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Numerical Cognition in Action: Reaching Behavior Reveals Numerical Distance Effects in 5- to 6-Year-Olds

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Abstract

This study investigates how children's numerical cognition is reflected in their unfolding actions. Five- and 6-year-olds (N = 34) completed a numerical comparison task by reaching to touch one of three rectangles arranged horizontally on a digital display. A number from 1 to 9 appeared in the center rectangle on each trial. Participants were instructed to touch the left rectangle for numbers 1-4, the center rectangle for 5, and the right rectangle for 6-9. Reach trajectories were more curved toward the center rectangle for numbers closer to 5 (e.g., 4) than numbers further from 5 (e.g., 1). This finding indicates that a tight coupling exists between numerical and spatial information in children's cognition and action as early as the preschool years. In addition to shedding new light on the spatial representation of numbers during childhood, our results highlight the promise of incorporating measures of manual dynamics into developmental research.

Keywords: cognitive development, numerical distance effect (NDE), reach tracking, spatial cognition

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A longstanding question in numerical cognition concerns the extent to which children and adults mentally represent numbers in terms of space. Early evidence of the integration of numerical and spatial information came from a study by Moyer and Landauer (1967) in which adults identified which of two numbers (e.g., 8 vs. 5) was numerically larger by flipping a switch with their left or right hand. Response times on the task decreased linearly as the distance between the numbers increased, with smaller differences (e.g., 4 vs. 3) generating longer response times than larger differences (e.g., 2 vs. 8). This *numerical distance effect* (NDE) has been interpreted as evidence that numerical symbols are encoded in terms of their analog magnitudes along a mental number line that maps numerical relations onto spatial relations (e.g., Dehaene, Bossini, & Giraux, 1993; Dehaene, Dupoux, & Mehler, 1990; Restle, 1970).

A more recent but related question concerns the extent to which bodily states shape and reflect how we represent and reason about numbers (e.g., Lakoff & Núñez, 2000). To shed light on this question, researchers have turned to techniques such as mouse tracking and 3-dimensional reach tracking to measure how numerical cognition is reflected in continuous hand movements (e.g., Chapman et al., 2014; Dotan & Dehaene, 2013; Faulkenberry, 2016; Faulkenberry & Rey, 2014; Fischer & Hartmann, 2014; Marghetis, Núñez, & Bergen, 2014; Santens, Goossens, & Verguts, 2011; Song & Nakayama, 2008). These techniques provide a more direct measure of the spatial representation of number than discrete button presses and present new opportunities to develop and test models linking numerical cognition to action (e.g., Dotan & Dehaene, 2013). Although mouse tracking and reach tracking have been used extensively to investigate numerical cognition in adults, little research has used these techniques to explore the development of numerical cognition during childhood.

The current study addresses this gap in the literature by investigating the extent to which children's hand movements reflect the spatial representation of numbers. Ishihara et al. (2006) explored this question with adults by having participants reach to touch numbers between 1 and 9 as they appeared one at a time in one of five locations arranged horizontally on a touchscreen. Participants' initiation times (the time elapsed between stimulus onset and movement onset) were fastest when the magnitude of the number was congruent with its location on the screen. For example, responses to 9 were fastest when the digit was presented at the rightmost response location. Movement times (the time elapsed between movement onset and response completion), however, did not reveal evidence of the integration of numerical and spatial information. This finding led the researchers to conclude that the integration of numerical and spatial information was restricted to early planning-related processes and did not influence processes related to action execution.

Although the results of Ishihara et al. (2006) suggested that the integration of numerical and spatial information did not extend to online movements, the study did not directly measure movement trajectories. To address this limitation, Song and Nakayama (2008) measured participants' hand movements as they performed a numerical comparison task. They presented participants with three rectangles arranged horizontally on a digital display. On each trial, a number ranging from 1 to 9 appeared in the center rectangle. Participants were instructed to touch the left rectangle for numbers 1-4, the center rectangle for 5, and the right rectangle for 6-9. All responses were initiated from a designated starting location and movements were recorded by having participants wear a motion-tracking device on their pointing finger. Reach trajectories revealed a NDE, with reaches to the left and right targets showing more curved trajectories as the distance between the presented number and the standard of 5 decreased. For example, reach movements were more curved toward the center rectangle for responses to 4 and 6 (a distance of 1 from the standard) than for responses to 2 and 8 (a distance of 3 from the standard).

