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Learning About Time: Knowledge of Formal Timing Symbols Is Related to Individual Differences in Temporal Precision

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Throughout the life span, we are capable of representing quantities in the absence of language, or nonsymbolically. Additionally, over the course of development, we learn many symbolic measurement systems for representing quantities such as time and number. Despite substantial evidence of a relation between the acquisition of symbolic and nonsymbolic numerical acuity (see Halberda, Mazzocco, & Feigenson, 2008), no work has explored whether a similar relation exists between understanding temporal units of measurement and timing precision. That is, does a child's understanding of words like "second," "minute," and "hour" have any relation to their ability to tell which of two events lasted longer? Six- and 7-year-old children ($n = 102$, $M_{age} = 83.44$ months, 52 females), who are in the process of learning temporal units of measurement, completed a temporal discrimination task (assessing nonsymbolic temporal acuity) and a symbolic timing assessment. Results revealed a positive correlation between children's nonsymbolic temporal acuity and their understanding of temporal units of measurement. Importantly, this correlation held when controlling for age and numerical acuity, suggesting a unique relation between children's temporal acuity and their understanding of temporal units of measurement. This study is the first to show a relation between symbolic and nonsymbolic representations of time.

Keywords: time discrimination, duration, nonsymbolic timing, symbolic representation, temporal measurement

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Over development, children learn various measurement systems (i.e., symbol systems) to represent abstract quantity concepts (i.e., number, time, space, etc.). While these symbols (e.g., Arabic numerals for number, units of measurement for time, etc.) allow for the exact measurement of quantity, it is unknown whether an understanding of these systems may be related to our ability to perceive and/or discriminate these quantities in the absence of symbols (often referred to as nonsymbolic representations of quantity). Despite a plethora of research demonstrating a link between nonsymbolic numerical acuity and symbolic representations of number (i.e., verbal counting, mathematics achievement; Bonny & Lourenco, 2015; Chen & Li, 2014; Halberda et al., 2008; Libertus, Feigenson, & Halberda, 2011; Mazzocco, Feigenson, & Halberda, 2011a, 2011b; Schneider et al., 2017), it is unknown whether a similar relation holds for other quantities such as time. In the current study, we tested the relation between nonsymbolic and symbolic representations of time in 6–7-year olds, children who are in the process of learning temporal units of measurement in school.

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The current study is important for several reasons. First, while age-related increases in temporal precision are well-documented (see Brannon, Suanda, & Libertus, 2007; Droit-Volet, 2013; Odic, 2018), the source of these changes is unknown. One possibility is that brain maturation and/or other general cognitive abilities may contribute to more precise quantity tracking (e.g., Lipton & Spelke, 2003). However, it has also been suggested that the acquisition of quantity symbols may play a role in altering the precision with which quantities are tracked nonsymbolically (e.g., Pica, Lemer, Izard, & Dehaene, 2004; Posid & Cordes, 2015; Shusterman, Slusser, Halberda, & Odic, 2016). While the current investigation is correlational and thus cannot speak to the question of causality (i.e., whether nonsymbolic timing abilities form the foundation for learning about symbolic representations of time, or alternatively, whether learning about temporal symbols may shape our nonsymbolic timing abilities), this study sets the stage by providing the first data to establish the existence of such a relation. Second, although a relation between symbolic and nonsymbolic numerical abilities has been established, it is important to note that both numerical symbols and nonsymbolic representations of number are discrete in nature, which may facilitate this relation. If structural isomorphisms underlie this link, it may be more difficult to find a similar association between temporal acuity and an understanding of discretized temporal units of measurement (e.g., an understanding of seconds, minutes, etc.), as nonsymbolic representations of time are inherently continuous. Lastly, recent work identifying links between timing abilities and formal mathematics (Hamamouche & Cordes, 2019; Kramer, Bressan, & Grassi, 2011; Odic et al., 2016; Skagerlund & Träff, 2016) further emphasizes the importance of understanding children's developing temporal abilities. Thus, understanding if a relation exists between symbolic and nonsymbolic timing may provide hints at the source of age-related increases in timing precision, shed light on the mechanisms underlying the relation between numerical acuity and verbal counting, and also inform our understanding of temporal development in childhood.

Types of Temporal Representations

Nonsymbolic Temporal Processing

Throughout the life span, humans and nonhuman animals are capable of representing time in the absence of language (e.g., Brannon et al., 2007; Droit-Volet, 2013; Droit-Volet & Wearden, 2001; Meck & Church, 1983; Platt & Davis, 1983; Provasi, Rattat, & Droit-Volet, 2011; vanMarle & Wynn, 2006). This ability, referred to as our *nonsymbolic* representations of time, is considered the most basic and intuitive form of quantity representation. Critically, nonsymbolic representations of time do not rely on linguistic or symbolic information. These representations are often measured using discrimination tasks, in which participants are asked to determine which of two durations was longer.

