE B*	β	*p* value
Model 1				
Age	0.034*	0.016	0.212	.043
Model 2				
Age	0.000	0.021	0.001	.991
Reading	−0.002	0.001	−0.168	.172
Math	0.003*	0.001	0.359	.017

Note. R^2 change = 0.060, $p = .057$.
* $p < .05$.

Although our data are consistent with the idea of the development of two distinct timing mechanisms, improved strategy use over development may also explain our pattern of results. That is, an alternative possibility is that as children get older, they may be more likely to employ better timing strategies (e.g., counting the seconds) for making accurate temporal judgments, particularly in the supra-second range. Previous work supports this hypothesis; the majority of adults use a counting strategy during timing tasks (Fraisse, 1963), and this strategy reduces variability in adults' temporal discriminations, particularly for longer durations (e.g., Grondin, Meilleur-Wells, & Lachance, 1999; Hinton & Rao, 2004). Moreover, work with children reveals that performance on a temporal discrimination task is enhanced when children are instructed to use a counting strategy (Clément & Droit-Volet, 2006; Levin & Wilkening, 1989; Wilkening, Levin, & Druyan, 1987). Thus, the older children and adults in our sample could have acquired symbolic timing strategies, which may account for the pattern of developmental divergence found.

Although it is possible that children employed counting strategies, we do not think that this is likely the case. Previous work indicates that 5- to 8-year-olds rarely spontaneously count during timing tasks (Wilkening et al., 1987) and, anecdotally, children did not seem to use counting strategies during the Time Discrimination task. Moreover, counting becomes an effective strategy only when durations are longer than 1000 ms (Grondin et al., 1999). As such, the use of a counting strategy could not account for our finding that older children demonstrated better performance for supra-second timing compared with sub-second timing for the smallest ratio tested (2:3; $p = .024$), which involved supra-second discriminations that differed by less than 1 s (e.g., 1500 ms vs. 2000 ms). In addition, intermixing sub- and supra-second trials throughout the Time Discrimination task would have required children to employ distinct strategies from trial to trial, which necessarily would have proved to be challenging. Thus, we believe that our findings are more consistent with the emergence of two distinct timing systems. Additional research, in which participants are explicitly told to not count during timing tasks (e.g., Rattat & Droit-Volet, 2012) and/or when participants are told to explicitly count, is needed to fully understand whether these data provide evidence for two unique timing systems or reflect enhanced strategy use over development.

Why might distinct timing systems emerge at around 8 years of age? In the United States, there is great emphasis on learning temporal units of measurement (e.g., telling time from analog and digital clocks, learning temporal units of measurement [i.e., how long a "second" and "minute" lasts]; National Governors Association Center for Best Practices & Council of Chief State School Officers, 2010) in first and second grades (6- and 7-year-olds). By the time children reach third grade (~8 years of age), many state standards require that children be able to tell time to the nearest minute. According to these guidelines, the 8-year-olds and adults in our study undoubtedly had more experience with temporal units of measurement than the 6- and 7-year-olds. Our results indicate that sub-second and supra-second timing may diverge during a critical period in children's formal education during which temporal symbols are taught. Future work exploring relations between children's symbolic and nonsymbolic representations of time is needed to directly assess how learning temporal symbols may mold our nonsymbolic timing abilities, addressing the question of whether symbolic learning may result in the developmental divergence between sub- and supra-second timing that we observe in middle childhood.

Relation to academic achievement

The second goal of our study was to determine whether sub- and supra-second timing may differentially relate to math and reading achievement. In line with previous work, our findings revealed that overall timing abilities—combined across both the sub- and supra-second range—significantly predicted math performance above and beyond age in childhood. Importantly, however, neither timing system contributed unique variance in the model. Given that the younger children in our sample did not differ in their performance on sub- and supra-second discrimination, it is possible that our age range was particularly well suited for revealing the divergence between sub- and supra-second timing but was not appropriate for testing the unique contributions of each timing system to formal math. That is, given that the majority of children in our sample (i.e., 6- and 7-year-olds) performed comparably on sub- and supra-second timing, this may have precluded the possibility of determining whether one system contributes more to mathematics performance. Alternatively, we believe that these findings also align with our initial hypothesis that the need to manipulate ordered magnitudes may be a key factor in the relation between timing (regardless of the duration range) and mathematics, at least at this point in development. Future studies should evaluate whether math abilities become more heavily tied to timing in one of these ranges when following the dissociation between sub- and supra-second timing in middle childhood. Regardless, our findings reveal that, at least at this point in development, neither timing system offers greater predictive power for math abilities while also bolstering previous claims of a strong link between timing and mathematics (Odic et al., 2016; Skagerlund & Träff, 2016).