In light of recent research indicating that reach tracking is suitable for use with children (Erb & Marcovitch, 2018a, 2018b; Erb, Moher, Song, & Sobel, 2017, 2018), the present study extends a version of the Song and Nakayama (2008) procedure to a group of 5- and 6-year-olds. Song and Nakayama's investigation suggests that the spatial representation of numbers extends beyond early planning-related processes in adults to influence their online actions. It is currently unknown when in development this integration of numerical and spatial information is evident in action execution. Previous research indicates that the NDE can be observed in children's response times by age 5 (Sekuler & Mierkiewicz, 1977; Temple & Posner, 1998). Given that response time differences reflect both early planning-related processes and later processes related to action execution, however, it is unclear whether the effects previously observed in children reflect processes related to action planning, action execution, or both; the reach tracking methodology allows us to address this question.

Methods

Participants

Thirty-four right-handed 5- to 6-year-olds (*M* = 73.1 months, *SD* = 7.4 months, range = 61.1 to 83.5 months, 23 females) participated in the experiment and are included in the final sample. Two additional children were tested but committed an extreme number of errors (>20%) and were excluded from further analysis. All children had normal reaching behavior and normal or corrected-to-normal vision. Participants were recruited from a list of birth records or through contact at a local children's museum. The Institutional Review Board at Brown University approved the protocol and all testing took place at Brown University's campus.

Materials

A Plexiglas screen was mounted onto a table approximately 48 centimeters in front of the participant and a rear-mounted projector was used to display the task onto the screen. Participants wore a small motion-tracking marker on their right index finger and an electromagnetic position and orientation recording system (Liberty, Polhemus) was used to record reach movements and response selections at a rate of approximately 160 Hz. The task was programmed in MATLAB (Mathworks).

Procedure

Participants first completed a 9-point calibration sequence followed by 16 trials of a baseline task. In the baseline task, an orange smiley face or a purple star appeared toward the top left or right of the display and participants reached to touch the image once it appeared. This task served to familiarize participants with apparatus and the basic procedure. Participants initiated their movements in the baseline task and the experiment from a Styrofoam starting block located 27 cm in front of the Plexiglas screen. Each trial would initiate once the participant's finger rested on the starting block for 500 ms, after which time a crosshair appeared toward the top center of the screen for 500 ms. If the participant moved his or her hand away from the starting block before the stimulus appeared, the task paused and did not resume until the participant returned their finger to the starting block for 500 ms.

Following the baseline task, participants were introduced to the numerical comparison task (see Figure 1). Participants were told that three rectangles would appear toward the top of the screen, and the experimenter gestured to the location of each rectangle. The experimenter stated that a number would appear in the center rectangle and explained that the participant's task was to press the left rectangle for numbers 1-4, the center rectangle for 5, and the right rectangle for numbers 6-9 ["If you see a 1, 2, 3, or 4, I want you to touch this rectangle (gesturing to the left response location). If you see a 5, I want you to touch this rectangle (gesturing to the center response location). If you see a 6, 7, 8, or 9, I want you to touch this rectangle (gesturing to the right response location)."]. The experimenter then repeated the rules of the task and quizzed the participants on one number from each location (e.g., "Which rectangle do you touch if you see a 7? What about a 2? What if you see a 5?"). If the participant answered any of these questions incorrectly, the experimenter repeated the rules and quizzed the participant again until he or she answered the questions correctly. The experimenter then informed participants that they would have a limited amount of time to respond, and instructed the children to perform the task quickly (“You can’t take too long to touch the rectangle, so try to go quick, okay?”).

