DOI: 10.1111/cdev.13780

EMPIRICAL ARTICLE

CHILD DEVELOPMENT

Children gradually construct spatial representations of temporal events

Katharine A. Tillman[1] | **Eren Fukuda**[2] | **David Barner**[3,4]

[1]Department of Psychology, The University of Texas at Austin, Austin, Texas, USA
[2]Department of Psychology, University of Wisconsin-Madison, Madison, Wisconsin, USA
[3]Department of Psychology, University of California, San Diego, San Diego, California, USA
[4]Department of Linguistics, University of California, San Diego, San Diego, California, USA

Correspondence
Katharine A. Tillman, Department of Psychology, The University of Texas at Austin, 108 E Dean Keeton Street, Austin, TX 78712, USA.
Email: ktillman@utexas.edu

Funding information
James S. McDonnell Foundation

Abstract

English-speaking adults often recruit a "mental timeline" to represent events from left-to-right (LR), but its developmental origins are debated. Here, we test whether preschoolers prefer ordered linear representations of events and whether they prefer culturally conventional directions. English-speaking adults (n = 85) and 3- to 5-year-olds (n = 513; 50% female; ~47% white, ~35% Latinx, ~18% other; tested 2016–2018) were told three-step stories and asked to choose which of two image sequences best illustrated them. We found that 3- and 4-year-olds chose ordered over unordered sequences, but preferences between directions did not emerge until at least age 5. Together, these results show that children conceptualize time linearly early in development but gradually acquire directional preferences (e.g., for LR).

INTRODUCTION

Time and space are deeply interwoven in human experience and culture. For example, diverse societies use spatial artifacts to depict, measure, and track time. Languages often use the same words to refer to both time and space (e.g., a *long* nap and a *long* rope). When we read, our progress through a temporal narrative is contingent on our progress along a spatial path on the page. Multiple sources of evidence suggest that adults have implicit associations between locations in time and positions in space, for example, associating leftward space with the past and rightward space with the future (see Bonato et al., 2012, for a review; Casasanto & Bottini, 2014; Droit-Volet & Coull, 2015; Ishihara et al., 2008; Pitt et al., 2021; Santiago et al., 2007). Based on evidence that the direction of this *mental timeline*, or MTL, differs cross-culturally (e.g., Bergen & Chan Lau, 2012; Fuhrman & Boroditsky, 2010; Nachshon, 1983; Ouellet et al., 2010; Tversky et al., 1991) some have argued that it is learned, and reflects differences in writing direction or visual scanning habits (see Pitt & Casasanto, 2020, for discussion). Others have argued that humans begin life with an innate predisposition to conceptualize time according to a left-to-right (LR) MTL, and that cultural learning may optionally modify this default tendency (Bulf et al., 2016; Chatterjee, 2001; Chatterjee et al., 1999; Dehaene et al., 1993; Vicario et al., 2007). Some prior research with English-speaking children suggests that their preferences for LR representations of time do not arise until relatively late in development (e.g., Pitt et al., 2021; Tillman et al., 2018). However, these studies' methods may have been insufficiently sensitive to detect preferences in preschoolers (Autry et al., 2019). Here, we explored children's developing preferences for visual representations of time using a series of tasks that varied in difficulty, assessing both whether children prefer ordered lines to unordered representations and also whether they prefer particular spatial directions.

Although the question of how the MTL is formed is fundamentally developmental, most previous studies of the MTL have been limited to adult populations. Many

Abbreviations: BT, bottom-to-top; CTC, Children's Title Checklist; LR, left-to-right; MTL, mental timeline; RL, right-to-left; TB, top-to-bottom.

researchers argue that some type of MTL is universal in adults (Gell, 1992), consistent with the possibility that humans have an innate tendency to represent events linearly. However, cross-cultural comparisons showing reliable differences in the orientation and direction of the MTL suggest that these preferences are learned (e.g., Bergen & Chan Lau, 2012; Boroditsky & Gaby, 2010; Fuhrman & Boroditsky, 2010; Nachshon, 1983; Núñez & Sweetser, 2006; Ouellet et al., 2010). For example, while the LR MTL is robust in speakers of English and many other languages written using an LR orthography (Casasanto & Bottini, 2014; Droit-Volet & Coull, 2015; Ishihara et al., 2008; Santiago et al., 2007; for review, see Bonato et al., 2012), speakers of languages written from right-to-left (RL) often construe time from RL (Ouellet et al., 2010; Tversky et al., 1991). Other space-time mappings do not involve the horizontal axis, and reflect a wide variety of other spatial frames of reference (Bender & Beller, 2014). For example, speakers of Mandarin Chinese, which is written vertically from top-to-bottom (TB) and also contains vertical space-time metaphors (e.g., an earlier month is the "up" month), often construe of time from TB (e.g., Fuhrman & Boroditsky, 2010). Time can also be construed along the sagittal axis, in relation to the body: in English and related languages, the past is described as "behind" and the future "ahead," while for the Aymara, the reverse is true, with the future described as "behind" (Núñez & Sweetser, 2006). Moreover, in some cultures, time is not oriented with respect to either the eye's progress across a page or the body's progress through space, but instead with respect to cardinal directions (e.g., for the Pormpuraaw people of Australia, time flows from east to west; Boroditsky & Gaby, 2010) or external environmental cues (e.g., for the Yupno people of Papua New Guinea, time flows downhill to uphill; Núñez et al., 2012). Although much less is known about space-time mappings in school-aged children, previous studies also find differences across groups, reporting that English-speaking children organize time-denoting stickers from LR (Tillman et al., 2018; Tversky et al., 1991), whereas Arabic-speaking children represent time from RL (Tversky et al., 1991).

These cross-cultural differences in the direction of adults' and schoolchildren's MTL are consistent with the possibility that humans are born without biases in how they represent time spatially, but acquire them gradually through experience via exposure to practices such as reading and writing (see Pitt & Casasanto, 2020, for discussion). However, it is also possible that humans begin life with a predisposition to organize time into spatial sequences, perhaps even with directional biases, but that these biases are subject to later modification (e.g., resulting in alternative directional preferences in different cultures or individuals). For example, humans may prefer to represent time linearly because straight lines organize sequences of events with the smallest possible distance between points, minimizing time and effort required by visual processing. Similarly, an LR preference might be explained as stemming from early developing cortical lateralization, predicting preferences that emerge prior to exposure to reading and writing (Dadda et al., 2009; De Hevia et al., 2012; Vallortigara et al., 2010). Compatible with such ideas, it has been argued that all infants begin life with a bias toward representing time in an LR MTL, which is later either strengthened or weakened by experience with cultural practices like reading (Bulf et al., 2016; De Hevia et al., 2012; Maass & Russo, 2003). Another possibility is that the tendency to organize time in an ordered, linear fashion is "built in," but specific directional biases are not. Consistent with this, recent work shows that adults from an indigenous culture with low literacy and exposure to cultural artifacts representing time produce ordered linear representations of temporal sequences but do not demonstrate a directional bias (Pitt et al., 2021).

Although some previous researchers have argued for the existence of innate space-time mappings on the basis of studies in preverbal infants, the majority of these studies have focused on the question of how infants represent *magnitudes* across domains, and, therefore, have not directly addressed the origins of the MTL. For example, when shown stimuli that vary in length, quantity, or duration, infants appear to spontaneously align them, suggesting that they expect a stimulus that has "more" in one domain (e.g., a longer length) to have to "more" of another (e.g., a longer duration; de Hevia et al., 2014; Lourenco & Longo, 2010; Srinivasan & Carey, 2010). Other studies have shown mappings between magnitudes and their *positions* in space. These include reports that both infants and non-human animals associate "few" with the left side of space and "many" with the right side of space (e.g., de Hevia et al., 2014; Rugani et al., 2017; but see also Cheung & Lourenco, 2016; de Hevia et al., 2017), which have been taken as evidence for the hypothesis that the LR "mental *number*-line" may be innate. Also suggesting that the LR mental number-line may be, at minimum, very early-developing, young preschoolers spontaneously count objects from LR (Göbel et al., 2018; Shaki et al., 2012) and expect numbers to be organized from LR (Opfer et al., 2010). However, these biases are absent in illiterate adults (Shaki et al., 2012) and they can be temporarily switched after children observe adults reading a storybook aloud in the opposite direction, suggesting considerable malleability (Göbel et al., 2018). Although most studies, especially those of infants and very young children, only investigated LR representations of number, not time, they have been taken by some researchers as evidence that all "mental lines" reflect the same evolutionarily ancient hemispheric asymmetry in the brain (Brooks et al., 2014; Chatterjee, 2001; Chatterjee et al., 1999; Rosen et al., 1987; Rugani et al., 2010, 2015; Vallortigara et al., 2010; Vicario et al., 2007 but see Pitt & Casasanto, 2020, for evidence that the MTL and mental number-line are distinct). Nevertheless, the evidence that infants have lateralized representations of temporal duration is mixed (Cheung & Lourenco, 2016; de Hevia et al., 2017, 2020), and, critically, none of the studies discussed above provide evidence for organization of temporal sequences into spatial timelines.

Here, we are interested in mental representations of temporal event sequences (rather than magnitudes). We ask whether young children, like adults, spontaneously organize event sequences into spatial timelines in which position in space corresponds to location in time. Few prior developmental studies have found evidence consistent with this possibility. Although it does not test for the presence of a MTL per se, one prior study does show that infants may be best able to learn patterns of shapes when they are presented in an LR sequence (Bulf et al., 2017). A second study shows that, when preschoolers are asked to place cards on a table to represent different colors as they are shown sequentially on a computer screen, they are most likely to place the cards in an LR line (Autry et al., 2019). Importantly, as we will discuss further in the General Discussion, in both these cases, the stimuli were simple shapes or colors, and did not represent events or narratives. Given this relative paucity of direct evidence for an MTL in developmental populations, the present study took a step in this direction by testing whether 3- to 5-year-old preschoolers prefer linear spatial representations of events. This age group provides a good entry point to this question because, if an MTL is present in infants, then evidence of an MTL of some form should be found in older children as well. Consequently, though the presence of an MTL in this group would leave open a role for early learning, the absence of an MTL would provide important evidence against innateness. Furthermore, this age group is interesting because it reflects the period during which children in North America typically begin to receive exposure to reading and writing, although this age varies across individuals, schools, countries, and cultures. Although preschoolers' ability to read and write is typically limited, many receive exposure to structured spatial input that could potentially influence the MTL. For example, text in books and visual scanning habits by caretakers may provide important visual cues (Göbel et al., 2018; Patro et al., 2016). Finding evidence of an MTL in preschoolers would be an important step toward determining the nature of environmental input required to shape it.