Substantial work has characterized our nonsymbolic timing abilities. Like other quantities, nonsymbolic representations of time adhere to Weber's Law (Gibbon, 1977; Hamamouche & Cordes, 2019), such that the speed and accuracy with which discriminations are made is dependent upon the ratio between the two durations, rather than their absolute difference (Stevens, 1957). For example, the ease with which 1 second is discriminated from 2 seconds is comparable to that with which 5 seconds is discriminated from 10 seconds because both comparisons involve a twofold ratio change. Moreover, our ability to make these discriminations becomes more precise with age (e.g., Droit-Volet, Clément, & Fayol, 2008; Odic, 2018; Odic, Libertus, Feigenson, & Halberda, 2013). Six-month-old infants reliably detect a twofold change in duration of two stimuli, but fail to detect a 1.5-fold change. Within a few months, however, their timing abilities improve such that 10-month-old infants can detect a 1.5-fold change (Brannon et al., 2007; Feigenson, 2007; vanMarle & Wynn, 2006). The precision with which we discriminate time continues to improve throughout childhood, such that the ratio that can be discriminated approaches one with age (see Odic, 2018).

Although it is clear that quantity discriminations become more precise throughout development, the source of developmental change is unclear. Maturation of neural mechanisms subserving these quantity representations (e.g., Lipton & Spelke, 2003) and/or burgeoning linguistic capacities, specifically pertaining to the domain of relevance (e.g., learning temporal units of measurement; Posid & Cordes, 2015; Shusterman et al., 2016), have both been suggested as potential sources of increased precision, at least in the domain of number. In this study, we explore the possibility that the acquisition of temporal units of measurement may be related to increased precision in temporal acuity over the course of development (see Piazza, Pica, Izard, Spelke, & Dehaene, 2013).

Symbolic Representations of Time

Although nonsymbolic representations of time have been extensively explored, few studies have assessed children's symbolic understanding of time (i.e., understanding of temporal units of measurement). Just as temporal acuity increases over development, an understanding of temporal units of measurement also increases, but through learning. For example, children's use of temporal vocabulary (e.g., words such as "seconds," "minutes," etc.) increases particularly during the early elementary years (e.g., Ames, 1946; Bradley, 1947; Harrison, 1934; Oakden & Sturt, 1922; Tillman & Barner, 2015). However, despite using temporal vocabulary early on, children often lack a full understanding of the words' meanings (Ames, 1946; Shatz, Tare, Nguyen, & Young, 2010). For example, children as young as four years old are able to successfully order durations associated with these words (e.g., a minute is less than an hour) without knowing the approximate duration associated with each temporal word (Tillman & Barner, 2015; see also Friedman, 1977). In addition to understanding temporal vocabulary, children also learn to use clocks and stopwatches to track time during early childhood. Much like understanding the meaning of temporal words, this process takes several years to master (Friedman & Laycock, 1989).

It is unknown whether a relation exists between temporal acuity and an understanding of temporal units of measurement; however, one study hints at the likelihood of this relation. Arlin (1990) asked children whether clocks move faster, slower, or do not change speed while they sleep—an indicator of children's symbolic understanding of time. Then, children watched as two puppets danced for the same amount of time (15 seconds), but at different speeds (140 beats per minute vs. 40 beats per minute) and were asked whether one puppet danced longer than the other or if the puppets danced for the same amount of time (a proxy for nonsymbolic timing). Results revealed that children who understood that the clock maintains its speed at night were more likely to say that the puppets danced for the same amount of time, suggesting that a relation may exist between symbolic and nonsymbolic timing (Arlin, 1990). While these data point to a possible relation between representations of time, the tasks used were not pure measures of nonsymbolic and symbolic timing. Thus, the current study is the first to characterize this relation by using a standard nonsymbolic temporal discrimination task and a broader assessment of children's symbolic timing abilities.

Relations Between Symbolic and Non-Symbolic Quantity Representations

While the relation between symbolic and nonsymbolic timing has been left untested, numerous studies have reported a link between symbolic and nonsymbolic numerical acuity (e.g., Chen & Li, 2014; Schneider et al., 2017). Numerical discriminations in early infancy have been found to predict performance on standardized math assessments several years later (Starr, Libertus, & Brannon, 2013), and preschoolers' approximate sense of number predicts their math abilities at age 6 (Halberda et al., 2008). This relation holds even in adulthood (e.g., Libertus, Odic, & Halberda, 2012), although less consistently so (Gilmore, McCarthy, & Spelke, 2010; Inglis, Attridge, Batchelor, & Gilmore, 2011; Skagerlund & Träff, 2016).