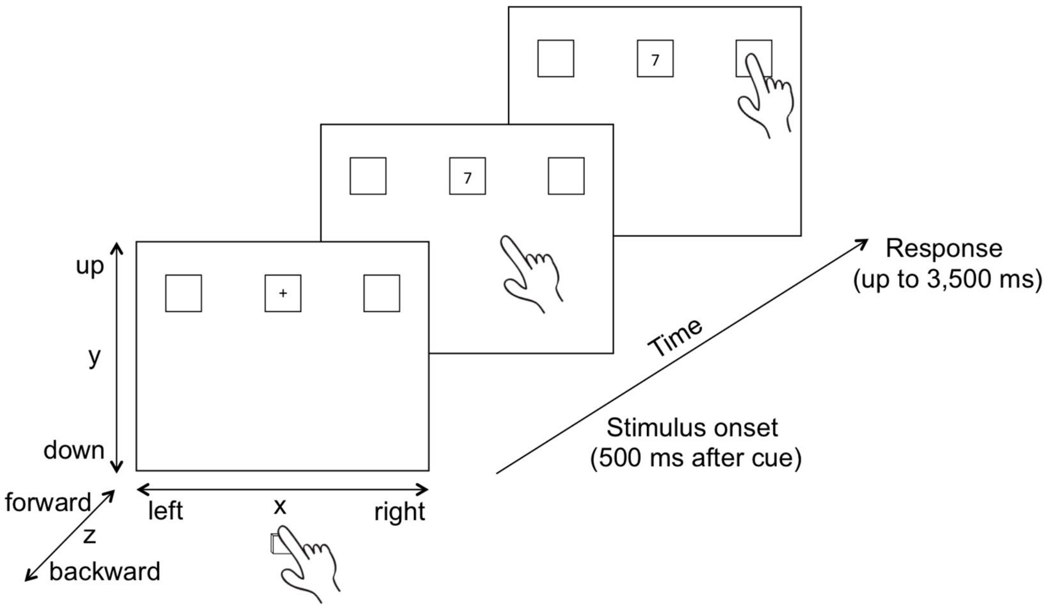

Figure 1. Illustration of the numerical comparison task. A digit (1-9) appeared in the center rectangle after a cue. Participants were instructed to touch the left rectangle for numbers 1-4, the center rectangle for 5, and the right rectangle for 6-9. Reach movements were recorded along the *x* (left-right), *y* (up-down), and *z* (forward-backward) axes. Figure adapted from Song and Nakayama (2008).

Participants completed two blocks of the numerical comparison task. Each block consisted of 45 trials, with each digit from 1 to 9 appearing five times in a randomized order. The task was displayed on a white background. The three rectangles were white with a black border, measuring 4.2 cm x 4.3 cm. Before each number appeared, a crosshair 0.6 cm x 0.6 cm appeared in the center of the middle rectangle for 500 ms. Each number was presented in the center of the middle rectangle in black text and had a max width of 1.2 cm and a height of 1.3 cm. Participants had 3,500 ms to respond after stimulus presentation. Correct responses in the allotted amount of time resulted in a high tone sounding, while incorrect responses or responses that exceeded the time limit resulted in a low tone sounding. The first 10 trials of the first block served as practice and were excluded from analysis.

Data Processing

The processing procedures used in the current study were largely adapted from Moher and Song (2013). Three-dimensional resultant speed scalars were created for each trial using a differentiation procedure in MATLAB. These scalars were then submitted to a second order, low-pass Butterworth filter with a cutoff of 10 Hz. Movement onset was calculated as the first point on each trial after stimulus onset at which hand movement speed exceeded 25.4 cm/s. Each individual trial was visually inspected as in previous work (Song & Nakayama, 2006, 2007); for trials in which the default threshold clearly missed part of the movement or included substantial movement back to the starting point, thresholds were adjusted manually.