Previous studies have reported that, while elementary-school aged children demonstrate biases favoring culturally conventional linear representations of time, preschoolers do not, suggesting that these preferences are learned, rather than innate. Such studies have asked children to construct spatial representations of events by placing items on timelines (Friedman, 1990; Hudson & Mayhew, 2011; Tillman et al., 2017), placing stickers on blank paper (Tillman et al., 2018; Tversky et al., 1991), sorting picture cards (Bornens, 1990; Fivush & Mandler, 1985), or drawing (Dobel et al., 2007). For example, in one study, researchers asked 4-year-olds to arrange stickers representing events, and found that a large majority failed to produce any type of linear arrangement (Tillman et al., 2018). Moreover, the children who did produce a line failed to demonstrate an LR bias. Nonetheless, these studies leave open the possibility that 4-year-olds associate time with linear spatial arrangements but are simply unable to generate those sequences themselves (see Autry et al., 2019 for discussion). In other words, it is possible that the tasks that have been used to assess the MTL in older children, and which are impossible for infants, are also too difficult for preschoolers, and thus failed to detect evidence of linear representations or LR biases in preschoolers.

To summarize the prior literature, infants readily associate temporal and spatial magnitudes (e.g., de Hevia et al., 2014), and they can learn a pattern of shapes that are shown one at a time in a line from LR (Bulf et al., 2017). Children also demonstrate LR biases on a variety of tasks involving spatial representations of other abstract domains, such as number (e.g., Opfer et al., 2010). When colors are flashed one-at-a-time on a screen, 3-year-olds place matching colored cards on a table in LR lines, in a task that does not involve temporal language or narratives (Autry et al., 2019). However, when asked to represent events or points in time, preschoolers (unlike older children and adults) do not systematically organize them in lines with an isomorphism between position in space and event order, and they do not show evidence of an LR bias (Tillman et al., 2018). This collection of results leaves open whether the different elements of the MTL (such as linearity and direction) might represent innate defaults versus learned conventions.

To address this, we tested a large sample of preschoolers ($n = 514$ across three experiments) on a new task that greatly reduced demands on children. We asked them to express a preference in a two-alternative forced-choice task, rather than requiring them to construct lines on their own. Preschoolers and adult controls were told brief stories describing three-step event sequences and then asked to choose which of two spatial depictions of each story was "better." In Experiment 1, we tested whether children have directional preferences by asking them to choose between LR, RL, TB, and bottom-to-top (BT) representations of events (see Figure 1). Although LR mappings were of particular interest because they are consistent with the layout of print and temporal artifacts in our participants' culture, and they have also been argued by some to be an innate default, we were also interested in whether children might show preferences for TB over BT along the vertical axis, which is also consistent with text orientation (and might also reflect the use of a sagittal axis, given that the cards were laid flat on the table in front of the child). In Experiment 2, we tested if children were sensitive to whether the order of the images matched that of the events they depicted, by asking them to choose between ordered and unordered

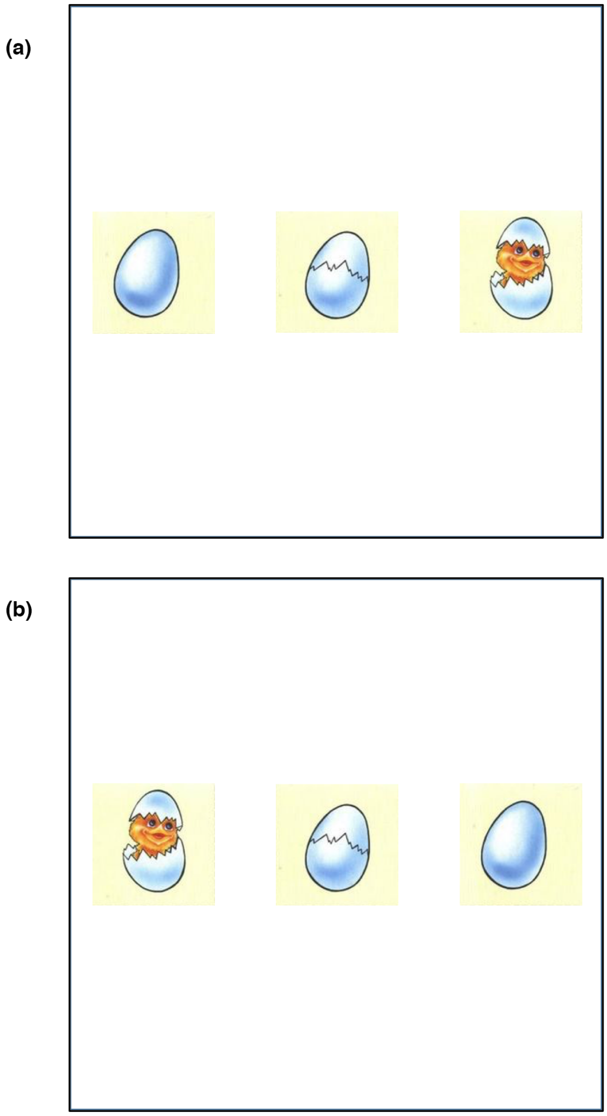


FIGURE 1 Example stimuli. On the first trial, participants heard the story "First there was an egg. Then the egg cracked. And a baby chick popped out!" In the horizontal condition, they chose between cards showing (a) left-to-right and (b) right-to-left sequences of images

sequences. We reasoned that only an ordered set of images can represent time linearly because only an ordered set allows tracing of a straight path between images that preserves the temporal sequence of events. Therefore, we predicted that children who represent time in a linear fashion should prefer ordered over unordered arrays. In Experiment 3, we replicated Experiments 1 and 2 using a modified procedure including additional scaffolding to aid children's comprehension of the task. Finally, we conducted a parent survey to explore the relation between children's early literacy skills and their performance on the space-time task.

As we will show, our effort to simplify our methods was successful. We found that even 3-year-olds prefer ordered over unordered sequences (Experiment 3). Nevertheless, despite this evidence that they were able to comprehend the task, children under age 5 did not demonstrate directional preferences in any of our experiments, suggesting that although children have an early tendency to conceive of time according to spatial sequences, they do not have a preference for LR (or any other spatial configuration) before the age of 5.

EXPERIMENT 1

In Experiment 1, we tested whether adults and children have preferences between different spatial sequences after hearing a story. Specifically, we asked whether participants preferred LR representations of events to RL representations and (in another condition) whether they preferred LR to TB. As discussed in the Introduction, LR biases have been posited to be the result of innate biases or the result of experience with English text and other artifacts. We also tested whether participants have preferences between TB and BT representations of events. Although vertical representations of time have been less-studied in English speakers than horizontal ones, and no direction preferences along the vertical axis would be predicted on accounts in which the LR direction is uniquely privileged, a preference for TB over BT is also consistent with accounts in which mental representations of time reflect the layout of text or calendars, which are organized both from LR and TB in the participants' cultural group. Experiment 1 was not pre-registered and was relatively exploratory in nature.

Methods

Participants

A total of 271 participants were included in Experiment 1, including 62 three-year-olds (M_{age} = 3;6, range 3;0–4;0), 63 four-year-olds (M_{age} = 4;6, range 4;0–5;0), 61 five-year-olds (M_{age} = 5;0, range 5–6;0), and 85 adult controls (at least 18 years of age). Forty-four percent of child participants were girls. Data collection occurred between September 2016 and March 2017. Children were recruited from museums and daycares in the greater San Diego, CA, area. The sample was drawn from a local population with the following demographic characteristics: 33% white, 45% Hispanic or Latino, 9.7% Asian, 5.1% Black or African American, 0.6% American Indian or Native American. Adults were workers on Amazon Mechanical Turk living in the United States; information on race and gender was not collected. An additional 23 children were tested but excluded from all analyses because they were outside the target age range (n = 11), English was not their primary language (n = 2), they spoke a second language with a non-LR orthography (n = 4), they failed to complete the task (n = 2), clerical error (n = 3), or developmental delay (n = 1). Five adults were excluded from analysis due to speaking a language with non-LR orthography (*n* = 2) and lack of attention to the task, as indexed by failing a "catch" trial (*n* = 3). All participants spoke English as their primary language, and none spoke a secondary language with non-LR orthography. Adults and parents of children provided informed consent to participate. Children were awarded a small prize, and adults were compensated $1 for a task that took approximately 5 min to complete.

Stimuli

We composed eight stories, each describing a three-step temporal event that was intended to be familiar to children in the target age range. Four cards were created to match each story. Each card showed three images that represented the steps in the story in consecutive order from a particular direction: either LR, RL, TB, or BT. For an example, see Figure 1. All stimuli are shown in Table A1, and additional details about the stimuli can be found in Supporting Information.

Conditions

Participants were randomly assigned to three conditions: horizontal, vertical, or perpendicular. In the horizontal condition, participants (*n* = 21 three-year-olds, 22 four-year-olds, 21 five-year-olds, 29 adults) were asked to choose between cards that depicted stories either from LR or RL (see Figure 1; Figure A1). In the vertical condition, participants (*n* = 20 three-year-olds, 20 four-year-olds, 20 five-year-olds, 29 adults) were asked to choose between cards that depicted stories from TB and BT (Figure A1). In the perpendicular condition (*n* = 21 three-year-olds, 21 four-year-olds, 20 five-year-olds, 27 adults), participants were asked to choose between images arranged from LR and TB. This last condition was included to assess whether a preference between the horizontal and vertical axes might emerge at a different point in development than preferences within an axis (e.g., for LR vs. RL in the horizontal axis). For example cards showing all directions, see Figure A1.

Procedure for children

The experimenter (seated next to the child) introduced the task, saying "We're going to play a picture game together. Every time we play, I'm going to tell you a story, and you're going to pick the card that matches the story. Each card shows three pictures of things that happened in the story, and you're going to pick the one that has them all in the right order, just how they happened in the story." Next, on each of eight trials, the experimenter recited the story. For example, on the first trial, the child heard the Egg story: "First there was an egg. Then the egg cracked. And a baby chick popped out!" As shown in Figure 1 (horizontal condition), the experimenter then simultaneously placed two cards on the table, and asked, "Which card shows that story? Which one is *better*? Is it *this one* [point to card] or *this one* [point to card]?" After the child pointed to their choice, the cards were removed, and the next trial began.

