Journal of Numerical Cognition
jnc.psychopen.eu | 2363-8761

PsychOpen publishing psychology

Research Reports

Narrowing the Early Mathematics Gap: A Play-Based Intervention to Promote Low-Income Preschoolers' Number Skills

Nicole R. Scalise*[a], Emily N. Daubert[a], Geetha B. Ramani[a]

[a] Department of Human Development and Quantitative Methodology, University of Maryland, College Park, MD 20742, USA.

Abstract

Preschoolers from low-income households lag behind preschoolers from middle-income households on numerical skills that underlie later mathematics achievement. However, it is unknown whether these gaps exist on parallel measures of symbolic and non-symbolic numerical skills. Experiment 1 indicated preschoolers from low-income backgrounds were less accurate than peers from middle-income backgrounds on a measure of symbolic magnitude comparison, but they performed equivalently on a measure of non-symbolic magnitude comparison. This suggests activities linking non-symbolic and symbolic number representations may be used to support children's numerical knowledge. Experiment 2 randomly assigned low-income preschoolers (Mean Age = 4.7 years) to play either a numerical magnitude comparison or a numerical matching card game across four 15 min sessions over a 3-week period. The magnitude comparison card game led to significant improvements in participants' symbolic magnitude comparison skills in an immediate posttest assessment. Following the intervention, low-income participants performed equivalently to an age- and gender-matched sample of middle-income preschoolers in symbolic magnitude comparison. These results suggest a brief intervention that combines non-symbolic and symbolic magnitude representations can support low-income preschoolers' early numerical knowledge.

Keywords: numerical knowledge, early mathematics, low-income, interventions

Journal of Numerical Cognition, 2017, Vol. 3(3), 559–581, doi:10.5964/jnc.v3i3.72

Received: 2016-07-29. Accepted: 2017-06-05. Published (VoR): 2018-01-30.

*Corresponding author at: Department of Human Development and Quantitative Methodology, University of Maryland, College Park, MD 20742, USA. E-mail: nbrooke@umd.edu

Mathematical knowledge lays the foundation for success in science, technology, engineering, and mathematics (STEM) disciplines, and thus plays a critical role in the education and training of the next generation of STEM professionals (PCAST, 2012; Sadler & Tai, 2007). Yet even before the start of formal schooling, children from low-income households underperform on a variety of basic number skills compared to middle-income children, including counting, recognizing numerals, and comparing numbers (Jordan, Kaplan, Olah, & Locuniak, 2006; Starkey, Klein, & Wakeley, 2004). Moreover, math performance at the start of school predicts long-term math achievement in later grades (Duncan et al., 2007; Watts, Duncan, Siegler, & Davis-Kean, 2014), making early gaps especially concerning. Data from older students suggest that the income-based math achievement gap may widen over time. Among a nationally representative sample of U.S. eighth graders, only 18% of students from low-income households performed at or above the proficient level in math, compared to 48% of students from middle- and upper-income households (U.S. Department of Education, Institute of Education Sciences, National Center for Education Statistics, 2015). The gaps in math achievement are attributed to children from low-income households having fewer and less supportive experiences with math, both at home and in school (Clements & Sarama, 2007; Dyson, Jordan, & Glutting, 2013; Siegler, 2009).

The present study investigates two hypotheses related to the early math achievement gap between children from low-income and middle-income families. The first is that consistent, reliable gaps between low- and middle-income preschoolers' symbolic numerical knowledge, defined as culturally specific verbal and visual labels for numbers (i.e., verbally stated or written numerals), may not be replicated in parallel measures of non-symbolic numerical knowledge, defined as nonverbal representations of approximate quantities (i.e., sets of objects). The second is that exposure to dual representations of symbolic and non-symbolic number can help low-income children build their numerical knowledge and improve their foundational math skills. Both hypotheses are informed by a theory of numerical development, which proposes that children's understanding of symbolic and non-symbolic numerical magnitudes underlie their later math achievement (Siegler, 2016). Investigating these two hypotheses will help elucidate the nature of the differences in numerical knowledge between children from lower- and higher-income backgrounds as well as ways to narrow this SES-related gap in young children.