Initiation time was calculated as the time elapsed between stimulus onset and movement onset; movement time was calculated as the time elapsed between movement onset and response completion; total time was calculated as the time elapsed between stimulus onset and response completion. Trajectories for calculating curvature were measured in two-dimensional *xy* space by calculating a line from the start to the end point of the movement, and measuring the orthogonal deviation of the actual movement from that line at each sample. Curvature was defined as the maximum point of deviation in centimeters divided by the length of the line from the start to the end points of the movement in centimeters (following Desmurget, Jordan, Prablanc, & Jeannerod, 1997; Moher & Song, 2013).

Movements that were curved toward an alternative response target were scored as positive (e.g., a movement ending at the left response target that was curved toward the right), whereas movements that were curved away from an alternative response target were scored as negative (e.g., a movement ending at the right response target that was curved toward the right). Direction of curvature (rightward or leftward) was determined by comparing the maximum point of deviation to a line connecting the start and end points of a movement. Given that all curved movements ending at the center target would be in the direction of an alternative response target, all movements to the center target were scored as positive regardless of the direction of curvature.

Results

Following Song and Nakayama (2008), we analyzed performance as a function of each number's distance from the Standard of 5: Distance 4 (D4) = 1 and 9, Distance 3 (D3) = 2 and 8, Distance 2 (D2) = 3 and 7, and Distance 1 (D1) = 4 and 6. We also evaluated the effect of response location (left vs. right) in light of recent research indicating that movement direction can influence how the NDE is expressed in reaching behavior (Faulkenberry, 2016). Thus, performance was analyzed with a series of 4 (Distance: D4, D3, D2, D1) x 2 (Location: Left, Right) repeated measures ANOVAs. To control for post-error adjustments in performance (e.g., Danielmeier & Ullsperger, 2011), only accurate trials preceded by an accurate trial were included in the following analyses for each of the measures but error rate.

Distance Scores

Average performance on each measure is presented in Figure 2. Mauchly's Test of Sphericity indicated that a number of analyses violated the assumptions of sphericity, p-values < .05. Consequently, the results from these analyses are reported using a Greenhouse-Geisser correction.

Error rates revealed a significant main effect of Distance, $F(1.84, 60.81) = 5.93$, $p = .005$, $\eta_p^2 = .15$ (see Figure 2A), with a significant linear trend, $F(1, 33) = 9.68$, $p = .004$, $\eta_p^2 = .23$, and a significant quadratic trend, $F(1, 33) = 5.99$, $p = .020$, $\eta_p^2 = .15$. The interaction between Distance and Location approached significance, $F(2.29, 75.69) = 2.72$, $p = .065$, $\eta_p^2 = .08$. Follow-up tests revealed that the effect of Distance did not reach significance for responses to the left target, $F(2.27, 75.01) = 1.04$, $p = .37$, $\eta_p^2 = .03$, but did reach significance for responses to the right target, $F(1.58, 52.08) = 6.09$, $p = .007$, $\eta_p^2 = .16$, with a significant linear trend, $F(1, 33) = 8.41$, $p = .007$, $\eta_p^2 = .20$, and a significant quadratic trend, $F(1, 33) = 5.88$, $p = .021$, $\eta_p^2 = .15$.

Initiation times revealed a significant interaction between Distance and Location, $F(3, 99) = 3.66$, $p = .015$, $\eta_p^2 = .10$ (see Figure 2B). Follow-up tests revealed a significant effect of Distance for responses to the left target,

$F(2.22, 73.14) = 3.86$, $p = .022$, $\eta_p^2 = .10$, with a significant linear trend, $F(1, 33) = 7.85$, $p = .008$, $\eta_p^2 = .19$. The effect of Distance did not reach significance for responses to the right target, $F(3, 99) = 1.90$, $p = .13$, $\eta_p^2 = .05$.