The two cards were placed side-by-side in the vertical and perpendicular conditions but were positioned one above the other in the horizontal condition. This was because, when horizontal cards were placed side-by-side in pilot testing, having all six images aligned in a row across the two cards appeared confusing for children. The positioning of the two cards, including the location of the more conventionally ordered choice, was counterbalanced across subjects and items, in two trial orders, one of which was the reverse of the other. Every child heard the Egg story first (see Figure 1). Half the children heard the remaining stories in the order listed in Table A1, and half heard them in the reverse order.

Procedure for adults

Adults (*n* = 85) completed a computerized version of the task, created using Qualtrics and posted as an HIT on Amazon Mechanical Turk. On each trial, the participant read the story, then clicked an arrow to advance to the next screen, which showed the two "cards" (squares outlined in black) arranged in the same positions as they were for children, and the test question ("Which card shows that story? Which one is *better*?"). The participant clicked a radio button below the card they thought was better, and then clicked an arrow to advance to the next trial. The two trial orders were the same as those used in the children's procedure, except that two additional "catch trials" were included after test trials 3 and 6. In these cases, one of the two options contained a non-chronological sequence, for example, the Watermelon story arranged from LR versus an unordered horizontal sequence, which showed (from LR) sliced watermelon, eaten watermelon slices, and then an intact watermelon. Adults who failed either of these trials (*n* = 3) by choosing the non-chronological sequence were excluded due to suspected inattention to the task. After finishing the task, participants answered a series of questions about their language exposure.

Parent survey

A subset of parents of 4-year-olds in Experiment 1 (*n* = 16) completed a survey about their child's emergent literacy skills and an adaptation of the Children's Title Checklist (CTC), a previously used measure of print exposure in children (Sénéchal et al., 1996, 1998). Survey data were also collected in Experiments 2 and 3. Further description of the survey, and its results are described in the section on Experiment 3.

RESULTS

Direction preferences in adults

To assess direction preferences in adults, we calculated the percentage of trials, out of 8, on which each participant chose the card with each direction. We found robust direction preferences in all three conditions. Because several distributions were non-normal, we report the medians as our measure of central tendency throughout the results. The median percentage of trials on which adults chose LR cards was 100%, 95% CI [100–100] in the horizontal condition (LR vs. RL) and 87.5% [75–100] in the perpendicular condition (LR vs. TB). In the vertical condition (TB vs. BT), adults chose the TB card on a median 100% [100–100] of trials. In all subsequent analyses, we considered these adult-preferred directions to be the "conventional" choices, and the contrasting directions to be "unconventional" choices. As shown in Figure 2, the median percentage of trials (across all conditions) on which adults chose conventional directions was 100% [100–100], which was far greater than chance guessing would predict, one-sample sign test, $s = 81$, $p < .001$. The effect size, $r = .91$, was calculated using the wilcoxonOneSampleR() function from the *rcompanion* package in R, based on the Wilcoxon one-sample signed-rank test. We also calculated the percentage of individuals who consistently chose the conventional spatial representation of time on at least 7 out of 8 trials, and found that 86% of adults did so.

Direction preferences in children

To analyze children's data, we conducted a mixed-effects logistic regression, which modeled the likelihood of choosing the conventional direction as a function of the child's age (as a continuous, scaled variable), and condition (horizontal, vertical, or perpendicular). In this model, and in all subsequent models discussed in Exp. 1–3, we also included an interaction term and a random intercept for subjects. Age was a significant predictor which improved the fit of the model, $\beta = .31$, $p = .02$; $\chi^2(1) = 8.3$, $p = .004$, compared with a reduced model that did not include this predictor. However, we did not find a significant effect of condition, and this factor did not improve the model, $\chi^2(2) = 1.8$, $p = .41$. Therefore, although children's choices became overall more conventional over time, this first analysis did not find a difference between the development of LR and TB preferences. Because we did not find a significant effect of condition, Figure 2 plots all data from each age group. Figure S3 shows the data from each condition separately.

Including stories (e.g., Egg, Watermelon) as an additional random effect resulted in non-convergence of the model. As shown in Figure S1, there were some differences in children's performance across these items, but

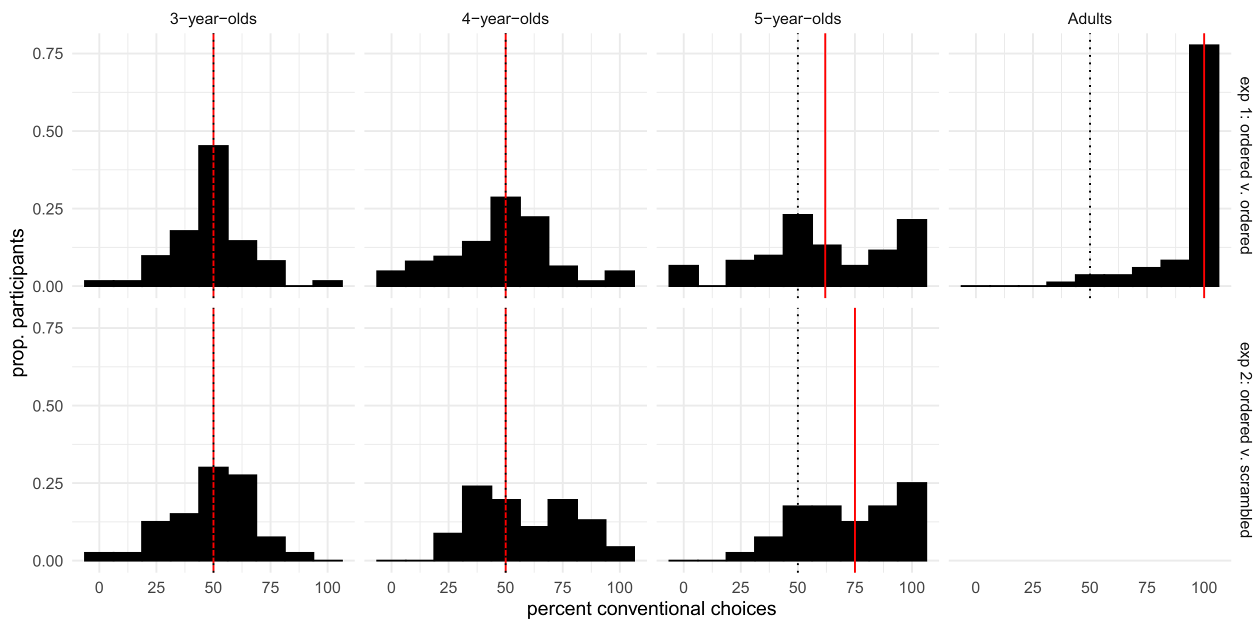


FIGURE 2 Frequency of preferences for conventional visual representations of time in Experiments 1 and 2. In Experiment 1 (top row), participants chose between two ordered, linear sequences with different directionalities. In Experiment 2 (bottom row), children chose between ordered sequences and scrambled (i.e., unordered) sequences. Adults were not tested in Experiment 2. Red solid lines represent medians. Dotted lines represent chance. Data from Experiments 1 and 2, separated by condition, can be found in Supporting Information (Figure S3)

they were inconsistent across age groups and conditions. When story was included as an additional main effect, along with age and condition, it was not a significant predictor of children's performance in Exp. 1, $\chi^2(1) = 6.1$, $p = .5$, or subsequent experiments.

While these analyses indicate that children's preferences for conventional representations of events increased with age, they do not establish when such preferences first emerge. To explore this, we examined each age group separately. As shown in Figure 2, neither 3-year-olds' nor 4-year-olds' performance differed from chance: the median percentage of trials on which children from both groups chose the conventional direction was 50% [50–50], one-sample sign tests, both $s's < 16$, $ps > .6$. However, the median percentage of trials on which 5-year-olds chose conventional directions was 62% [50–75], greater than chance guessing would predict, one-sample sign test, $s = 32$, $p = .02$, effect size $r = .37$.

Finally, we calculated the percentage of children within each age group who consistently chose a conventional representation of time on at least 7 out of 8 trials, which was the number of trials required for an individual to perform statistically significantly higher than chance (exact binomial test, $p = .04$). We found that 2% of 3-year-olds, 6% of 4-year-olds, and 33% of 5-year-olds did so. We also calculated the proportion of children who met a more lenient criterion of 6 out 8 trials and nonetheless still found that only 10%, 13%, and 39% of 3-, 4-, and 5-year-olds (respectively) chose the conventional cards with this level of consistency (see Figure 2 for full distributions).

Discussion

The results of Experiment 1 indicate that children begin to express conventional direction preferences on this task, along both the horizontal and vertical axes, around 5 years of age, similar to prior findings using a production task (Tillman et al., 2018). However, there are two potential problems with this study. First, although Experiment 1 suggests that 3- and 4-year-old children don't have strong directional preferences on this task, it leaves open whether they prefer ordered sequences over unordered ones. All of the images used in Experiment 1 were in sequential order with respect to the narrative, despite sometimes violating conventional adult-preferred directionality. Second, the failures of younger children on this task, while compatible with a lack of preference, are also consistent with a failure to understand the task. We reasoned that if the task is understandable to 3- and 4-year-old children, but they simply lack directional preferences, then they may succeed on a version of the task that probes a preference for ordered versus unordered spatial representations of events, even while failing to prefer specific directionalities. In Experiment 2, we explored this possibility by asking children to choose between ordered sequences of images and unordered, "scrambled" sequences (e.g., an LR sequence of an egg, a baby chick, and then a cracked egg, which we called the "scrambled egg" condition). If children prefer ordered over scrambled sequences, this would suggest both that they can organize time spatially and that they understand the task but that they simply don't yet have directional preferences.

EXPERIMENT 2

The purpose of Experiment 2 was to explore whether children prefer ordered linear representations of sequential temporal events to representations in which the events are depicted out of order. We assessed both whether children prefer LR images to scrambled horizontal sequences and whether they prefer TB images to scrambled vertical sequences. Finding equal preference for both LR and TB over scrambled images would provide evidence that children have an ordered linear representation of time, but no clear LR bias. A stronger preference for LR over scrambled images than for TB versus scrambled would provide evidence both for ordered linear representations and for a potential LR bias. Finally, a lack of preference for either LR or TB versus scrambled images would suggest both a lack of ordered linear representations and a lack of directional bias. As it built directly on our findings in Experiment 1, Experiment 2 was somewhat less exploratory in nature.