Theoretical Background

According to Siegler and colleagues (Siegler, 2016; Siegler & Lortie-Forgues, 2014; Siegler, Thompson, & Schneider, 2011), numerical development consists of increased understanding of the numerical magnitudes of a continually expanding range of numbers. They propose that children's symbolic magnitude representations can be mapped onto their non-symbolic number representations. Non-symbolic magnitude representations are evident in infancy (e.g., Lipton & Spelke, 2003; Xu & Spelke, 2000), and have been collectively termed the Approximate Number System (ANS; Libertus, Feigenson, & Halberda, 2011). In general, the precision of the ANS to reliably differentiate between non-symbolic sets increases throughout infancy and early childhood (Libertus & Brannon, 2009). As young children continue to refine their non-symbolic magnitude representations, they simultaneously acquire symbolic number skills, including knowledge of number words (e.g., one, two, three) and numeral symbols (e.g., 1, 2, 3) (Siegler, 2016). These early forms of numerical knowledge underlie later mathematical skills, such as arithmetic (Geary, Hoard, & Hamson, 1999).

Both symbolic and non-symbolic numerical knowledge are related to mathematics learning. Studies have demonstrated that the ability to compare the magnitude of two numerals (a form of symbolic number representation) and two sets of objects (a form of non-symbolic number representation) is associated with mathematics achievement among children and adults (Chen & Li, 2014; De Smedt, Noël, Gilmore, & Ansari, 2013; Fazio, Bailey, Thompson, & Siegler, 2014; Schneider et al., 2016). However, based on their integrative review of the literature, De Smedt and colleagues (2013) conclude that the data on non-symbolic magnitude comparison tasks predicting general mathematics achievement are mixed, with some studies demonstrating significant effects and others not. In contrast, the data on measures of symbolic magnitude comparison tasks showed a reliable relation to math achievement across studies: participants with poor performance on symbolic magnitude comparison tasks tended to have lower mathematics achievement both concurrently and up to 2 years later (De Smedt et al., 2013). Similarly, recent meta-analyses report a significant, albeit weak, relation between non-symbolic numerical knowledge and mathematics achievement (Chen & Li, 2014; Fazio et al., 2014; Schneider et al., 2016). The relation was maintained while controlling for general cognitive abilities (Chen & Li, 2014), but may decrease as children enter formal schooling environments (Fazio et al., 2014). When both symbolic and non-symbolic magnitude knowledge were included as predictors of children's math achievement, they each significantly explained a portion of the variance, however the effect size for measures of symbolic magnitude knowledge was larger (Fazio et al., 2014). Across studies of children and adults, the effect size is consistently higher for symbolic than non-symbolic comparison tasks (Schneider et al., 2016). In sum, preschoolers' symbolic magnitude comparison skills predict their later mathematics success (Geary et al., 1999), and tend to be more predictive of mathematics achievement than measures of non-symbolic magnitude comparison (Kolkman, Kroesbergen, & Leseman, 2013; van Marle, Chu, Li, & Geary, 2014).

Given the significance of symbolic and non-symbolic magnitude knowledge during early childhood, it is important to understand whether there are income-based gaps present in both types of numerical skills. Although there are documented gaps between children from low-income and middle-income families on measures of symbolic magnitude comparison (e.g., determining which is the larger number; Jordan et al., 2006; Ramani & Siegler, 2011), no studies to date have measured children's performance on a parallel measure of non-symbolic magnitude comparison. Previous work demonstrated that children from low-income backgrounds performed equivalently to children from middle-income backgrounds on non-symbolic arithmetic problems, but were less accurate on symbolic (verbal) arithmetic problems (Gilmore, McCarthy, & Spelke, 2010; Jordan, Huttenlocher, & Levine, 1992). A second study found that children's socioeconomic status does not impact performance on non-symbolic estimation tasks (Mejias & Schiltz, 2013). These findings suggest that children from low-income backgrounds may also be equally proficient on nonverbal, non-symbolic magnitude comparison tasks that do not include additional calculation or estimation demands. If so, low-income children's non-symbolic magnitude understanding could potentially be used to promote their symbolic magnitude understanding.

Traditional numerical playing cards provide simultaneous exposure to symbolic and non-symbolic magnitude representations, in the form of Arabic numerals and sets of objects (e.g., hearts, diamonds, spades, clubs). Exposing children to materials with multiple redundant cues to numbers and their magnitudes can help build their numerical knowledge (Ramani & Siegler, 2008; Siegler & Booth, 2004). In creating an intervention for low-income preschoolers using numerical cards, we sought to capitalize on participants' non-symbolic magnitude knowledge to support their symbolic magnitude knowledge, as well as engender the motivational and learning benefits of playful, game-based activities.