Importantly, while a well-documented relation exists between symbolic and nonsymbolic numerical abilities (e.g., Bonny & Lourenco, 2015; Halberda et al., 2008; Starr et al., 2013; for a review, see Feigenson, Libertus, & Halberda, 2013), it is unclear

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whether this relation is specific to number, or if it holds for other quantities. Thus, in the present study, we investigate whether a relation exists between nonsymbolic and symbolic timing. That is, does the acquisition of formal measurement terms in the timing domain (such as learning how long a "second" or a "minute" lasts; hereafter referred to as "temporal units of measurement") relate to our ability to perceive the duration of a stimulus? Unique to number, both symbolic and nonsymbolic representations of number are discrete in nature, such that structural similarities may support the link between the two. Such structural isomorphisms fail to hold for nondiscrete quantities, such as time, making the existence of a relation between the two less straightforward. Despite this, recent work suggests that this relation holds in the domain of space (Lauer & Lourenco, 2016; Lourenco & Bonny, 2017). For example, Lourenco and Bonny (2017) found children's ability to discriminate cumulative surface area to be related to a formal understanding of geometry. Importantly, nonsymbolic representations of space are continuous, whereas spatial units of measurement are discrete. Moreover, there is evidence that children are not only able to map between continuous and discrete magnitudes (see Babai, Nattiv, & Stavy, 2016), but they are also capable of employing strategies used to compare continuous magnitudes to situations in which magnitudes are discretized (Boyer & Levine, 2015). Given these findings, we predict a relation between nonsymbolic and symbolic timing.

Additionally, many similarities among temporal, spatial, and numerical processing (see Walsh, 2003) also lend support for our hypothesis that children's nonsymbolic and symbolic timing abilities are correlated. For instance, numerical, spatial, and temporal discriminations adhere to Weber's Law (e.g., Brannon, Lutz, & Cordes, 2006; Izard, Sann, Spelke, & Streri, 2009; Provasi et al., 2011), and precision in these domains increases over development (Odic, 2018). Moreover, the precision of temporal, numerical, and spatial discriminations follow comparable developmental trajectories in infancy (for a review, see Feigenson, 2007). In addition, temporal, numerical, and spatial acuity predict math achievement (see Lourenco, Bonny, Fernandez, & Rao, 2012; Odic et al., 2016). These similarities and others have led many to contend that a single common magnitude system is responsible for processing quantities (Cantlon, Platt, & Brannon, 2009; Walsh, 2003). That is, it has been posited that it is no coincidence that temporal, numerical, and spatial processing show similar behavioral signatures because all three quantitative magnitudes are thought to be represented via a common neural locus and neural code. Thus, those in favor of the common magnitude system would also predict a relation between nonsymbolic and symbolic timing given (1) the similarities among numerical, spatial, and temporal processing and (2) the presence of relations between nonsymbolic and symbolic in other quantitative domains.

Even in the absence of a common magnitude system wherein each magnitude relies upon a unique system (see Hamamouche & Cordes, 2019; Odic, 2018), one might still find reason to predict a relation between nonsymbolic and symbolic timing. For one, individuals who have a greater symbolic understanding of time may be better able to encode time. Moreover, people with a greater understanding of temporal units of measurement may employ more efficient strategies when timing, again leading to enhanced nonsymbolic timing abilities. Thus, regardless of the system(s) responsible for quantity processing, we predict a relation between nonsymbolic and symbolic timing in children.

While we predict a relation between nonsymbolic and symbolic timing, what if the relation does not exist? Such a finding would be surprising, as it would suggest that our acquisition of symbolic time is entirely unrelated to our timing abilities. This lack of relation would point to a striking dissociation between symbolic and nonsymbolic timing abilities, while possibly leading some to question current theories of numerical development. Moreover, a lack of relation would also hint at differences in temporal and numerical processing.

The Current Study

In the current study, we investigated whether a relation exists between nonsymbolic and symbolic timing abilities in 6–7-year-old children. Because people tend to master temporal symbols by adulthood, we purposely explored this relation in a population likely to show maximal variability in temporal symbol understanding—children who are in the process of learning temporal symbols in school. Children completed a nonsymbolic timing task (Temporal Discrimination) and two assessments of symbolic timing (Temporal Units of Measurement Questionnaire and a Temporal Estimation task).

Method

Participants

One hundred and two 6–7-year-olds (M_{age} = 83.44 months, 52 females) participated. An additional 7 children completed only a single task in its entirety and were not included in the analyses. This age range was chosen to focus on a period of development during which children begin acquiring formal units of measurement for time in the classroom (National Governors Association Center for Best Practices, 2010). In particular, according to the Common Core standards, first graders are learning how to tell time to the nearest hour and half hour. By second grade, students should be able to recognize the relations between different temporal units of measurement (e.g., a minute is longer than a second). As such, this age range was chosen so as to maximize variability in symbolic understanding across our sample.

Children from the greater Boston area were recruited at afterschool programs (n = 7), local museums or parks (n = 54), or during a short visit to the lab (n = 41). The battery of tasks took approximately 15 min to complete. Required sample size was based on a priori calculations in G*Power (Faul, Erdfelder, Buchner, & Lang, 2009) requiring 0.80 power for detecting a medium effect size on central analyses. All methods were approved by the Boston College IRB.