Methods

Participants

There were 126 participants in Experiment 2, including 40 three-year-olds (M_{age} = 3;6, range 3;0–4;0 years), 46 four-year-olds (M_{age} = 4;6, range 4;0–5;0 years), and 40 five-year-olds (M_{age} = 5;4 years, range 5;0–6;0 years). They were randomly assigned to one of two conditions, with 20 three-year-olds, 23 four-year-olds, and 20 five-year-olds in each. Fifty-five percent of participants were girls. Data collection occurred between November 2016 and May 2017. Children were recruited from museums and daycares in the San Diego, CA, area (n = 79) and the Comox Valley, British Columbia, Canada (n = 47). Demographics of the US population were the same as those reported in Experiment 1. The Canadian sample was drawn from two small cities, Comox and Courtenay, with the following (combined) demographic makeup: 90% white, 5% First Nations or aboriginal, 4% Asian, 1% Black, <1% Hispanic or Latino. An additional 15 children were tested but excluded due to being outside the target age range (n = 4), not speaking English as their primary language (n = 6), speaking a second language with a non-LR orthography (n = 3), experimenter error (n = 1), or clerical error (n = 1).

Materials and procedures

Materials and procedures were identical to those used in the horizontal and vertical conditions of Experiment 1, except that each RL card was replaced with a scrambled horizontal card (see Figure A1e), and each BT card was replaced with a scrambled vertical card (Figure A1f). Thus, in the horizontal scrambled condition children compared an LR card with an unordered sequence that was oriented horizontally, and in the vertical scrambled condition children compared a TB card with an unordered sequence that was oriented vertically.

Results

We conducted a mixed-effects logistic regression modeling the likelihood of choosing the ordered image as a function of the child's age (as a continuous, scaled variable) and condition (horizontal scrambled or vertical scrambled). As in Experiment 1, we found that age was a significant predictor improving the fit of the model, $\beta = .36$, $p = .003$; $\chi^2(1) = 26.3$, $p < .001$, but that condition did not improve model fit, $\beta = -.17$, $p = .3$; $\chi^2(1) = 1.2$, $p = .3$. Thus, as before, although older children were more likely to choose ordered sequences than were younger children, we found no evidence that children performed better for LR than for TB. As shown in Figure 2 (bottom row), when we examined individual age groups, we found that 5-year-olds were much more likely to choose ordered images than chance would predict, median = 75% [62–88], one-sample sign test, $s = 29$, $p < .001$, effect size $r = .71$. In contrast, the median percentage of ordered image selections was 50% in both the 3- and 4-year-old groups (95% CI for 3-year-olds, [50–62]; for 4-year-olds, [50–75]), which was not different from chance, one-sample sign tests, both $s < 16$, both $p > .3$.

Finally, when we calculated the percentage of individual children who chose the ordered representation of time on at least 7 of 8 trials (i.e., who performed significantly above chance) we found that 3% of 3-year-olds, 17% of 4-year-olds, and 42% of 5-year-olds did so. The proportions of 3-, 4-, and 5-year-olds who chose the ordered representation on at least six trials were 10%, 13%, and 55%, respectively. In the case of the 5-year-olds, it is notable that although the preference for ordered representations is strong at the group level (i.e., the median is far above chance), only about half the individual children in the sample clearly demonstrated the behavior (see Figure 2). We return to the potential sources of individual differences in the General Discussion.

Discussion

The results of Experiment 2 indicate that children begin showing a preference for images representing temporal events in sequential order in this task around age 5. The median proportions of 3- and 4-year-olds preferring conventional (Exp. 1) and ordered (Exp. 2) cards were both 50%, consistent with the possibility that many children may have been randomly guessing in both tasks.

Relative to prior tasks, which have typically required the use of complex timelines or the creation of visual representations of time by the child (e.g., Busby Grant & Suddendorf, 2009; Friedman, 2000, 2002; Friedman & Kemp, 1998; Hudson & Mayhew, 2011; Tillman & Barner, 2015; Tillman et al., 2017; Tversky et al., 1991), the two-alternative forced choice task used in Experiments 1 and 2 imposed relatively low response demands. Still, this method may have posed other challenges. In particular, it is possible that some 3- and 4-year-olds had difficulty remembering the story, interpreting the individual pictures, or connecting the pictures to the steps in the stories they had heard (see Cohn, 2020, for discussion). If so, these difficulties could have prevented us from detecting the presence of direction or orientation biases.

We reasoned that, to succeed at the task, the child must mentally create an isomorphism between the temporal order of the events in the story and the spatial positions of the images on the card. Although one obstacle to this is understanding how time and space are related, another challenge is identifying which images on the cards correspond to which events. For example, if the child did not understand that the picture of the cracked egg on the card corresponds to the egg cracking event in the story, they might fail to situate it in the middle of the story. They might, therefore, be unable to use this knowledge to situate the corresponding image in the middle of the spatial sequence. If so, the child might fail the task regardless of their preferences for how time should be spatially represented.

To address this, unlike in Experiments 1 and 2, where the pictures were only presented at test, in Experiment 3, they were also presented during the story-telling phase as each event was described. The images were shown one at a time in the center of the screen. This created an alignment between the events in the story and the pictures, without presenting the pictures in any spatial arrangement relative to one another. Furthermore, children were asked to repeat back each story to the experimenter (in their own words) prior to the test phase, to ensure that they had heard and encoded it. Finally, in the test phase, children chose the card showing the spatial arrangement of the three images they felt best matched the temporal sequence of those images (paired with their verbal descriptions) that they had just observed in the story-telling phase.

EXPERIMENT 3

In Experiment 3, we repeated all five conditions from the previous experiments with this modified procedure designed to further reduce task difficulty. Experiment 3 was confirmatory in nature, given that it was in large part a replication of Experiments 1 and 2 (with modifications).

Methods

Participants

Given the relative success of 5-year-olds in Experiments 1 and 2, here we focused on 3- and 4-year-olds. A total of 202 participants were included in Experiment 3, including 101 three-year-olds (M_{age} = 3;6, range 3;0–4;0 years) and 101 four-year-olds (M_{age} = 4;6, range 4;0–4;11 years). Fifty-four percent of participants were girls. Data collection occurred between June 2017 and March 2018. Children were randomly assigned to one of five conditions: horizontal (20 three-year-olds and 20 four-year-olds), vertical (21 three-year-olds and 20 four-year-olds), perpendicular (20 three-year-olds and 21 four-year-olds), scrambled horizontal (20 three-year-olds and 20 four-year-olds), or scrambled vertical (20 three-year-olds and 20 four-year-olds). Children were recruited from daycares and museums in San Diego, CA, (n = 127) and the Comox Valley, BC, (n = 75) with the same demographics reported in Experiments 1 and 2. An additional 12 children were excluded from analysis because they were outside the target age range (n = 1), English was not their primary language (n = 2), they failed to complete the task (n = 2), or had completed a prior version of the experiment (n = 7).

Procedures and materials

As shown in Table 1, procedures in Experiment 3 were similar to those in Experiments 1 and 2, except that children viewed images on a computer screen during the storytelling phase of each trial, rather than only seeing them in the test phase after the story. At the start of the session, the experimenter said, "Every time we play, I'm going to show you a story on the computer, and you're going to pick the card that matches the story." On each trial, while reading the three steps of the story, the experimenter presented the image corresponding to each step. The pictures were shown sequentially in the center of the screen. For example, while hearing, "First, there was an egg" the child was presented with the picture of the whole egg (see Table 1). Then, while saying "Then, the egg cracked," the experimenter advanced the slide to show the cracked egg (replacing the previous image in the same location). She advanced to slide again to show the hatching egg while reciting the final "…and a baby chick came out!".

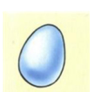
Next, also unlike in Experiments 1 and 2, the experimenter asked the child to repeat back the story they had just heard, to help ensure that children had processed the story. The experimenter asked, "Now, can you tell me what happened in that story?," and prompted the child with "and then what happened?" if necessary. If the child did not accurately repeat all three steps, the experimenter reiterated them. Children were not shown the images again during this story-repetition phase. To avoid penalizing younger children for shyness, those who did not repeat the story on every trial were not excluded, nor were trials in which children did not repeat the story without assistance. Below, we report analyses that examine whether such children differed from those who were able to repeat the story.

The test phase was identical to Experiments 1 and 2. Two cards were placed on the table and the child was asked to select the one that best showed the story.

Parent survey

Some of the participating children's parents (n = 79 in Experiment 3) also completed a survey on their children's

TABLE 1 Design of Experiments 1 and 2 versus experiment 3

Exp.	Story	Repeat	Test
1 and 2	"First there was an egg, then the egg cracked, and a baby chick came out!"	N/A	"Which one shows that story? Which is better?" 
3	"First there was an egg…"  "Then the egg cracked…"  "And a baby chick came out!" 	"Now can you tell me what happened in that story?"	"Which one shows that story? Which is better?" 

emergent literacy and print exposure. Parents indicated whether their child attended preschool, and answered eight yes-or-no questions about their child's reading and writing skills. Questions included whether their child was able to identify or write *some* letters, identify or write *all* letters, read or write their own name, and read or write at least five other words. Each child was given a writing score of 0–4 and a reading score of 0–4, based on their parent's responses. Secondly, to assess children's print exposure in the home, the parent completed an adaptation of the Children's Title Checklist (CTC; Sénéchal et al., 1996; see Supporting Information). The CTC is a list containing 40 popular children's book titles (e.g., *Where the Wild Things Are*) and 20 foils that were not real titles (e.g., *Three Cheers for Gloria*). Parents were instructed to indicate each title they were familiar with (whether or not they had read the book) by checking a box next to the title. Each child was later assigned a print exposure score equivalent to their parent's number of hits minus false alarms.

Results

Story repetition

Prior to completing the test phase, children in Experiment 3 were asked to repeat the story back in their own words, with the goal of helping them to encode it in memory. Children repeated the whole story back accurately on 77% of trials, including 63% of trials for 3-year-olds and 90% of trials for 4-year-olds. Unsurprisingly, the number of trials on which children repeated back the story on the first try was correlated with their age, $r = .5$, $p < .001$. Nevertheless, when this factor was included in a logistic regression model along with age and condition, it was unrelated to performance in the card selection task, $\beta = .1$, $p = .15$; $\chi^2(1) = 2.1$, $p = .15$. Given this, all data were retained for the following analyses, regardless of whether the child repeated back the story independently on a given trial.