Movement times revealed a significant main effect of Distance, $F(2.29, 75.49) = 15.34$, $p < .001$, $\eta_p^2 = .32$, with a significant linear trend, $F(1, 33) = 34.76$, $p < .001$, $\eta_p^2 = .51$, and a significant quadratic trend, $F(1, 33) = 4.61$, $p = .039$, $\eta_p^2 = .12$ (see Figure 2C). The effect of Location and the interaction between Distance and Location did not approach significance in movement times, *p*-values > .11.

Total times revealed a significant main effect of Distance, $F(2.43, 80.05) = 12.71$, $p < .001$, $\eta_p^2 = .28$, with a significant linear trend, $F(1, 33) = 26.55$, $p < .001$, $\eta_p^2 = .45$ (see Figure 2D). The effect of Location and the interaction between Distance and Location did not approach significance in total times, *p*-values > .36.

Reach curvatures revealed a significant main effect of Distance, $F(2.31, 76.31) = 6.67$, $p = .001$, $\eta_p^2 = .17$, with a significant linear trend, $F(1, 33) = 16.07$, $p < .001$, $\eta_p^2 = .33$ (see Figure 2E). Reach curvatures also revealed a significant main effect of Location, $F(1, 33) = 28.16$, $p < .001$, $\eta_p^2 = .46$, with larger curvatures observed for responses to the left target relative to the right target. Importantly, no interaction was observed between Distance and Location in reach curvatures, $F(2.57, 84.74) = 1.04$, $p = .37$.