Procedure

After parental consent was obtained, the experimenter gave parents a Parent Timing Questionnaire (modeled after LeFevre et al., 2009). Like LeFevre et al. (2009), we included questions about the frequency of using calendars and dates (separated into two questions as opposed to a single question in LeFevre et al., 2009), and wearing a watch. We also added new questions that related to reading digital and analog clocks, discussing time, and using a timer.[1] Because responses to this questionnaire were not correlated with any of the child timing measures, we concluded that it was not an accurate depiction of the children's timing abilities and thus excluded it from the main analyses.

Children were tested in a quiet testing space. Children completed the following tasks in a single session in a set order: (1) Temporal Discrimination Task (assessment of nonsymbolic timing abilities), (2) Temporal Units of Measurement Questionnaire (assessment of symbolic timing abilities), (3) Temporal Estimation Task (assessment of symbolic timing abilities), and (4) Numerical Discrimination Task (assessment of nonsymbolic numerical abilities).

Temporal Discrimination Task (Modeled after Hamamouche & Cordes, 2019)

The Temporal Discrimination Task served as an assessment of the children's nonsymbolic temporal acuity. Children saw a cartoon chicken and cow presented side-by-side on the computer screen. Children were told that the chicken and cow were going to take turns playing musical instruments for a certain amount of time and their task was to decide which animal played their instrument longer. On every trial, the chicken (always located on the left) played its trumpet first, followed by a 1500 ms interstimulus interval, and then the cow (always located on the right) played its trumpet. When each animal played their trumpet, children heard a sound accompanied by the presence of a box around the relevant animal (both a visual and auditory cue). The trumpet of each animal made a unique sound, such that the chicken's trumpet always sounded like a horn and the cow's trumpet sounded like a train. Children indicated which animal played the trumpet longer by pointing, and the experimenter recorded the response by pressing specified keys on a keyboard.

Children completed eight practice trials, during which they were encouraged to ask the experimenter questions. The practice trials were identical to the test trials except that the ratio between the two durations presented was 3.2. In order to ensure that children could clearly hear the stimuli, after completing the practice trials, the experimenter asked all children to put headphones on for the remainder of the task. Although the experimenter could not hear the sound of the discrimination stimuli, (s)he could still see the box appearing around each character, and thus the experimenter was not naïve to the stimuli.

During test, the durations of the stimuli ranged from 200 ms to 4000 ms. The pairs of durations presented on every trial differed by one of four ratios: 1.25, 1.5, 2, 2.25 (modeled after Hamamouche & Cordes, 2019; Odic et al., 2016). The cow played the instrument longer on exactly half of all trials. In test, children completed 32 trials: 4 ratios (1.25, 1.5, 2, 2.25) × 8 times each, with all manipulations intermixed in the same block of trials.[2] All stimuli were presented and data were recorded using a Xojo program on a Mac laptop.

Temporal Units of Measurement Questionnaire (Modeled after Oakden & Sturt, 1922; Tillman & Barner, 2015)

This was a measure of children's temporal symbol understanding. An experimenter read children 13 questions relating to how long it takes to do everyday activities (e.g., "How long does it take you to brush your teeth?"), reading analog and digital clocks, and identifying which duration is longer (e.g., "Which is longer a minute or a second?"). The experimenter read each question to the child and recorded their responses using pen and paper. The measure showed strong internal consistency, $\alpha = .861$. See the Appendix.

Temporal Estimation Task (Modeled after Bueti, Walsh, Frith, & Rees, 2008)

This task served as a second assessment of children's symbolic timing abilities. On a laptop using a Xojo program, children were asked to hold the left arrow key on a keyboard for a set amount of time (5, 9, 14 seconds; order counterbalanced). On each trial, the experimenter prompted the child by saying, "Hold down this key [pointing to the left arrow key] for [5, 9, or 14] seconds." The experimenter did not suggest strategies to the child; however, if the child began using a strategy such as counting, they were not stopped.

Numerical Discrimination: Panamath (Halberda et al., 2008)

The Numerical Discrimination Task was added to the battery of tasks halfway through data collection, thus only a subset of children ($n = 59$) completed the task. We included this to assess whether discrimination performance in general, or temporal discrimination in particular, was related to an understanding of temporal units of measurement. During the numerical discrimination task, children saw two separate, but simultaneously presented, dot arrays containing either blue or yellow dots on the computer screen and were asked which color contained more dots. Children completed 88 trials in which dot arrays ranged from 5 to 21 dots. All dot arrays were displayed for 1951 ms, and the two arrays differed by one of the following ratios: 1.28, 1.47, 1.75, 2.75. In half of the trials, the cumulative area of each dot array was equated, such that the larger dot array contained smaller individual dots on average. In the other half of the trials, the dots in both arrays were the same size on average. As such, the larger numerosity also contained a larger surface area. Children stated their answer out loud and the experimenter recorded their responses by pressing corresponding keys on the keyboard.

After completing all tasks, children and their parents were debriefed, and children picked out a prize for participation.