Scrambled conditions

Data from the two "scrambled" conditions (i.e., comparisons of ordered vs. unordered cards) were analyzed in the same fashion as data from Experiment 2. We modeled the likelihood of choosing the ordered image as a function of age (as a continuous, scaled variable) and condition (horizontal scrambled or vertical scrambled) using a mixed-effects logistic regression. Age significantly improved the fit of the model, $\beta = .26$, $p = .1$; $\chi^2(1) = 15.8$, $p < .001$, and there was an interaction of age and condition, $\beta = .51$, $p = .04$; $\chi^2(1) = 4.4$, $p = .04$. Older children were more likely to choose ordered images, and, unexpectedly, the preference for ordered over scrambled images was more pronounced in the vertical scrambled condition (TB vs. scrambled) than in the horizontal scrambled condition (LR vs. scrambled).

The frequency distributions of responses in Experiment 3 are shown in Figure 3, with the scrambled conditions represented in the top two rows. We found that the median percentage of trials in which 3-year-olds chose the ordered card was 62% [50–62] in the horizontal scrambled condition. Unlike our finding in Experiment 2, this was significantly greater than chance, one-sample sign-test, $s = 12$, $p = .003$, effect size $r = .66$. However, the median percentage among 3-year-olds was only 50% [38–61] in the vertical scrambled condition, which was not different from chance, $s = 3$, $p = .5$. The median percentage of trials in which 4-year-olds chose the ordered card was also 62% [52–99] in the horizontal scrambled condition and 94% [64–100] in the scrambled vertical condition. Again, unlike our findings of Experiment 2, 4-year-olds performed better than chance in both the horizontal scrambled condition, $s = 14$, $p = .001$, effect size $r = .67$; and the vertical scrambled condition, $s = 16$, $p < .001$, effect size $r = .81$. Assessing the performance of individual subjects, we found that the proportion of 3-year-olds who performed significantly above chance by choosing the ordered image on at least 7 of 8 trials was 15% in the horizontal scrambled condition and 0% in the vertical scrambled condition, whereas the proportion of 4-year-olds who did so was 40% in the horizontal scrambled condition and 60% in the vertical scrambled condition. The proportion of 3-year-olds who chose the ordered image on at least six trials was 20% in the horizontal scrambled condition and 10% in the vertical scrambled condition, while the percentage of 4-year-olds who did so was 45% in the horizontal scrambled condition and 70% in the vertical scrambled condition.

Our finding that 4-year-olds showed a stronger preference for ordered images in the vertical scrambled condition than the horizontal scrambled condition was unexpected. Although this finding does not support the hypothesis that the LR axis is uniquely privileged, we have no theoretical explanation for why space-time mappings along the vertical axis would be stronger in children this age. One possibility is that young children tend to represent time along the sagittal axis, that is, forward or backward relative to the position of the body. Given that each card was laid flat on the table, the three images in the vertical scrambled condition were more closely oriented with the sagittal axis, allowing children to use distance from the body as a cue to temporal order.

Ordered conditions

So far we have shown that, with the methodological changes introduced in Experiment 3, preschoolers often

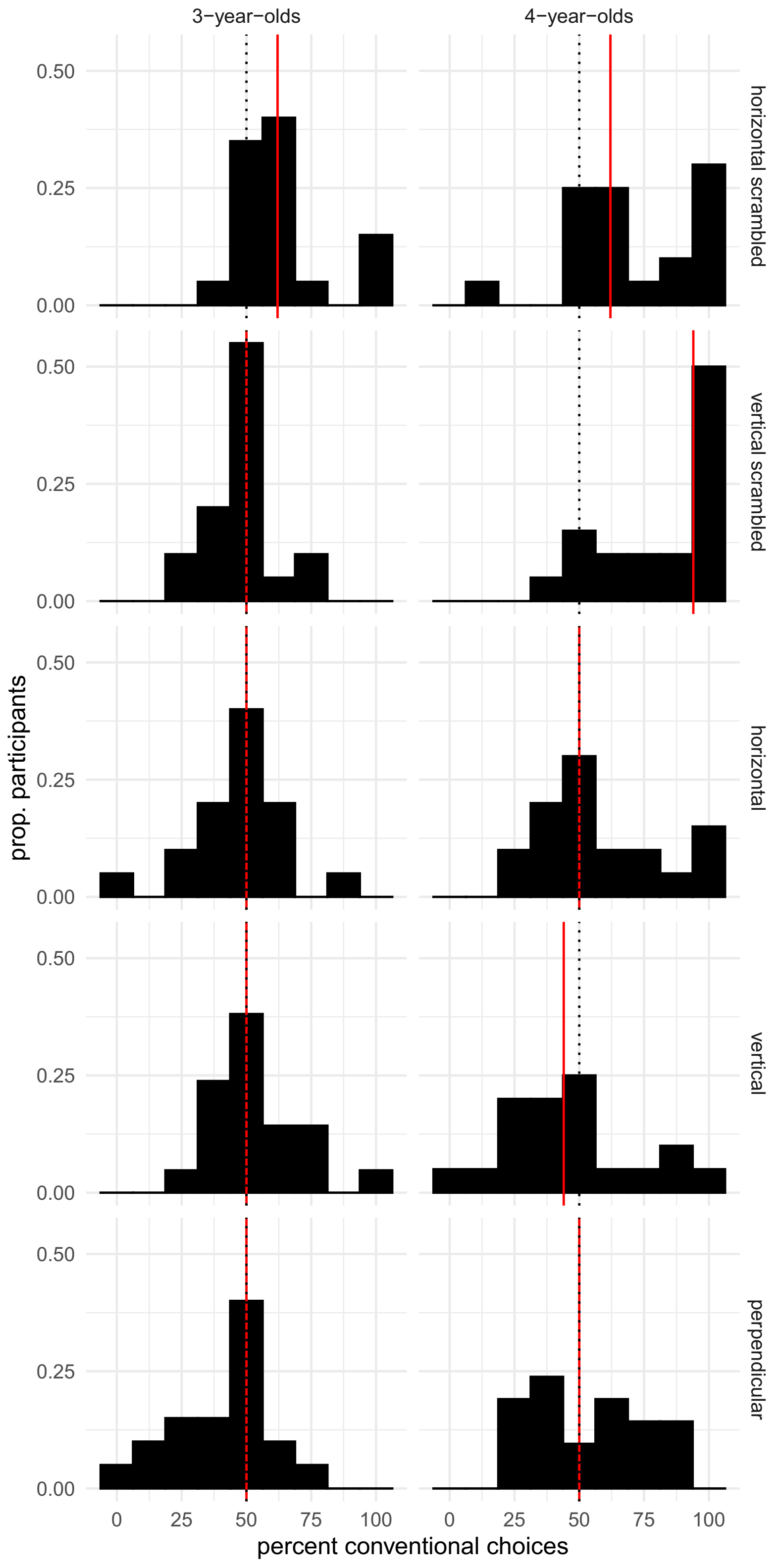


FIGURE 3 The proportions of preschoolers who chose conventional linear representations of time in Experiment 3. The "conventional" choice was left-to-right in the horizontal scrambled, horizontal, and perpendicular conditions and top-to-bottom in the vertical scrambled and vertical conditions. Red vertical lines indicate medians. Dotted lines indicate chance

demonstrated preferences for ordered over unordered sequences of images. This result indicates that children of this age were able to understand the task. Next, we considered data from the three conditions in which *both* cards showed ordered sequences to test whether they had direction preferences. A mixed-effects logistic regression modeled the likelihood of choosing the conventional direction as a function of age (continuous and scaled) and condition (horizontal, vertical, or perpendicular). Only the interaction between factors was significant, $\beta = .5$, $p = .04$; 2(2) = 6.3, $p = .04$. As shown in Figure 3, and replicating our results in Experiment 1, the median percentages of conventional choices made by 3-year-olds in the horizontal, vertical, and perpendicular conditions were all exactly 50%, 95% CIs, respectively [38–50]; [43–62]; [27–50], consistent with chance responding, one-sample sign tests, horizontal, s = 5, $p = .77$; vertical, $s = 7$, $p = 1$; perpendicular, $s = 3$, $p = .15$. The median percentage of conventional choices made by 4-year-olds in the vertical condition was 44% [27–50]. Although this percentage did not significantly differ from 50%, it is notable that it was *lower* than chance and thus closer to an "unconventional" preference for BT over TB, which was also observed in 4-year-olds in the vertical condition in Experiment 1 (see Figure S3) and in a prior production task (Tillman et al., 2018). If present, a preference for BT may indicate that some young children represent time along a sagittal axis in which earlier events are closer to the body, in contrast to the strong preference for TB we observed in the scrambled vertical condition. The median percentage of conventional choices was 50% in both the horizontal condition, 95% CI [39–73], and in the perpendicular conditions [38–70]. Again, none of these medians were significantly different from chance (horizontal, $s = 8$, $p = .79$; vertical, $s = 5$, $p = .3$; perpendicular $s = 10$, $p = 1$). The percentages of individual 3-year-olds who selected the conventional image on at least 7 of 8 trials in the horizontal, vertical, and perpendicular conditions were 5%, 5%, and 0%, respectively. For 4-year-olds, these percentages were 20%, 15%, and 14%, respectively. The percentage of 3-year-olds who selected the conventional image on at least six trials in the horizontal, vertical, and perpendicular conditions was 5%, 19%, and 5%, respectively. For 4-year-olds, these percentages were 30%, 20%, and 29%.

In summary, although the methodological changes in Experiment 3 helped children to differentiate ordered from unordered sequences, they did not affect most children's ambivalence regarding the directionality of ordered sequences. This pattern suggests that the lack of directional preferences in our previous studies were not simply due to children's inability to comprehend the task. Instead, these findings are more consistent with the hypothesis that such preferences emerge robustly only after the age of 5.

Ordered conditions versus scrambled conditions

To test whether the preference of 3- and 4-year-olds for ordered sequences was indeed stronger than their apparently random preferences for specific directions, we conducted an analysis that directly compared performance on these tasks. To do so, we compared children's performance on the ordered conditions (horizontal, vertical, and perpendicular) that required comparisons between two ordered sequences, and the scrambled conditions (horizontal scrambled and vertical scrambled) requiring comparisons between one ordered and one scrambled sequence. We modeled the likelihood of choosing the conventional image as a function of age (as a continuous, scaled variable) and comparison type (ordered condition vs. scrambled condition; collapsed across condition within each type). We found that age significantly improved the model, $\beta = .47$, $p < .001$; 2(1) = 10.3, $p = .001$, as did comparison type, $\beta = -.75$, $p < .001$; $\chi^2(1) = 25.8$, $p < .001$, and there was a significant interaction between these factors, $\beta = -.40$, $p = .005$; $\chi^2(1) = 7.8$, $p = .005$. Thus, children were more likely to choose conventionally ordered cards over unordered cards than over unconventionally ordered ones, and this difference increased with age.