Play-Based Early Mathematics Interventions

A number of recent early mathematics interventions have incorporated playful, informal learning activities (Clements & Sarama, 2007; Ramani & Siegler, 2008; Wilson, Dehaene, Dubois, & Fayol, 2009). Playful learning activities and games broadly represent a developmentally appropriate mechanism for teaching young children in an engaging and supportive way (Hassinger-Das et al., 2017; Singer, Golinkoff, & Hirsh-Pasek, 2006; Weisberg, Hirsh-Pasek, & Golinkoff, 2013). These activities can also give children opportunities to practice their early numeracy skills (Ramani & Eason, 2015). When offered an engaging learning context and the opportunity for active participation, children tend to benefit more than those who are directly taught or allowed to freely explore without guidance (Hassinger-Das et al., 2017; Weisberg et al., 2013). For example, Siegler and Ramani (2009) randomly assigned preschoolers to play a linear numerical board game, a circular numerical board game, or a set of non-playful, typical numerical activities (counting aloud, counting objects, identifying numerals) for four 15-20 min sessions over a 3-week period. They found that children who played the numerical board games outperformed children in the other two conditions on tasks measuring their numerical magnitude knowledge. Similarly, Ferrara and colleagues (2011) found that parent-child dyads who engaged in a playful, interactive block building activity to assemble a target structure used significantly more spatial language than dyads who were given pre-assembled block structures to interact with for the same amount of time. These patterns of findings underscore that playful learning activities may lead to greater learning than engaging in non-playful activities, particularly for preschool-aged children.

Children similarly appear to benefit from playful, informal mathematics activities in the home (LeFevre et al., 2009; Melhuish et al., 2008; Ramani, Rowe, Eason, & Leech, 2015). Previous research has demonstrated that parental reports of engaging in informal mathematics activities at home (e.g., playing board games with dice or spinners) predict children's math achievement (LeFevre et al., 2009; Melhuish et al., 2008; Ramani et al., 2015). Furthermore, self-report and observational data suggest that low-income families engage in fewer informal mathematical learning activities in the home than middle-income families (Saxe, Guberman, & Gearhart, 1987; Starkey et al., 2004), perhaps indicating one type of experience that contributes to the income-based early math achievement gap.

Given the engagement and motivational benefits of playful learning, combining play with a game that integrates a theory of numerical development may be a particularly effective method to promote specific skills. Numerical card games can provide parallel symbolic and non-symbolic magnitude representations, which allow children to rely on either type of information to engage with the materials (i.e., identifying a numeral, making a comparison between two quantities). Further, specific card games can vary in the type and amount of numerical knowledge they rely on to complete the game. For example, a common numerical card game for young children, *War,* involves two players dividing a deck of cards between them. Each player then turns over one of their cards and together they determine which has the larger quantity. The player whose card has the larger quantity keeps both cards and the player with the most cards at the end of the game wins. The game offers children the opportunity to practice counting, identifying numerals, and importantly, making magnitude comparisons between two numbers to determine which of the numbers represented on the cards is largest. Other card games for young children, such as *Memory*, involve players turning over pairs of facedown cards to try to find a match. The player who finds the most pairs wins. When played with numerical cards, games like *Memory* may offer similar practice with counting and recognizing numerals, but focus on children's ability to remember the location of cards as opposed to making magnitude comparisons between numbers. Thus, cards can provide children with multiple representations of numerical magnitudes, and card games can vary on the type of practice with numbers that children have while playing them.

The Current Paper

In the current paper, we pursued two goals. The first goal was to determine whether preschoolers from low-income households were less accurate than preschoolers from middle-income households on parallel tasks of symbolic and non-symbolic magnitude comparison. In Experiment 1, we hypothesized that we would find income-based performance gaps on a symbolic numerical magnitude comparison task during which participants are shown two Arabic numerals and then asked, "Which is more: X or Y?" In contrast, we predicted that low-income children would show similar accuracy to their middle-income peers on a parallel measure of non-symbolic magnitude comparison with quantities less than ten. In this task, children are shown two sets of dots and similarly asked to indicate which set has more. These hypotheses are based on previous research, which has found SES-related gaps in verbally stated, symbolic numerical tasks, but not on nonverbal numerical tasks (Gilmore et al., 2010; Jordan et al., 1992; Ramani & Siegler, 2011).