In contrast to previous work, we did not find timing abilities in either the sub- or supra-second range to predict reading achievement. Although past research has linked sub-second timing and reading (see Farmer & Klein, 1995; Reed, 1989; Tallal, 1980), to our knowledge only one study has reported a relation between reading and supra-second timing (Plourde et al., 2017). Although the majority of previous studies have employed implicit timing tasks (e.g., temporal ordering; Hood & Conlon, 2004; see also Farmer & Klein, 1995), more recent studies have explored the link between timing and reading using explicit timing tasks (Casini et al., 2017; Plourde et al., 2017). The distinction in implicit and explicit timing tasks is particularly important given research suggesting that explicit timing, but not implicit timing, improves with age (Droit-Volet & Coull, 2016). In contrast to our current findings, studies that employed explicit timing tasks have found relations between timing and reading abilities (Casini et al., 2017; Plourde et al., 2017). However, importantly, these previous studies have purposely included children with lower reading abilities (i.e., children with dyslexia) and/or a wide range of reading skills in their samples. Our sample, on the other hand, performed at or above age-appropriate levels on our reading assessment. Thus, it is possible that the relationship between timing and reading holds for only those individuals with notably low reading achievement. Thus, our findings highlight the need to determine whether the relation between timing and reading abilities holds in children with reading disabilities.

Although we aimed to test a unique relation between academic achievement and timing abilities, research suggests that domain-general abilities (e.g., working memory, processing speed, executive functioning) also play an important role in the development of these skills (e.g., Droit-Volet, Wearden, Zelanti, 2015; Droit-Volet, & Zélanti, 2013a, 2013b; Zelanti & Droit-Volet, 2011). Although we did not test domain-general abilities in the current study, previous work suggests that timing abilities and math continue to correlate in childhood even when controlling for working memory abilities (Odic et al., 2016), thereby making it unlikely that domain-general skills account for the current findings. However, future work should continue to investigate the role of domain-general abilities in academic achievement, as well as timing abilities.

Conclusions

Given the pervasiveness of timing in our everyday lives, it is critical to understand how children develop basic timing abilities. Our study suggests that sub-second timing and supra-second timing have comparable developmental origins that diverge in middle childhood. Whereas previous developmental work has collapsed across these duration ranges, our work highlights the importance of considering each timing system even in childhood. Future work investigating which factors contribute to this developmental shift will be important in furthering our knowledge of children's developing timing abilities.

Our data also suggest that overall timing abilities contribute unique variance to math ability but not to reading ability. Although not assessed in the current work, these results may have important implications for understanding and treating developmental disorders, such as dyscalculia and dyslexia, in which timing and academic abilities both are impaired. Previous work has shown that musical instruction, which results in improved timing abilities, enhances reading performance in children with and without reading difficulties (e.g., Flaugnacco et al., 2015; Forgeard et al., 2008; Moreno et al., 2009; Rolka & Silverman, 2015). Given the link between timing and math in the current study, it is possible that musical training may result in similar improvements in math performance. This may be a particularly useful intervention for individuals with math learning disabilities who often experience comorbid timing deficits.

In conclusion, our study has uncovered a developmental dissociation in timing abilities while also pointing to a number of new directions for future research. What causes this dissociation at this point in development? Might each timing system offer unique predictive power to reading and math achievement later in development after sub- and supra-second timing diverge?

Acknowledgments

The authors thank Katherine Chandler, Kylie Gallo, Eliza Gross, Maddy Katz, Taylor Reader, and Carolyn Patterson for their assistance with data collection and coding.

Appendix A. Methods and results from achievement tasks with adult sample

Given methodological differences in the reading and math tasks presented to our child and adult samples, we chose to report the relations between timing and academic achievement in adulthood here.