Parent survey

Prior studies argue that direction-specific mappings between time and space in children and adults are a result of reading and writing experience (e.g., Autry et al., 2019; Bergen & Chan Lau, 2012). Our finding that robust preferences for conventionally ordered representations of time only emerged around that age when children enter school is consistent with this possibility. To provide a slightly stronger test of this, we next asked how children's responses were related to their parents' report of their early literacy and print exposure. Because parents of children tested in daycares or preschools were not available to complete the survey, survey data were only available from a subset of parents ($n = 98$ across studies; see Table S1). We thus collapsed across all conditions and experiments for which we had any parent-report data. The results of this analysis should, therefore, be interpreted with caution. Examining the relation between children's likelihood of preferring conventional representations of events and these literacy measures, we found a significant correlation of task performance with writing scores, $r = .26$, $p = .01$, but not with reading scores, $r = .18$, $p = .07$, or print-exposure scores, $r = -.06$, $p = .6$. When all of these factors were included in a linear regression also including comparison type (ordered vs. scrambled conditions), only comparison type, $\beta = .17$, $p = .002$, and writing scores, $\beta = .06$, $p = .04$, were significant predictors of children's performance on the picture-selection task, model $F(5, 89) = 3.5$, adjusted $R^2 = .12$, $p = .006$. However, as expected, several literacy factors were themselves correlated, including reading and writing scores, $r = .63$, $p < .01$, and writing scores and age, $r = .57$, $p = .01$.

Discussion

With additional scaffolding to support children's comprehension of the task, we detected modest preferences for ordered horizontal sequences in both 3- and 4-year-olds, and a strong preference for ordered vertical sequences in 4-year-olds. Given that children who repeated back the story did not perform better than those who did not (controlling for age), we believe the more critical modification was showing the child each individual picture while telling them the corresponding part of the story, prior to asking them to choose a spatial representation of the entire three-part event. This methodological change led to improvements in preschoolers' performance in the "scrambled" conditions (relative to Exp. 2), and showed that preschoolers were not simply responding randomly due to incomprehension of the task. However, they did not appear to affect children's directional preferences. Unlike 5-year-olds and nearly all adults (Exp. 1), younger children did not demonstrate any detectable preference for LR over either RL or TB representations of events, nor for TB over BT representations. Because this was true *despite* their demonstrated sensitivity to the ordering of images in the scrambled conditions, particularly in 4-year-olds, the overall pattern of results is consistent with the hypothesis that most English-speaking children do not develop direction preferences for spatial representations of temporal events before the age of 5.

GENERAL DISCUSSION

We explored the development of mental associations between time and space by asking whether preschoolers prefer spatial representations of temporal events that have a conventional ordered linear structure over those that do not. As in previous studies, we found that English-speaking adults strongly preferred spatial representations of events that were sequentially ordered across the horizontal axis from LR, consistent with their reading and writing direction. We also found that children begin to prefer depictions of events ordered from LR to those ordered from RL at around 5 years of age. However, directional preferences were not unique to the LR direction: both adults and 5-year-olds also preferred TB representations of events to BT ones. We found that children under age 5 required more scaffolding to ensure that they comprehended the task. When this was given, even 3- and 4-year-olds demonstrated preferences for sequential images to images that were out-of-order with respect to the narrative. This result suggests that children have an early preference for event representations to be organized into ordered lines, but leaves open when this emerges, and whether it is learned or the product of some kind of innate predisposition to represent time in a linear spatial sequence. Nonetheless, unlike adults and older children, 3- and 4-year-olds did *not* display conventional directional preferences when choosing between two ordered sequences. These findings suggest that specific directional associations between temporal narratives and spatial positions (e.g., an LR bias) are not innate, but are learned gradually during childhood.

Our findings are consistent with past work showing that although elementary-school children and adults have culture-specific biases in the way they spatially represent temporal events (e.g., Bergen & Chan Lau, 2012; Fuhrman & Boroditsky, 2010; Nachshon, 1983; Ouellet et al., 2010; Tillman et al., 2018; Tversky et al., 1991), most preschoolers do not (Tillman et al., 2018; but see Autry et al., 2019). Due to concerns that the difficulty of prior tasks may have led to underestimation of children's knowledge, here we designed a series of increasingly simple tasks. Unlike prior tasks, these did not require children to use a complex timeline (Busby Grant & Suddendorf, 2009; Friedman, 2000, 2002; Friedman & Kemp, 1998; Hudson & Mayhew, 2011; Tillman & Barner, 2015; Tillman et al., 2017), to produce symbolic, spatial representations of time (Tillman et al., 2018; Tversky et al., 1991), or to interpret sequential images and create their own narratives to describe them (e.g., Berman, 1988; Bulf et al., 2017; Poulsen et al., 1979; Trabasso & Nickels, 1992; Trabasso & Stein, 1994; Zampini et al., 2013, 2017). Instead, this task provided the child with the temporally organized narrative (a verbal story) and the spatial stimuli (sequences of images organized in lines). In the case of Experiment 3, we also provided a demonstration of which part of the event each image was meant to represent (i.e., simultaneous presentation of each image with the relevant part of the story, prior to the test). Moreover, the child needed only to point to a card to respond to the test questions. Using these methods, we found evidence that direction preferences do not emerge until around the time that North American children begin their formal education in kindergarten. Suggesting that this was not simply a result of overall task difficulty, we found that preschoolers were able to distinguish representations of time that were well-ordered with respect to the verbal narrative from ones that were not.

Our methods revealed an earlier preference for ordered linear representations of time than did some previous work. For example, in one prior study, researchers asked 4-year-olds to place stickers on paper to represent the relative locations of temporal events like breakfast, lunch, and dinner. When the experimenter did not provide any spatial priming, not only did a large majority of children fail to show a preference for LR to RL representations of time (consistent with the present results), most also did not produce ordered linear arrangements at all (Tillman et al., 2018). This contrasts with the present finding that even some 3-year-olds demonstrated a preference for ordered to unordered sequences in a two-alternative forced-choice task. Thus, while task difficulty cannot account for the lack of directional preferences in the current study, the need to produce linear representations of temporal events in prior studies may indeed have made those tasks less sensitive to some aspects of children's knowledge.

Still, it remains possible that even the present results underestimate children's early knowledge. All of the arrangements we used in all three experiments, including the "scrambled" cards that were out-of-order with respect to the narrative, were nevertheless geometrically arranged in lines. It is, therefore, possible that we would have found even earlier or stronger preferences for ordered lines if they had been contrasted with completely non-linear arrangements, for example, triangles.

In contrast to both the findings of the sticker-placement task and the present results, another recent study argues that 3-year-olds have an LR-specific MTL. In their Color Card task, Autry et al. (2019) asked children to place cards on a table one at a time as the corresponding colors appeared sequentially on a computer screen. They found that preschoolers made LR arrangements more frequently than chance. Future research should explore both low-level and possible theoretical explanations of this discrepancy. First, future work should rule out low level differences related to testing modality. For example, whereas our study asked children to select a picture to represent a story, Autry et al. required children to physically sort cards, raising the possibility that handedness played a role in sorting direction (since nearly all participants were right handed). Also, unlike the present task, the Color Card task made no reference to abstract time words or task-external temporal events. Although, as discussed above, we do not believe children had any global difficulty with the stimuli in the present task that could account for this discrepancy in results, differences in task difficulty should be considered.

More interesting theoretical explanations for differences in children's performance across tasks also exist. One possibility is that the Color Card task required a fundamentally different type of temporal cognition than the task used in the current study. Although it does not explicitly address tasks like those discussed here, a recent theory of temporal cognitive development makes a potentially relevant distinction between temporal *updating*, an evolutionarily ancient ability to keep track of perceptual changes in the environment as they unfold, and temporal *reasoning* about the ordering of events (Hoerl & McCormack, 2019). Temporal reasoning, which emerges around age 4 or 5, is thought to be required when the events under consideration are not ongoing or if there is a mismatch between the order information about events is received and the order those events actually occurred (Hoerl & McCormack, 2019). Paralleling this distinction, the Color Card task required children to spatially represent an ongoing perceptual sequence, while our card selection task required them to consider event sequences that were not ongoing. To choose between the two spatial representations in the current card selection task, participants needed to reason retrospectively about a multi-step narrative that had already "occurred" during the story-telling phase. In the sticker-placement task, children were also required to consider temporal items in an order that did not match their actual ordering, by placing two event-denoting stickers relative to one representing an intermediate time (Tillman et al., 2018; Tversky et al., 1991). In the Color Card task, there was no narrative to recall, and children only represented one item in the sequence at a time. Thus, it is possible that the Color Card task, like sequencing tasks used with infants (e.g., Bulf et al., 2017), primarily relied upon temporal updating, while our task, like the sticker-placement task, required temporal reasoning.

Importantly, the distinction between temporal updating and temporal reasoning cannot, on its own, explain why children appear to exhibit directional biases in some time-related tasks and not others. The "dual-systems" theory does not focus on how time is spatially represented and provides no explanation for why differential reliance on the systems should affect the ability to detect space-time mappings in children, whether the updating system might be subject to spatial biases, or how and when culturally conventional spatial representations of time are used during the development of temporal reasoning. Nevertheless, we believe exploring the relations among children's ability to process simple temporal sequences (e.g., unrelated colors and shapes), reason about temporal narratives (e.g., meaningful multi-step events), and use space to represent each, might be a fruitful direction for future research.

Although our study provides strong evidence that directional preferences are gradually learned in childhood, it leaves open whether the MTL is entirely learned, or if it might be the result of a biologically determined tendency to represent time in a linear spatial fashion. The present findings fail to support accounts on which humans have an innate bias to represent time specifically from LR, since such preferences were not found in our youngest participants, despite the fact that they did show a preference for ordered linear sequences (e.g., Bulf et al., 2016; Chatterjee et al., 1999; Dehaene et al., 1993; Vicario et al., 2007). However, they leave open the ontogenetic origin of children's preference for ordered linear sequences and whether it is driven by innate biases of some form or learned before the age of 3. In addition, if such a predisposition were innate, it is unclear what might explain it—a question seldom discussed in the developmental literature. One possibility, mentioned in the Introduction, is that physical lines may provide a natural format for representing time because they minimize distance between points, potentially reducing the effort required to visually perceive relations between depicted events. However, although this factor might play a role, the mere efficiency of lines as a representational format could not alone explain a preference to use lines to represent time. In addition, children would need to conceive of time as a linear dimension, recognize that time can be represented spatially, and notice that spatial lines and temporal sequences partake in an analogy that permits physical lines to represent temporal sequences. Finally, even given all of this, children would need to prefer such an efficient use of space to represent temporal sequences.