The second goal was to assess whether approximately one hour of playing numerical card games with symbolic and non-symbolic representations would lead to improvements in participants' early symbolic and non-symbolic numerical knowledge. Expanding on the results of Experiment 1, Experiment 2 examined whether a magnitude comparison card game, based on the card game *War*, could improve low-income children's numerical knowledge. The game involves players comparing two cards with both symbolic number representations (Arabic numerals) and non-symbolic number representations (circles). The dual representations allow children to practice comparing symbolic magnitudes with non-symbolic quantities to use for additional support in making their decision. For example, although a child may not know if 7 is more or less than 2, they are likely able to tell that a card with seven circles has more circles than a card with only two. Other components of the game involve counting non-symbolic representations and identifying numerals, which could also contribute to improvements to symbolic numerical knowledge. Likewise, the repeated practice comparing non-symbolic quantities may improve children's non-symbolic magnitude skills, which have been shown to malleable with targeted practice (e.g., Wang, Odic, Halberda, & Feigenson, 2016). As a comparison group, half of the children were randomly assigned to play a memory and matching game (*Memory*) with the same numerical cards. Since the game focuses on children's ability to remember the location of cards, it allowed for the effects of magnitude comparison training to be isolated from any effects of practice counting and identifying numerals.

We examined whether playing the two games would improve children's symbolic numerical knowledge, specifically their symbolic numerical magnitude comparison skills, verbal counting from 1-10, and identifying written numerals from 1-10, as well as their non-symbolic numerical magnitude knowledge. We hypothesized that children in both conditions would improve their counting and numeral identification skills because all children had similar exposure in playing with the numerical cards. However, we hypothesized that only children who played the magnitude comparison card game would improve their symbolic magnitude comparison skills because of their unique experiences making comparisons during the game. We did not have specific predictions regarding children's performance on the non-symbolic numerical tasks, given that we expected children's non-symbolic numerical knowledge to be proficient for small quantities less than 10. Finally, we investigated whether low-income children's magnitude comparison skills post-intervention would be comparable to the numerical knowledge of same-age peers from middle-income backgrounds.

Experiment 1

The goal of Experiment 1 was to determine whether SES-related differences in numerical magnitude knowledge are specific to symbolic representations, or whether low-income preschoolers would show similar performance gaps on non-symbolic magnitude measures compared to middle-income preschoolers. To equate the non-symbolic and symbolic measures of numerical magnitude, both used the same number range of 1 through 9. If children performed equivalently on small number comparisons using non-symbolic representations, it might be possible to capitalize on their non-symbolic comparison skills to foster their symbolic magnitude comparison skills with similar quantities.

Method

Participants

Participants were 46 preschoolers. Informed consent was obtained for all participants from their parent or guardian. Twenty-three preschoolers were recruited from one Head Start center in a mid-Atlantic state, ranging in age from 3 years, 4 months to 5 years, 6 months (*M* = 4 years, 8 months, *SD* = 0.60; 30% female; 57% African American/Black, 17% Caucasian, 9% Asian, 17% Multiracial; 87% not Hispanic/Latino, 13% Hispanic/Latino). Head Start is an American federally funded early childhood education program targeted at families living at or below the poverty line. The program seeks to promote young children's school readiness skills (social, emotional, and academic), healthy development (perceptual, motor, and physical), and family wellbeing (Administration for Children and Families [ACF], 2016). For enrollment in the 2014-2015 school year, the U.S. federal poverty guideline for a family of four was $23,850.

The remaining 23 preschoolers were recruited from middle-income households. These children were part of a larger study on mathematics and memory development that assessed their knowledge in those areas during two brief sessions. The preschools were located in the same geographic area as the Head Start center, and all participants were recruited during the same academic year. The middle-income preschoolers were selected as an age- and gender-matched sample to the low-income participants, ranging in age from 3 years, 8 months to 5 years, 9 months (*M* = 4 years, 9 months, *SD* = 0.57; 30% female; 61% Caucasian, 26% African American/Black, 4% Asian, 9% Multiracial; 96% not Hispanic/Latino, 4% Hispanic/Latino). Self-reported annual household incomes ranged from $76,000 to over $151,000 (23% of incomes were between $76,000 and $100,000; 9% of incomes were between $101,000 and $150,000; and 68% of incomes were $151,000 or more). Annual household incomes for a family of four ranging from $58,000 to $172,000 were considered middle-income for the metropolitan area where participants were recruited (Pew Research Center, 2016).