Data Coding and Analyses

Temporal Units of Measurement Questionnaire. Accuracy (percent correct) was the dependent variable for the Temporal

[1] In our sample, we found higher rates of using calendars and dates ($M = 3.79$, $SD = 1.23$ compared to LeFevre et al., 2009, $M = 3.0$, $SD = 1.1$, $t(244) = 5.27$, $p < .001$), and wearing watches ($M = 1.7$, $SD = 1.18$ versus LeFevre et al., 2009, $M = 1.2$, $SD = 1.4$, $t(244) = 2.93$, $p < .01$), likely due to differences in the age range our samples.

[2] A programming error led 19 participants to only receive 6 iterations of a 2-fold ratio change (and 2 iterations of a 1.75 change) on the time discrimination task. While these trials were included in analyses involving overall time discrimination performance, these trials were excluded in analyses concerning ratio effects.

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Units of Measurement Questionnaire. Responses indicating uncertainty (i.e., "I don't know," "I haven't learned that yet") were counted as incorrect. One child did not complete the Temporal Units of Measurement Questionnaire.

Temporal discrimination. Percent correct was the dependent variable for the Temporal Discrimination Task. One child's score was three standard deviations below the mean, and thus was excluded from the analyses. The data from one child were not saved due to a computer error, and one child showed a side bias by always choosing one of the characters, and thus, these children's responses were not included in the analyses.

Temporal estimation. Absolute average error was calculated and used as the dependent variable for the Temporal Estimation Task. Error was calculated by taking the absolute value of the difference between the child's response to each duration and the actual duration to be estimated. This value was then divided by the duration to be estimated. Then, the average error across the three trials was calculated. Two participants did not understand the task and thus were excluded from the analyses. The average error from two participants was more than three standard deviations above the mean, and these participant's data were excluded from analyses involving temporal estimation. Four children did not complete this task (time constraints, wanting to discontinue participation, etc.).

Numerical discrimination. Percent correct was the dependent variable for the Numerical Discrimination Task. Two children had overall scores more than three standard deviations below the mean, and thus their performance was excluded. After implementing the task, 11 children ($n = 7$ due to time constraints, $n = 4$ program error) did not complete the Numerical Discrimination Task, and thus their scores were not included. One additional child was excluded due to parental interference during the numerical discrimination task.

Results

See Table 1 for average performance on each task. Children performed above chance on the Temporal Discrimination, $t(98) = 23.84$, $p < .001$, $N = 99$, and the Numerical Discrimination, $t(44) = 32.78$, $p < .001$, $N = 45$. Table 2 shows the correlations between tasks.

Ratio Effects for Temporal and Numerical Discrimination

Previous research has reported ratio effects in temporal and numerical discriminations, such that larger ratios are easier to discriminate (indicative of Weber's Law; see Gibbon, 1977; vanMarle & Wynn, 2006). To test for ratio effects in our temporal data, we conducted a repeated measures ANOVA on performance on trials for each of the four ratios in our Temporal Discrimination Task. There was a significant effect of Ratio, $F(3, 294) = 44.47$, $p < .001$, $\eta_p^2 = .312$, $N = 99$, such that performance was worse on smaller ratios compared to larger ratios (ps $< .001$, except for the comparison between the two easiest ratios, $p = 1.0$; see Figure 1a). A comparable repeated measures ANOVA testing for ratio effects in our numerical discrimination data also revealed a main effect of Ratio, $F(3, 132)$, $= 33.49$, $p < .001$, $\eta_p^2 = .432$, $N = 45$, indicating better performance on trials consisting of a larger ratio (all ps $< .01$, except for the comparison between the two middle ratios, $p = .08$; see Figure 1b).

Table 1
Mean Performance (Standard Deviation in Parentheses) on Each Task

Temporal Discrimination	Temporal Units of Measurement Questionnaire	Temporal Estimation Proportion Error	Numerical Discrimination
79.48% (12.31) $N = 99$	76.00% (18.22) $N = 101$	.54 (.27) $N = 94$	91.74% (8.54) $N = 45$

Temporal Estimation Performance

Children's estimates increased with increasing duration on the Temporal Estimation Task ($F(2, 186) = 27.36$, $p < .001$, $\eta_p^2 = .227$, $N = 94$; all ps $< .01$). Despite this, the amount of error was comparable regardless of the duration children were asked to produce ($F(2, 186) = 1.94$, $p = .15$, $\eta_p^2 = .020$).

The Relation Between Non-Symbolic and Symbolic Timing in Childhood

Performance on our two measures of children's symbolic timing understanding, the Temporal Estimation Task and the Temporal Units of Measurement Questionnaire, were correlated, $r = -.376$, $p < .001$, $N = 94$. As such, we calculated a composite symbolic timing score by averaging children's performance on the Temporal Units of Measurement Questionnaire and the Temporal Estimation Task to be used for all analyses. Because a higher score on the Temporal Units of Measurement Questionnaire was indicative of better performance, but a higher error score on the Temporal Estimation Task was indicative of lower performance, we calculated a z-score for each task separately, and then multiplied the Temporal Estimation z-score by −1. Finally, we averaged the two z-scores into a single composite symbolic timing score. Five participants only had one of the symbolic timing measures, and thus were not included in the analyses involving the composite symbolic timing score. All analyses remain consistent when considering only one of the symbolic timing measures, except where indicated.