Method

Design

Adults completed the following tasks in the following order: TOWRE assessment, Woodcock–Johnson Reading Fluency subtest, Time Discrimination task, and Arithmetic assessment.

Procedure

The procedure was consistent with the child protocol with the following exceptions. After completing the TOWRE reading assessment, adults also completed the Reading Fluency subtest of the Woodcock–Johnson III (Woodcock et al., 2001) as a secondary measure of reading ability. In this task, adults were presented with 98 short sentences, such as "A cow is an animal," and the participant was instructed to decide whether or not the statements were true (indicated by circling a "Y") or false (indicated by circling an "N"). Participants were given 3 min to read and assess as many statements as possible. The Time Discrimination task was completed following the Reading Fluency subtest. Following the Time Discrimination task, adults were given 3 min to complete as many two- and three-digit arithmetic (addition and subtraction) problems as quickly and accurately as possible. All arithmetic problems were presented on a computer screen. Adults were instructed not to use a calculator or cell phone to perform the calculations. Scratch paper was not provided, and participants were instructed to perform the calculations in their head.

Results

Data coding and analyses

Data coding was consistent with the child data except for the following.

Math performance

One participant did not complete the math task. Data from 1 participant was 3 standard deviations above the mean and was replaced with the next highest value within 3 standard deviations.

Test of word reading efficiency

One participant was excluded due to experimenter error. An additional 8 adults did not have a voice recording, and so their performance on the TOWRE was not included in the analyses.

Woodcock–Johnson reading fluency

The number of correctly assessed sentences served as the dependent variable for the Reading Fluency subtest.

Overall performance

Average performance on tasks is presented in Table A1, and correlations among tasks are presented in Table A2.

Relation to academic achievement

We performed three separate linear regressions: sub- and supra-second timing as predictors of (a) reading performance (TOWRE), (b) Reading performance (Reading Fluency), and (c) math performance. None of the regressions reached significance [TOWRE: $F(2, 60) = 0.506$, $p = .605$; Reading Fluency: $F(2, 68) = 1.730$, $p = .185$; math: $F(2, 68) = 0.291$, $p = .749$]. Next, we performed linear regressions with academic abilities (TOWRE, Reading Fluency, and math) as predictors of sub- and supra-second timing separately. Neither regression reached significance [sub-second: $F(3, 58) = 0.815$, $p = .491$;

Table A1
Average adult performance on all tasks.

TOWRE	Reading fluency	Overall timing (%)	Sub-second timing (%)	Supra-second timing (%)	Arithmetic
M = 103.70 (11.04)	*M* = 89.15 (10.92)	*M* = 85.71 (6.5)	*M* = 84.47 (7.46)	*M* = 86.95 (7.31)	*M* = 17.77 (7.22)

Note. Standard deviations are in parentheses.

Table A2
Correlations among tasks in the adult sample.

	1	2	3	4	5	6
1. Reading (TOWRE)						
2. Reading (Reading Fluency)	0.169					
3. Arithmetic	0.253*	0.157				
4. Sub-second timing	0.119	0.190	−0.05			
5. Supra-second timing	0.021	0.013	0.037	0.550**		
6. Overall timing	0.081	0.117	−0.008	0.883**	0.878**	

* $p < .05$.
** $p < .01$.

supra-second: $F(3, 58) = 0.073$, $p = .974$]. Lastly, we reran all of these analyses including all four age groups (with all measures converted to z scores), and none of the models was significant ($ps > .20$).

Discussion

Overall, our adult sample did not reveal relations between timing abilities and academic achievement. In line with our child data, timing abilities did not predict reading abilities in adulthood. However, unlike our findings in childhood, timing abilities were also unrelated to math abilities. Given that the math task consisted of performing arithmetic, it is possible that adults relied on memory strategies as opposed to actual calculation. Thus, a relation between timing and math may be more likely if the math task required more complex math concepts instead of facts that can be retrieved by memory. Moreover, given that previous findings have found timing and math to be correlated only in childhood, it is also possible that the relation between timing and math exists only when children are still in the process of learning the basics of mathematics. Consistent with this possibility is evidence demonstrating that the relation between nonsymbolic *number* discriminations and math are stronger in childhood than in adulthood (see Inglis, Attridge, Batchelor, & Gilmore, 2011).

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