Measures of Numerical Knowledge

Two measures of magnitude comparison skills were used to assess the numerical understanding of participants.

Symbolic magnitude comparison — Participants were asked to compare 20 pairs of symbolic numbers ranging from 1-9 presented in a paper booklet (Ramani & Siegler, 2008). After two practice trials with experimenter feedback, participants were shown 18 test pairs of numbers in the booklet and asked to indicate which number is larger. The test pairs were read aloud by the experimenter, without any accuracy feedback. Each number was counterbalanced for side of presentation (i.e., 3|8, 8|3). The ratio between pairs ranged from 1.1 (e.g., 8|9) to 9.0 (e.g., 9|1). The dependent measure was percentage of correct comparisons. The inter-item reliability was α = .80.

Non-symbolic magnitude comparison — Participants were asked to compare 20 pairs of magnitudes (dot arrays) displayed on a laptop computer. Using the Panamath software (e.g., Libertus, Feigenson, & Halberda, 2013), the children saw a set of yellow dots presented on the left side of the screen and a set of blue dots simultaneously presented on the right side of the screen for 2.8 seconds and were asked to press either a yellow or blue button to indicate which side had more dots. The dot quantities ranged from 1-9, and included numerical comparisons with ratios ranging from 1.3 (e.g., 7|9) to 3.5 (e.g., 2|7). The Panamath program counterbalanced each magnitude for side of presentation (i.e., 3|6, 6|3) and controlled for dot area and density.

Neither the Panamath program nor the experimenter provided accuracy feedback on the test trials. The dependent measure was the percentage of correct comparisons. Although other researchers using the Panamath program have also included Weber fractions as a dependent measure, which indicate the most difficult ratios between two sets to which the child can respond accurately, there is some evidence that Weber fractions are noisy and possibly inaccurate measures for such young children (Libertus et al., 2011). The inter-item reliability was $\alpha = .69$.

Procedure

All participants completed a series of math assessments individually with an experimenter within the child's preschool in a quiet area of the hallway or room nearby their classroom. The middle-income participants also completed non-computerized assessments of working memory. However, because the focus of the current study was preschoolers' symbolic and non-symbolic number knowledge, only the identical assessments of symbolic and non-symbolic magnitude comparison administered to both low- and middle-income participants were analyzed for this experiment. To sustain children's motivation, the symbolic magnitude comparison task was presented first followed by the non-symbolic magnitude comparison task, which participants considered more exciting because it was computer-based. During test trials, experimenters limited their feedback to general encouragement (e.g., "I can tell you're thinking hard about these") and progress (e.g., "We're almost done!"). Each assessment session lasted approximately 15 minutes, and children were given a sticker to thank them for their participation. The experimenter who interacted with the low-income participants was a Caucasian graduate student; the experimenters who interacted with the middle-income participants were one Caucasian graduate student, one Caucasian and one Asian American undergraduate student. All four experimenters were female.

Results

Independent samples *t*-tests showed that there were no accuracy differences between the lower- and middle-income samples on the non-symbolic magnitude comparison task (M = 84% vs. M = 89%; $t(44) = 1.14$, $p = .261$, $d = 0.34$). Although the mean difference in accuracy between the two groups was not statistically significant, the average accuracy of the middle-income preschoolers was 0.34 standard deviations higher than the accuracy of the low-income preschoolers. However, low-income preschoolers were significantly less accurate than the middle-income preschoolers on symbolic magnitude comparisons of the same numerical range and similar ratios (M = 77% vs. M = 93%; $t(44) = 3.52$, $p = .001$, $d = 1.04$). This gap in symbolic magnitude comparison skills represents a one standard deviation difference in mean accuracy between low-income and middle-income participants. The effect size for the symbolic numerical knowledge task was three times as large as the effect size for the symbolic magnitude comparison task ($d = 1.04$ vs. $d = 0.34$), and considered a large effect size by Cohen's benchmarks (Cohen, 1988). These results suggest the performance gap on symbolic magnitude comparison skills does not extend to less verbal, non-symbolic measures of magnitude comparison.