Previous work has shown that both nonsymbolic and symbolic abilities improve with age (Brannon et al., 2007; Tillman & Barner, 2015; vanMarle & Wynn, 2006). To test this, we conducted separate correlations between Age (in months) and performance on the Temporal Discrimination Task, and Age and performance on the Numerical Discrimination Task. We also conducted a comparable correlation with Age and our Composite Symbolic Timing Score. While Age was correlated with Symbolic Timing ability, $r = .390$, $p < .001$, $N = 94$, it was not correlated with Nonsymbolic Timing Abilities,[3] $r = .045$, $p = .657$, $N = 99$, or Nonsymbolic Numerical Abilities, $r = .277$, $p = .066$, $N = 45$.

Given prior work demonstrating a relation between numerical acuity and symbolic math (e.g., Halberda et al., 2008; Starr et al.,

[3] Based on other work suggesting a distinction in performance on sub- and supra-second timing emerges in childhood (Hamamouche & Cordes, 2019), we explored whether discrimination performance differed between sub and supra second ranges in our study; however, they did not, $p > .26$, $N = 100$.

Table 2
Correlations Between Performance on Tasks (Below Diagonal), Controlling for Age (Above Diagonal)

Task	1	2	3	4
1. Temporal Discrimination		.499** $N = 98$	−.260* $N = 92$	.321* $N = 42$
2. Temporal Units of Measurement Questionnaire	.469** $N = 98$		−.319** $N = 97$	.410** $N = 45$
3. Temporal Estimation	−.265* $N = 92$	−.376** $N = 94$		−.070 $N = 44$
4. Numerical Discrimination	.285 $N = 42$	.450** $N = 45$	−.124 $N = 45$	

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

2013), it was predicted that children with a greater symbolic understanding of time would also have more precise nonsymbolic representations of time. Specific to this hypothesis, we conducted a correlation between children's Symbolic and Nonsymbolic timing abilities. The correlation was significant, $r = .450$, $p < .001$, $N = 92$, suggesting that greater temporal precision is related to a stronger understanding of temporal symbols. We next conducted a partial correlation controlling for Age (in months) to test the relation between Symbolic and Nonsymbolic timing in childhood independent of age-related changes. Importantly, the correlation remained significant, $r = .464$, $p < .001$, $N = 92$, suggesting that this relation holds above and beyond age-related changes.[4] See Figure 2.

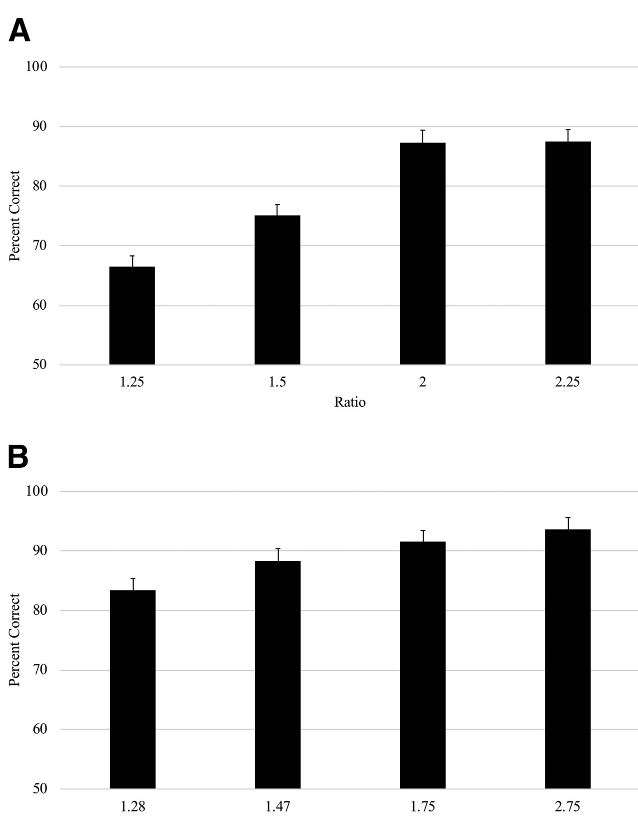

Figure 1. a. Performance on the Temporal Discrimination Task by ratio ($n = 99$). Error bars represent standard error. b. Performance on the Numerical Discrimination Task by ratio ($n = 45$). Error bars represent standard error.

To assess whether symbolic timing abilities predict nonsymbolic timing precision, even when controlling for differences in developmental maturity (i.e., age) and basic discrimination capacities, we conducted a hierarchical regression. In the first step, we entered Age and Numerical Discrimination as a predictor of Nonsymbolic timing. Although the model did not reach significance, $F(2, 39) = 2.670$, $p = .082$, Numerical Discrimination (B = .006 $p = .041$), but not Age (B = −.004, $p = .195$) predicted Nonsymbolic timing. Adding Symbolic Timing into the second step added additional variance (R^2 change = .140, $p = .011$), allowing the model to reach significance, $F(3, 38) = 4.476$, $p = .009$. Symbolic timing (B = .060, $p = .011$) significantly predicted Nonsymbolic timing, while Age (B = −.005, $p = .065$) and Numerical Discrimination (B = .005, $p = .070$) marginally predicted Nonsymbolic timing.[5] See Table 3. Thus, even when controlling for Age and for performance on a task with comparable demands in the domain of number, nonsymbolic timing was uniquely related to an understanding of temporal units of measurement.