Future work should consider these possibilities, and when children's preferences first emerge.

Although studies have come to different conclusions about the onset of the MTL, they provide convergent evidence that it develops gradually across the preschool and early school years. Across studies, school-aged children consistently prefer culturally conventional directions (e.g., Autry et al., 2019; Tillman et al., 2018; Tversky et al., 1991), while preschoolers' performance is weaker and more variable. Even in cases where we found evidence that, as a group, preschoolers performed above chance, the percentage of individual children who chose the conventional representation on at least 7 of 8 trials, which is required for an individual to perform significantly above chance, was often very low, indicating a fair degree of heterogeneity across children. This heterogeneity was also reflected by the presence of bimodal distributions across our experiments, suggesting that the MTL does not emerge at the same age in every child (see Figures 2 and 3). Why might some children, but not others, develop directional space-time mappings prior to entering school? Although these data should be interpreted with caution, preliminary findings from our parent survey suggest that precocious development of the MTL may be linked to earlier writing skills. While we did not find an effect of preschool attendance in this analysis, there is variation across preschools, elementary schools, and cultures in when children begin to receive explicit instruction on writing. Autry et al. (2019) also found a correlation between children's comprehension of print and their production of LR representations, further suggesting that literacy is linked to the development of the MTL.

To summarize, we have presented data from three experiments demonstrating a protracted developmental trajectory in children's acquisition of adult-like preferences for visual representations of events. Beginning at age 3, children were able to associate progress in time with relative order in space, but only after the images had been unveiled one at a time as the relevant elements of an accompanying story were told. However, conventional direction preferences did not emerge before the age of 5, when there is typically a substantial increase in children's exposure to spatial artifacts for time and explicit instruction in reading. Finally, even at that age, children's preferences for culturally conventional spatial representations of time remained far weaker than those of adults and were not limited to the LR direction.

ACKNOWLEDGMENTS

We thank Desia Bacon, Nicole Bonnano, Junyi Chu, Lara Haine, Ana Magallanes, Ashlie Pankonin, and Yiqiao Wang for assistance with data collection and recruitment; Caren Walker for early discussions of study design; and Jessica Sullivan for helpful comments on the manuscript. We are most grateful to our participating daycares and schools in the Comox Valley, BC, and San Diego, CA, areas, the Birch Aquarium and Fleet Science Center in San Diego, and the many children and families who participated in the study. We thank an anonymous reviewer for the suggestion that linear representations of time may be preferred because they minimize demands on visual processing. A subset of the data reported here also appeared in the *Proceedings of the 39rd Annual Meeting of the Cognitive Science Society* (Tillman et al., 2017), and funding for this project was provided by a grant to DB from the James S. McDonnell Foundation.

ORCID

Katharine A. Tillman https://orcid.org/0000-0001-9440-7239

REFERENCES

Autry, K. S., Jordan, T. M., Girgis, H., & Falcon, R. G. (2019). The development of young children's mental timeline in relation to emergent literacy skills. *Journal of Cognition and Development*, *21*, 1–22. https://doi.org/10.1080/15248372.2019.1664550

Bender, A., & Beller, S. (2014). Mapping spatial frames of reference onto time: A review of theoretical accounts and empirical findings. *Cognition*, *132*, 342–382. https://doi.org/10.1016/j.cognition.2014.03.016

Bergen, B., & Chan Lau, T. T. (2012). Writing direction affects how people map space onto time. *Frontiers in Psychology*, *3*. https://doi.org/10.3389/fpsyg.2012.00109

Berman, R. A. (1988). On the ability to relate events in narrative. *Discourse Processes*, *11*, 469–497. https://doi.org/10.1080/01638538809544714

Bonato, M., Zorzi, M., & Umiltà, C. (2012). When time is space: Evidence for a mental time line. *Neuroscience & Biobehavioral Reviews*, *36*, 2257–2273. https://doi.org/10.1016/j.neubiorev.2012.08.007

Bornens, M.-T. (1990). Problems brought about by "reading" a sequence of pictures. *Journal of Experimental Child Psychology*, *49*, 189–226. https://doi.org/10.1016/0022-0965(90)90055-D

Boroditsky, L., & Gaby, A. (2010). Remembrances of times east: Absolute spatial representations of time in an Australian Aboriginal Community. *Psychological Science*, *21*, 1635–1639. https://doi.org/10.1177/0956797610386621

Brooks, J. L., Della Sala, S., & Darling, S. (2014). Representational pseudoneglect: A review. *Neuropsychology Review*, *24*, 148–165. https://doi.org/10.1007/s11065-013-9245-2

Bulf, H., de Hevia, M. D., & Cassia, V. M. (2016). Small on the left, large on the right: Numbers orient visual attention onto space in preverbal infants. *Developmental Science*, *19*, 394–401. https://doi.org/10.1111/desc.12315

Bulf, H., de Hevia, M. D., Gariboldi, V., & Cassia, V. M. (2017). Infants learn better from left to right: A directional bias in infants' sequence learning. *Scientific Reports*, *7*, 1–6. https://doi.org/10.1038/s41598-017-02466-w

Busby Grant, J., & Suddendorf, T. (2009). Preschoolers begin to differentiate the times of events from throughout the lifespan. *European Journal of Developmental Psychology*, *6*, 746–762. https://doi.org/10.1080/17405620802102947

Casasanto, D., & Bottini, R. (2014). Mirror reading can reverse the flow of time. *Journal of Experimental Psychology: General*, *143*, 473–479. https://doi.org/10.1037/a0033297

Chatterjee, A. (2001). Language and space: Some interactions. *Trends in Cognitive Sciences*, *5*, 55–61. https://doi.org/10.1016/S1364-6613(00)01598-9

Chatterjee, A., Southwood, M. H., & Basilico, D. (1999). Verbs, events and spatial representations. *Neuropsychologia*, *37*, 395–402. https://doi.org/10.1016/S0028-3932(98)00108-0

Cheung, C.-N., & Lourenco, S. F. (2016). The associations between space and order in numerical and non-numerical sequences. *Consciousness and Cognition*, *45*, 124–134. https://doi.org/10.1016/j.concog.2016.08.013

Cohn, N. (2020). Visual narrative comprehension: Universal or not? *Psychonomic Bulletin & Review*, *27*, 266–285. https://doi.org/10.3758/s13423-019-01670-1

Dadda, M., Zandona, E., Agrillo, C., & Bisazza, A. (2009). The costs of hemispheric specialization in a fish. *Proceedings of the Royal Society B: Biological Sciences*, *276*, 4399–4407. https://doi.org/10.1098/rspb.2009.1406

De Hevia, M. D., Girelli, L., & Macchi Cassia, V. (2012). Minds without language represent number through space: Origins of the mental number line. *Frontiers in Psychology*, *3*, 466. https://doi.org/10.3389/fpsyg.2012.00466

de Hevia, M. D., Izard, V., Coubart, A., Spelke, E. S., & Streri, A. (2014). Representations of space, time, and number in neonates. *Proceedings of the National Academy of Sciences of the United States of America*, *111*, 4809–4813. https://doi.org/10.1073/pnas.1323628111

de Hevia, M. D., Macchi Cassia V., Veggiotti L., Netskou M. E. (2020). Discrimination of ordinal relationships in temporal sequences by 4-month-old infants. *Cognition*, *195*, 104091. https://doi.org/10.1016/j.cognition.2019.104091

de Hevia, M. D., Veggiotti, L., Streri, A., & Bonn, C. D. (2017). At birth, humans associate "few" with left and "many" with right. *Current Biology*, *27*, 3879–3884.e2. https://doi.org/10.1016/j.cub.2017.11.024

Dehaene, S., Bossini, S., & Giraux, P. (1993). The mental representation of parity and number magnitude. *Journal of Experimental Psychology: General*, *122*, 371–396. https://doi.org/10.1037/0096-3445.122.3.371

Dobel, C., Diesendruck, G., & Bölte, J. (2007). How writing system and age influence spatial representations of actions: A developmental, cross-linguistic study. *Psychological Science*, *18*, 487–491. https://doi.org/10.1111/j.1467-9280.2007.01926.x

Droit-Volet, S., & Coull, J. (2015). The developmental emergence of the mental time-line: Spatial and numerical distortion of time judgement. *PLoS One*, *10*. https://doi.org/10.1371/journal.pone.0130465

Fivush, R., & Mandler, J. M. (1985). Developmental changes in the understanding of temporal sequence. *Child Development*, *56*, 1437–1446. https://doi.org/10.2307/1130463

Friedman, W. J. (1990). Children's representations of the pattern of daily activities. *Child Development*, *61*, 1399–1412. https://doi.org/10.1111/j.1467-8624.1990.tb02870.x

Friedman, W. J. (2000). The development of children's knowledge of the times of future events. *Child Development*, *71*, 913–932. https://doi.org/10.1111/1467-8624.00199

Friedman, W. J. (2002). Children's knowledge of the future distances of daily activities and annual events. *Journal of Cognition and Development*, *3*, 333–356. https://doi.org/10.1207/S15327647JCD0303_4

Friedman, W. J., & Kemp, S. (1998). The effects of elapsed time and retrieval on young children's judgments of the temporal distances of past events. *Cognitive Development*, *13*, 335–367. https://doi.org/10.1016/S0885-2014(98)90015-6

Fuhrman, O., & Boroditsky, L. (2010). Cross-cultural differences in mental representations of time: Evidence from an implicit nonlinguistic task. *Cognitive Science*, *34*, 1430–1451. https://doi.org/10.1111/j.1551-6709.2010.01105.x

Gell, A. (1992). *The anthropology of time: Cultural constructions of temporal maps and images*. Routledge.