Discussion

In the present experiment, we found that the SES-related gaps in children's symbolic magnitude knowledge were statistically significant, however, the differences between low-income and middle-income participants on the parallel non-symbolic magnitude comparison task were not statistically significant. This suggests that with

PsychOpen
publishing psychology

these measures of symbolic and non-symbolic magnitude comparison, the gaps between middle- and lower-income children's numerical knowledge were specific to children's performance on a symbolic magnitude comparison measure. These findings are consistent with previous research examining SES-related differences on symbolic and non-symbolic measures of early arithmetic (e.g., Gilmore et al., 2010; Jordan et al., 2006). In general, symbolic numerical knowledge is thought to be highly dependent on the type of input and instruction that children receive (Jordan & Levine, 2009), and children from lower-income households experience less frequent and high quality math experiences at home and in school than middle-income children (Clements & Sarama, 2007; Siegler, 2009).

The pattern of effects found in this experiment may vary under different task specifications. The symbolic and non-symbolic magnitude comparison tasks used in Experiment 1 included slightly different ratios (1.1 to 9.0 versus 1.3 to 3.5) and numbers of test trials (18 versus 20 trials). However, the two tasks were equivalent on the range of quantities presented (1 – 9). In addition, previous work using the Panamath program with preschool children used shorter presentation times, larger quantities of dots, and more difficult comparison ratios than the ones used in the present study (e.g., Libertus et al., 2011, 2013). It is possible that the relative ease of the non-symbolic magnitude comparison task in the present study may be part of the reason why income-based performance gaps were not observed in the present study.

Nonetheless, our intention was to match the non-symbolic magnitude comparison task parameters closely to the demands of the symbolic magnitude comparison task to investigate the SES-related gaps in young children's numerical magnitude knowledge on quantities less than ten. The results of Experiment 1 demonstrate that low-income children are considerably more accurate (equivalent to middle-income children) in making non-symbolic comparisons than they are making symbolic comparisons between the same numbers. This implies that low-income children may benefit from magnitude comparison experiences that allow them to leverage their non-symbolic magnitude comparison skills to promote their symbolic magnitude comparison skills, a premise tested in Experiment 2.

Experiment 2

Building from the findings of Experiment 1, Experiment 2 tested an experimental, game-based intervention using numerical cards with both non-symbolic and symbolic numerical representations. Children from low-income households were randomly assigned to play one of two games using the same numerical cards. The first game is a magnitude comparison card game, based on the card game *War*, which involves players comparing the magnitude of two cards. The second game, based on the card game *Memory*, involves players finding matching pairs of cards. Thus, the two games offered similar exposure to numerical cards, but differed in the opportunities to make magnitude comparison judgments between two quantities. We hypothesized that the targeted practice with magnitude comparison while playing the magnitude comparison game (*War*) may support improvements in low-income preschoolers' symbolic magnitude comparison skills. Given that the games were otherwise similar (i.e., same numerical cards, practice counting, identifying numerals), we predicted that children in both the experimental magnitude comparison condition (*War*) and the control numerical card game condition (*Memory*) would experience similar gains on other foundational symbolic numerical skills, specifically their counting and numeral identification skills. Further, we hypothesized that the low-income preschoolers in the experimental condition would improve their symbolic magnitude comparison skills to a point of statistical equivalence with a group of age- and gender-matched middle-income preschoolers.

In addition to assessing whether playing the card games improved children's symbolic numerical knowledge, we were also interested in whether playing the games improved their non-symbolic magnitude knowledge. Therefore, we included two measures of children's non-symbolic magnitude knowledge, specifically a non-symbolic magnitude comparison task, similar to the one used in Experiment 1, and an additional non-symbolic comparison task, which gauged children's discrimination between ordinal quantities of objects (e.g., N and N +1). Previous research has shown that the performance of low-income children on computerized non-symbolic magnitude comparison tasks may be affected by their inhibitory control (Fuhs & McNeil, 2013), hence our second measure of non-symbolic magnitude knowledge was an non-computerized task developed for use with low-income preschoolers (Chu, Van Marle, & Geary, 2013).

Given that the low-income children had high accuracy on the non-symbolic measure of numerical magnitude knowledge in Experiment 1, no specific predictions were made about whether playing the magnitude comparison card game would lead to improved non-symbolic magnitude understanding. It is possible that the experience children have comparing numerical magnitudes using cards with both non-symbolic and symbolic representations could increase performance on non-symbolic measures of numerical knowledge. However, the highly accurate performance of low-income children on a measure of non-symbolic magnitude comparison in Experiment 1 suggests that it is also possible that no further gains would be observed from additional experience. To improve the sensitivity of the measure to detect improvements in non-symbolic magnitude comparison skills and provide a better match to the parameters in previously published studies with preschoolers, we increased the difficulty of the non-symbolic magnitude comparison measure by adjusting the quantities of the numbers and the presentation time.