Discussion

While the field of mathematical cognition has been immersed with investigations into the relation between symbolic and nonsymbolic number and, to a lesser degree, space as well (Gilmore et al. 2010; Halberda et al., 2008; Lauer & Lourenco, 2016; Libertus et al., 2011; Lourenco & Bonny, 2017; Mazzocco et al., 2011b; Starr et al., 2013), no work has explored this relation in the domain of time. Our study is the first to report a relation between symbolic and nonsymbolic timing abilities in children. As predicted, we found that nonsymbolic temporal acuity, as assessed by a temporal discrimination task, was significantly correlated with an understanding of temporal units of measurement in childhood. Importantly, these findings held even when controlling for age, revealing

[4] This correlation remains significant when controlling for pairwise comparisons.

[5] Adding performance on the Temporal Estimation Task alone did not contribute additional variance (R^2 change = .033, $p = .230$) to the model, and both models remined non-significant, ps > .05.

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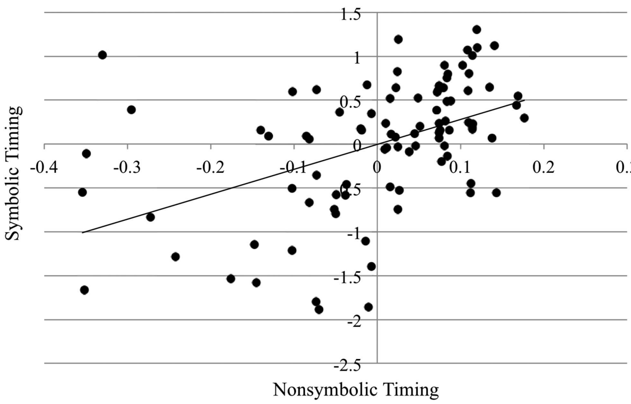

Figure 2. A strong positive relation exists between nonsymbolic timing abilities and symbolic timing abilities when controlling for age.

that these relations could not be accounted for by maturational changes that are expected to occur over the course of development. While investigations in numerical cognition have found this relation across a wide age span, we chose to test only 6–7-year-olds as this is the age at which temporal units of measurement are taught in the classroom and thus the point at which the greatest changes in symbolic knowledge occur. Future work testing the consistency of this relation across a larger age range may be important for further characterizing this link. While one might expect this relation to exist in adults, a growing body of evidence has questioned the presence of a relation between adults' symbolic and nonsymbolic representations of number (e.g., Gilmore et al., 2010; Inglis et al., 2011; Skagerlund & Träff, 2016). Moreover, adults are likely to adapt timing strategies, such as counting, that may not rely upon nonsymbolic representations of time, making it less likely this relation might hold in adulthood.

Our analyses also revealed that the relation between symbolic and nonsymbolic timing abilities held strong in a subset of participants even when controlling for numerical discrimination abilities and age, indicating that the link between symbolic and nonsymbolic timing abilities is not dependent on basic maturation and/or more domain-general task demands (i.e., decision-making, perceptual acuity, and/or working memory demands). Although previous work has linked domain-general abilities like information processing speed and working memory to explicit timing performance (Droit-Volet & Zélanti, 2013a, 2013b; Zélanti & Droit-Volet, 2011), our analyses suggest that these domain general abilities—likely implicated in performance in both the numerical and temporal discrimination tasks—are not the source of the link between nonsymbolic and symbolic timing abilities in our dataset.

While we believe our temporal discrimination task tapped into children's nonsymbolic timing abilities, it is also possible that children may have made their responses reliant upon some other quantitative dimension, such as the cumulative intensity of the stimuli. Although this remains a possibility, we do not believe this to be the case. While we predicted a relation between nonsymbolic and symbolic timing, there would be little reason to expect a relation between nonsymbolic cumulative intensity and symbolic timing. Thus, the strong correlation found between nonsymbolic and symbolic timing in the present study suggests that the temporal discrimination task is indeed tapping into children's timing abilities. Moreover, performance on our temporal discrimination task mimicked that of other studies investigating nonsymbolic timing using empty intervals, in which the duration to be timed is denoted by two brief tones at the beginning and end of the interval, in which cumulative intensity would not be an available cue (Grondin, 1993). To fully investigate this possibility, future work should ask children to discriminate between two empty intervals.