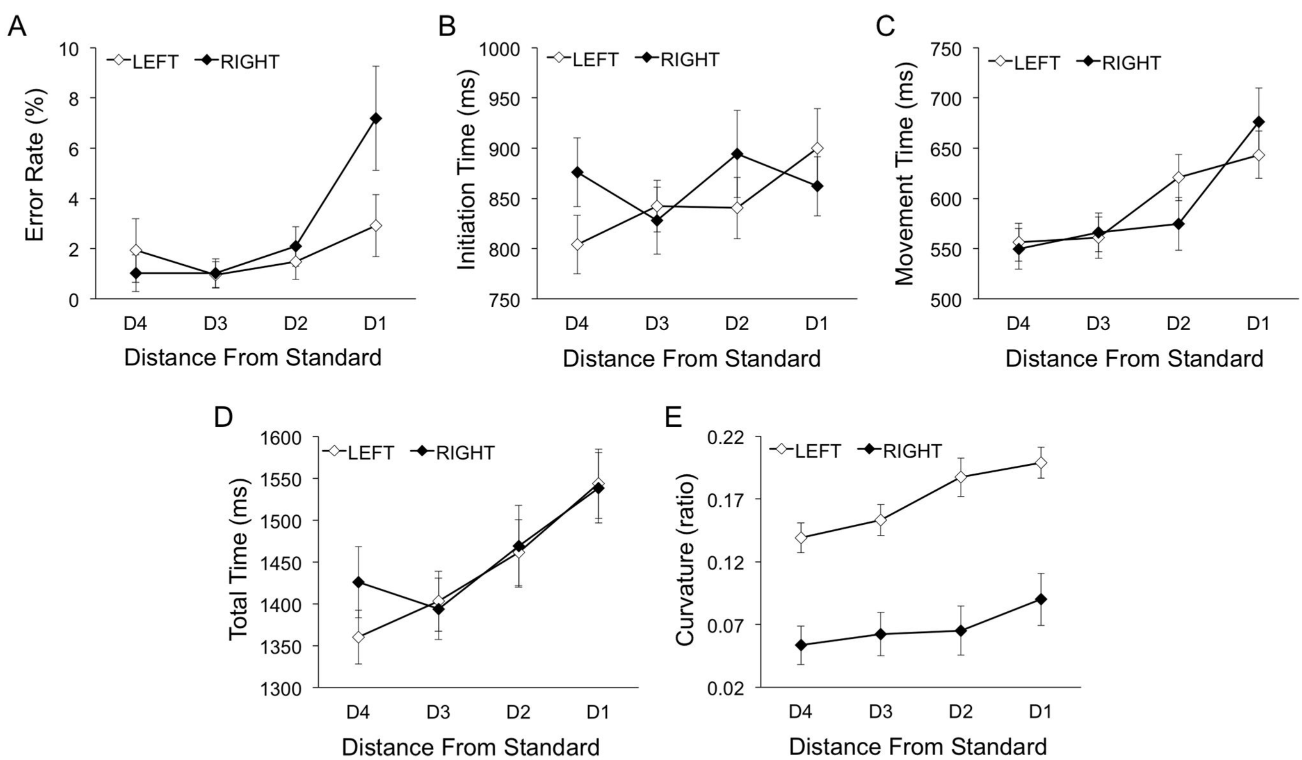

Figure 2. Average error rate (A), initiation time (B), movement time (C), total time (D), and curvature (E) for each distance score as a function of response location (left, right). Error bars indicate standard errors.

Standard Scores

Table 1 presents performance on each of the measures for each of the four Distance scores (collapsing across responses to the left and right targets) and for the standard of 5. Error rates and reach curvatures on the standard were comparable to those of D1 trials. Performance was potentially driven by the frequency with which each target was the appropriate response. In order to equate how frequently each number was presented, the left and right response targets were the correct response more frequently than the center response target. Consequently, children may have developed a bias to respond to either the left or right targets, resulting in worse performance on the standard. It is also important to note that reach curvatures to the center response target were all scored as positive, whereas movements to the left and right response targets were scored as positive or negative depending on whether the movement was curved toward or away from the alternative responses. Thus, average curvature may have been inflated for responses to the center response target relative to responses to the left or right targets.

Table 1

Mean Initiation Time, Movement Time, Total Time, Curvature, and Error Rate as a Function of Target-Standard Distances

Numerical Distance	Error Rate (%)	Initiation Time (ms)	Movement Time (ms)	Total Time (ms)	Curvature (ratio)
Distance 4 (1 & 9)	1.62 (1.32)	841 (30)	555 (18)	1396 (35)	0.098 (0.008)
Distance 3 (2 & 8)	1.36 (0.80)	837 (27)	565 (18)	1402 (33)	0.112 (0.009)
Distance 2 (3 & 7)	1.39 (0.63)	867 (34)	596 (22)	1463 (40)	0.125 (0.011)
Distance 1 (4 & 6)	7.74 (2.11)	882 (32)	658 (24)	1540 (37)	0.145 (0.013)
Standard (5)	5.91 (3.06)	846 (39)	622 (35)	1469 (62)	0.143 (0.014)

Note. Standard errors are shown in parentheses.

Discussion

The results of the current study indicate that the integration of numerical and spatial information is evident in children's online reaching behavior by as early as the preschool years. Children's movement times, total times, and reach curvatures revealed robust NDEs, whereas the NDE observed in initiation times was restricted to numbers less than five. These results are consistent with a number of previous studies investigating numerical cognition in adults that also revealed larger effects in reach trajectories than in initiation times (e.g., Faulkenberry, 2016; Faulkenberry, Cruise, Lavro, & Shaki, 2016; Faulkenberry, Montgomery, & Tennes, 2015; Song & Nakayama, 2008). Taken together, the existing data suggest that the NDE is more pronounced in measures that reflect how processes underlying action execution unfold over space and time (movement time and curvature) than in measures that reflect processes related to action planning (initiation time).

Our results are also consistent with a growing body of research that calls into question traditional divisions among perception, cognition, and action (Barsalou, 2008; Cisek & Kalaska, 2010; Lakoff & Johnson, 1999; Lakoff & Núñez, 2000; Varela, Thompson, & Rosch, 1991). From a traditional perspective, performance on numerical comparison tasks involves reasoning over abstract spatial-numerical representations that are maintained separately from representational states related to action execution. In contrast to this view, our data indicate that action and numerical cognition are tightly coupled by as early as 5 to 6 years of age, suggesting that reasoning processes may be operating over more concrete representational states grounded in action (Barsalou, 2008). From a developmental perspective, such a link between cognition and action would be quite natural given that action is so closely tied to the child's emerging understanding of space.