Göbel, S. M., McCrink, K., Fischer, M. H., & Shaki, S. (2018). Observation of directional storybook reading influences young children's counting direction. *Journal of Experimental Child Psychology*, *166*, 49–66. https://doi.org/10.1016/j.jecp.2017.08.001

Hoerl, C., & McCormack, T. (2019). Thinking in and about time: A dual systems perspective on temporal cognition. *Behavioral and Brain Sciences*, *42*, e244. https://doi.org/10.1017/S0140525X18002157

Hudson, J. A., & Mayhew, E. M. (2011). Children's temporal judgments for autobiographical past and future events. *Cognitive Development*, *26*, 331–342. https://doi.org/10.1016/j.cogdev.2011.09.005

Ishihara, M., Keller, P. E., Rossetti, Y., & Prinz, W. (2008). Horizontal spatial representations of time: Evidence for the STEARC effect. *Cortex*, *44*, 454–461. https://doi.org/10.1016/j.cortex.2007.08.010

Lourenco, S. F., & Longo, M. R. (2010). General magnitude representation in human infants. *Psychological Science*, *21*, 873–881. https://doi.org/10.1177/0956797610370158

Maass, A., & Russo, A. (2003). Directional bias in the mental representation of spatial events: Nature or culture? *Psychological Science*, *14*, 296–301. https://doi.org/10.1111/1467-9280.14421

Nachshon, I. (1983). Asymmetry in lateral directionality. *International Journal of Neuroscience*, *19*, 191–203. https://doi.org/10.3109/00207458309148655

Núñez, R., Cooperrider, K., Doan, D., & Wassmann, J. (2012). Contours of time: Topographic construals of past, present, and future in the Yupno valley of Papua New Guinea. *Cognition*, *124*, 25–35. https://doi.org/10.1016/j.cognition.2012.03.007

Núñez, R. E., & Sweetser, E. (2006). With the future behind them: Convergent evidence from aymara language and gesture in the crosslinguistic comparison of spatial construals of time. *Cognitive Science*, *30*, 401–450. https://doi.org/10.1207/s15516709cog0000_62

Opfer, J. E., Thompson, C. A., & Furlong, E. E. (2010). Early development of spatial-numeric associations: Evidence from spatial and quantitative performance of preschoolers. *Developmental Science*, *13*, 761–771. https://doi.org/10.1111/j.1467-7687.2009.00934.x

Ouellet, M., Santiago, J., Israeli, Z., & Gabay, S. (2010). Is the future the right time? *Experimental Psychology*, *57*, 308–314. https://doi.org/10.1027/1618-3169/a000036

Patro, K., Nuerk, H., & Cress, U. (2016). Mental number line in the preliterate brain: The role of early directional experiences. *Child Development Perspectives*, *10*, 172–177. https://doi.org/10.1111/cdep.12179

Pitt, B., & Casasanto, D. (2020). The correlations in experience principle: How culture shapes concepts of time and number. *Journal of Experimental Psychology: General*, *149*(6), 1048. https://doi.org/10.1037/xge0000696

Pitt, B., Ferrigno, S., Cantlon, J. F., Casasanto, D., Gibson, E., & Piantadosi, S. T. (2021). Spatial concepts of number, size, and time in an indigenous culture. *Science Advances*, *7*(33), eabg4141. https://doi.org/10.1126/sciadv.abg4141

Poulsen, D., Kintsch, E., Kintsch, W., & Premack, D. (1979). Children's comprehension and memory for stories. *Journal of Experimental Child Psychology*, *28*, 379–403. https://doi.org/10.1016/0022-0965(79)90070-5

Rosen, G. D., Galaburda, A. M., & Sherman, G. F. (1987). Mechanisms of brain asymmetry: New evidence and hypotheses. In D. Ottoson (Ed.), *Duality and unity of the brain* (pp. 29–36). Springer.

Rugani, R., Kelly, D. M., Szelest, I., Regolin, L., & Vallortigara, G. (2010). Is it only humans that count from left to right? *Biology Letters*, *6*, 290–292. https://doi.org/10.1098/rsbl.2009.0960

Rugani, R., Lunghi, M., Giorgio, E. D., Regolin, L., Barba, B. D., Vallortigara, G., & Simion, F. (2017). A mental number line in human newborns. *BioRxiv*, 159335. https://doi.org/10.1101/159335

Rugani, R., Vallortigara, G., Priftis, K., & Regolin, L. (2015). Number-space mapping in the newborn chick resembles humans' mental number line. *Science*, *347*, 534–536. https://doi.org/10.1126/science.aaa1379

Santiago, J., Lupáñez, J., Pérez, E., & Funes, M. J. (2007). Time (also) flies from left to right. *Psychonomic Bulletin & Review*, *14*, 512–516. https://doi.org/10.3758/BF03194099

Sénéchal, M., LeFevre, J.-A., Hudson, E., & Lawson, E. P. (1996). Knowledge of storybooks as a predictor of young children's vocabulary. *Journal of Educational Psychology*, *88*, 520. https://doi.org/10.1037/0022-0663.88.3.520

Sénéchal, M., Lefevre, J.-A., Thomas, E. M., & Daley, K. E. (1998). Differential effects of home literacy experiences on the development of oral and written language. *Reading Research Quarterly*, *33*, 96–116. https://doi.org/10.1598/RRQ.33.1.5

Shaki, S., Fischer, M. H., & Göbel, S. M. (2012). Direction counts: A comparative study of spatially directional counting biases in cultures with different reading directions. *Journal of Experimental Child Psychology*, *112*, 275–281. https://doi.org/10.1016/j.jecp.2011.12.005

Srinivasan, M., & Carey, S. (2010). The long and the short of it: On the nature and origin of functional overlap between representations of space and time. *Cognition*, *116*, 217–241. https://doi.org/10.1016/j.cognition.2010.05.005

Tillman, K. A., & Barner, D. (2015). Learning the language of time: Children's acquisition of duration words. *Cognitive Psychology*, *78*, 57–77. https://doi.org/10.1016/j.cogpsych.2015.03.001

Tillman, K. A., Marghetis, T., Barner, D., & Srinivasan, M. (2017). Today is tomorrow's yesterday: Children's acquisition of deictic time words. *Cognitive Psychology*, *92*, 87–100. https://doi.org/10.1016/j.cogpsych.2016.10.003

Tillman, K. A., Tulagan, N., Fukuda, E., & Barner, D. (2018). The mental timeline is gradually constructed in childhood. *Developmental Science*, *21*, e12679. https://doi.org/10.1111/desc.12679

Trabasso, T., & Nickels, M. (1992). The development of goal plans of action in the narration of a picture story. *Discourse Processes*, *15*, 249–275. https://doi.org/10.1080/01638539209544812

Trabasso, T., & Stein, N. L. (1994). Using goal-plan knowledge to merge the past with the present and the future in narrating. In M. M. Haith, J. B. Benson, R. J. Roberts & B. F. Pennington (Eds.), *The development of future-oriented processes* (pp. 323–349). University of Chicago Press.

Tversky, B., Kugelmass, S., & Winter, A. (1991). Cross-cultural and developmental trends in graphic productions. *Cognitive Psychology*, *23*, 515–557. https://doi.org/10.1016/0010-0285(91)90005-9

Vallortigara, G., Regolin, L., Chiandetti, C., & Rugani, R. (2010). Rudiments of mind: Insights through the chick model on number and space cognition in animals. *Comparative Cognition & Behavior Reviews*, *5*, 78–99. https://doi.org/10.3819/ccbr.2010.50004

Vicario, C. M., Caltagirone, C., & Oliveri, M. (2007). Optokinetic stimulation affects temporal estimation in healthy humans. *Brain and Cognition*, *64*, 68–73. https://doi.org/10.1016/j.bandc.20s06.12.002

Zampini, L., Suttora, C., D'Odorico, L., & Zanchi, P. (2013). Sequential reasoning and listening text comprehension in preschool children. *European Journal of Developmental Psychology*, *10*, 563–579. https://doi.org/10.1080/17405629.2013.766130

Zampini, L., Zanchi, P., Suttora, C., Spinelli, M., Fasolo, M., & Salerni, N. (2017). Assessing sequential reasoning skills in typically developing children. *Applied Psychology Bulletin*, *65*, 44–50.

SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.

How to cite this article: Tillman, K. A., Fukuda, E., & Barner, D. (2022). Children gradually construct spatial representations of temporal events. *Child Development*, *00*, 1–18. https://doi.org/10.1111/cdev.13780

APPENDIX

TABLE A1 Event stories

Event	First…	Then…	And…	Images (LR)
Egg	There was an egg	The egg cracked	A baby chick came out!	
Ice Cream	There was an ice-cream	It started melting	It was all gone!	
Drawing	Someone started drawing a stem	They added blue petals	It was a flower!	
Caterpillar	There was a caterpillar	It made a cocoon	It turned into a butterfly!	
Baby	A baby was born	He started growing	He was a big kid!	
Apple	There was an apple	Someone took a bite	They ate it all!	
Rose	A rose started growing	It opened	It got big and pink!	
Watermelon	There was a watermelon	We cut it all up	Everyone ate it!	

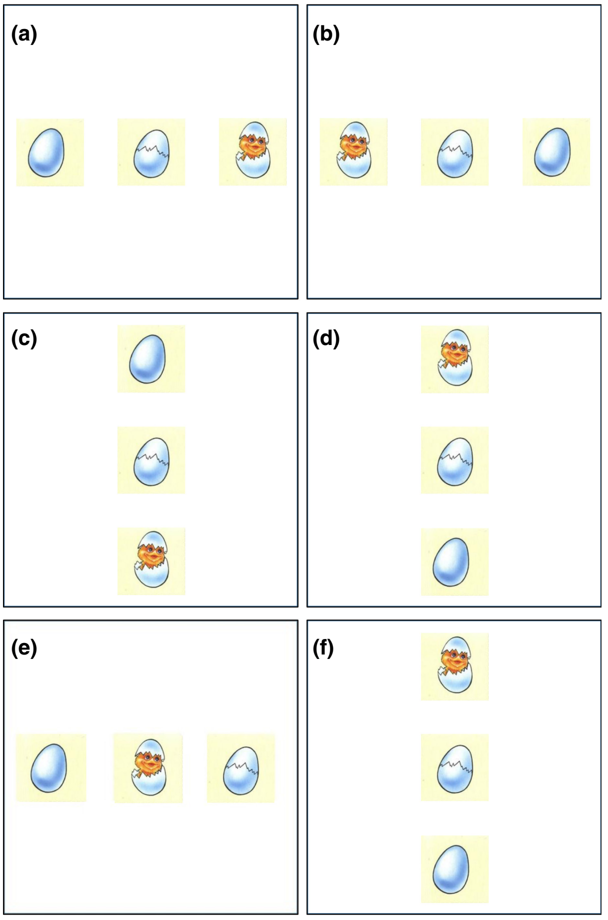


FIGURE A1 Example picture cards. The three images on each card depict the three stages in the Egg story (see Table 1). Cards used in Experiments 1 and 3: (a) LR, left-to-right, (b) RL, right-to-left, (c) TB, top-to-bottom, and (d) BT, bottom-to-top. Additional cards used only in Experiments 2 and 3: (e) scrambled horizontal and (f) scrambled vertical