Although we found a significant relation between nonsymbolic and symbolic timing abilities, our data cannot speak to whether this relation is causal or not, and if so, in which direction. One possibility is that learning symbolic temporal units of measurement may give children a more accurate understanding of the timing process. In this instance, after learning temporal symbols, children may be better able to encode durations and/or have heightened attention toward stimulus durations, leading to a more advanced ability to track time. Hints of a causal relation of this nature in the domain of number is supported by the work of Shusterman et al. (2016), in which it was found that young children learning to count demonstrate dramatic increases in nonsymbolic numerical acuity as soon as they master the basic counting principles. Similarly, Piazza et al. (2013) found adults in the Mundurucu tribes of Brazil with zero years of formal schooling to have significantly less precise numerical acuity than individuals with one or more years of schooling, suggesting that formal education shapes nonsymbolic numerical abilities. However, whether the acquisition of timing symbols similarly leads to improvements in nonsymbolic timing abilities is an open question.

If it is the case that nonsymbolic timing is shaped by the acquisition of temporal symbols, what is the source of the improvement in timing? The acquisition of symbols may make temporal durations more salient and relevant to children, leading to heightened attention and temporal acuity. Alternatively, learning a system of measurement may provide children with strategies for tracking time, such as counting seconds. Although anecdotally, none of the children in our study overtly counted and the durations included in our temporal discrimination task were too short to make counting a less effective strategy, this possibility should be explored in future research.

Alternatively, the link between symbolic and nonsymbolic timing abilities may hint at the possibility that children with greater nonsymbolic temporal precision may have a better foundation upon which to learn temporal units of measurement. That is, it may be easier for children to learn temporal units of measurement when they already have a precise ability to track time and discriminate

Table 3
Hierarchical Regression Showing the Unique Relationship Between Symbolic and Nonsymbolic Timing

Model	*B*	*SE B*	β	*p*-value
Step 1				
Age	−.004	.003	−.202	.195
Numerical Discrimination	.006	.003	.324	.041
Step 2				
Age	−.005	.003	−.275	.065
Numerical Discrimination	.005	.003	.267	.070
Symbolic Timing	.060	.022	.387	.011

Note. Only the second model was significant, $p = .009$. The R^2 change for Model 2 (.140, $p = .011$) reached significance.

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between durations. Again, evidence in the domain of number has suggested that nonsymbolic numerical abilities may form the foundation for the acquisition of numerical symbols. For example, nonsymbolic numerical discrimination abilities in infancy predict formal math achievement years later in preschool (Starr et al., 2013). Similarly, there is some evidence to suggest that training of nonsymbolic numerical abilities may even lead to improved math achievement in childhood (Hyde, Khanum, & Spelke, 2014; Park & Brannon, 2016; Wang, Odic, Halberda, & Feigenson, 2016). Future experimental work should investigate the nature of the relation between symbolic and nonsymbolic timing abilities to determine whether nonsymbolic timing abilities are predictive of symbolic acquisition and/or whether the acquisition of temporal symbols leads to subsequent improvements in nonsymbolic timing abilities.

If it is the case that a causal relation exists between symbolic and nonsymbolic timing, it would be important to explore why this may be and if other experiences may similarly shape timing abilities. For example, we know that nonsymbolic timing abilities become more precise over the course of development, even long before children acquire temporal symbols (Brannon et al., 2007; Feigenson, 2007; vanMarle & Wynn, 2006). Are there particular types of experiences that may promote temporal acuity more than others? If so, is it possible to promote nonsymbolic timing in the service of acquiring more precise symbolic understandings? The answers to these questions are important for shedding light on timing processes while also having educational implications.

In conclusion, our data are the first to indicate that children's understandings of temporal units of measurement are correlated with individual differences in temporal acuity. Future work will be important for better characterizing this relation. Is this relation casual? If so, in which direction? Does the acquisition of symbolic timing sharpen nonsymbolic temporal acuity, or does improving nonsymbolic temporal acuity promote the acquisition of temporal symbols? Or might a third variable contribute to this relation? Together, our study joins others in the field of numerical cognition suggesting that a child's ability to perceive quantity nonsymbolically is intricately linked to their formal understanding of symbols in that same quantitative domain.

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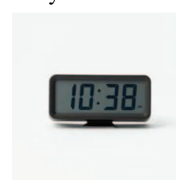
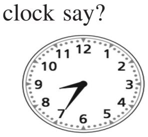
Appendix

Temporal Units of Measurement Questionnaire

1. How many minutes are in an hour?
2. How many seconds are in a minute?
3. How many hours are in a day?
4. A. What is longer a minute or a second?
   B. What is longer a minute or an hour?
   C. What is longer a second or an hour?
5. A. What is longer a month or a day?
   B. What is longer a day or a week?
   C. What is longer a week or a year?
   D. What is longer a year or a month?
6. How many minutes does it take you to brush your teeth?
7. How many minutes does it take you to eat dinner?
8. How many minutes have you been talking to me?
9. Kristen jumped for a week, John jumped for a day. Who jumped longer?
10. Jennifer jumped for 5 seconds, Ben jumped for 2 min. Who jumped longer?
11. What does this clock say?



12. What time does this clock say?



13. Kit left home this morning at 9:05. Jane left home 20 min after Kit left. What time did Jane leave at?

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