An open question raised by the current study concerns the extent to which the NDE observed in children's reaching behavior was driven by a spatial-numerical association of response codes (SNARC) effect, in which smaller numbers preferentially elicit a leftward response and larger numbers preferentially elicit a rightward response (e.g., Dehaene et al., 1993). Santens et al. (2011) had adult participants perform a similar task to that of Song and Nakayama (2008) (i.e., the task also used here), but tracked finger movements on a 2-dimensional touchscreen. Critically, participants completed the task with a congruent mapping (1-4 mapped to the left response, 6-9 mapped to the right) and an incongruent mapping (6-9 mapped to the left, 1-4 mapped to the right). The researchers observed the NDE in movement trajectories regardless of response mapping. This finding suggests that children's reach movements in the current study might not have been driven by the SNARC effect alone, although further research is needed to directly investigate this possibility.

The findings of Santens et al. (2011) also provide evidence against a *direct mapping account* of performance on numerical comparison tasks, which proposes that the location of a number on the mental number line corresponds directly to its location in response space. For example, the direct mapping account predicts that reach curvatures should be more curved to the left for responses to "1" than for responses to "3" in the incongruent mapping condition because "1" is mapped to the left of "3" on the mental number line. However, Santens and colleagues found that performance on the incongruent mapping condition was best accounted for by the numerical distance between the presented number and the standard, not by the location of the presented number on the mental number line. Consequently, Santens and colleagues favored a *competition account* (Verguts, Fias, & Stevens, 2005), which proposes that the NDE reflects the co-activation of competing responses, with smaller distances between two numbers generating more co-activation between response options than larger distances (see also Faulkenberry, 2014, 2016). Given that the current study did not feature an incongruent mapping condition, our findings do not provide direct support for either account. Consequently, future research should also evaluate the extent to which the direct mapping and competition accounts capture children's performance in numerical comparison tasks by including an incongruent mapping condition.

Incorporating an incongruent mapping condition into future investigations may also shed light on why initiation times in the current study revealed a significant NDE for responses to the left but not to the right. This asymmetry may reflect differences in how children represent numbers 1-4 relative to other numbers. For example, a large body of research indicates that children and adults process quantities numbering four and under differently than quantities numbering five and above (for a review, see Feigenson, Dehaene, & Spelke, 2004). If the asymmetry observed in initiation times does reflect a difference in how children represent numbers 1-4 relative to larger numbers, then the NDE should remain for numbers 1-4 regardless of whether these numbers are mapped to the left or right response locations. Alternatively, the observed asymmetry may reflect differences associated with generating movements to contralateral or ipsilateral response locations. This account predicts that the NDE should remain for numbers mapped to the contralateral response location regardless of whether the mapping is congruent or incongruent.

The results of the current study present important methodological implications for developmental research on numerical cognition. As mentioned in the introduction, techniques such as reach tracking and mouse tracking are increasingly used to study aspects of numerical cognition in adults (Chapman et al., 2014; Dotan & Dehaene, 2013; Faulkenberry & Rey, 2014; Fischer & Hartmann, 2014; Marghetis et al., 2014; Santens et al., 2011; Song & Nakayama, 2008). However, we are unaware of any previous research that has used these techniques to investigate the development of numerical cognition in children. Our results demonstrate that reach tracking is an appropriate technique for studying numerical cognition in children as young as age 5. Given recent research highlighting the important role that gesture plays in children's developing understanding of mathematics (Brooks & Goldin-Meadow, 2016; Gunderson, Spaepen, Gibson, Goldin-Meadow, & Levine, 2015; Novack, Congdon, Hemani-Lopez, & Goldin-Meadow, 2014), we believe that reach tracking and related techniques present a great deal of promise for future research investigating how children learn and express numerical knowledge at different points in development.

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Competing Interests

The authors have declared that no competing interests exist.

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