Method

We next describe the participants, measures of numerical knowledge, and procedures. We report all data exclusions and justifications for their removal, all experimental manipulations, and all measures collected in this study.

Participants

Participants were 70 preschoolers. Informed consent was collected for all participants from their parent or guardian. Forty-six low-income preschoolers were recruited from four Head Start centers in a mid-Atlantic state, comprising the main experimental sample, none of which participated in Experiment 1. Low-income preschoolers ranged in age from 3 years, 6 months to 5 years, 7 months (M = 4 years, 9 months, SD = 0.62; 48% female; 54% Caucasian, 35% African American/Black, 7% Asian, 4% Multiracial; 54% Hispanic/Latino, 46% not Hispanic/Latino). Three additional low-income children were recruited but were not included in the final analyses because the children did not complete the game sessions or the posttest tasks (n = 2), or the child had prolonged absences from school (n = 1).

Low-income participants were randomly assigned to either a numerical magnitude comparison card game condition (*War*) or to a numerical matching card game condition (*Memory*). The *War* card game condition included 24 children (M = 4 years, 8 months, SD = 0.67; 50% female). The *Memory* card game condition included 22 children (M = 4 years, 10 months, SD = 0.57; 46% female).

The remaining 24 preschoolers were from middle-income backgrounds (*M* = 4 years, 8 months, *SD* = 0.68; 50% female; 46% Caucasian, 25% African American/Black, 21% Multiracial, 8% Asian; 100% not Hispanic/ Latino) who were recruited from the larger study on math and memory development described in Experiment 1. The middle-income preschoolers were selected as an age- (within 4 months) and gender-matched sample to the low-income participants in the numerical magnitude comparison (*War*) condition. In order to provide the closest age- and gender-matched sample for comparison, 10 of the middle-income children served as matched-comparison participants in both Experiments 1 and 2. Self-reported annual household incomes ranged from $76,000 to over $151,000 (12% of incomes were between $76,000 and $100,000; 17% of incomes were between $101,000 and $150,000; and 71% of incomes were $151,000 or more). The matched sample of middle-income children did not participate in the intervention, but instead provided a comparison point for the symbolic magnitude knowledge of the low-income participants before and after the magnitude comparison card game intervention training.

Measures of Numerical Knowledge

Five measures were used to assess the low-income participants' numerical knowledge, described in detail below.

Rote counting — Participants were asked to count aloud from 1 through 10 (Ramani & Siegler, 2008). The dependent measure was the highest number counted to without errors divided by the highest possible score (i.e., 10). The inter-item reliability was α = .93 at the first administration.

Numeral identification — Children were presented with 10 randomly ordered cards, each with an Arabic numeral from 1 to 10, and asked to identify the numeral (Ramani & Siegler, 2008). The dependent measure was the percentage of numerals correctly labeled. The inter-item reliability was α = .91 at the first administration.

Non-symbolic ordinality — Children watched an experimenter sequentially hide two different numbers of objects (i.e., fuzzy pom-poms) in two opaque cups as a measure of non-symbolic magnitude discrimination (Chu et al., 2013). The experimenter dropped the objects into the cups one at a time and then asked the children to point to the cup that contained more objects. The task included the presentation of two practice trials and six test trials. The number of objects in each cup ranged from 1 to 7, and each test comparison involved a number and the next largest number (e.g., 5 vs. 6). The cup containing more objects was randomized and counterbalanced across comparisons. The dependent measure was the number of accurate comparisons (excluding two practice trials) divided by the highest possible score (i.e., 6). The inter-item reliability was markedly low at the first administration, α = .24 (see Discussion for potential explanations).

Symbolic magnitude comparison — Participants were asked to complete the same measure of symbolic magnitude comparison described previously in Experiment 1. The dependent measure was percentage of correct comparisons. The inter-item reliability was α = .84 at the first administration.

Non-symbolic magnitude comparison — Participants were asked to complete a series of comparisons between magnitudes (dot arrays) on a laptop computer, using the Panamath program described in Experiment 1. The settings were adjusted from those used in Experiment 1 to increase the task difficulty and better replicate those used in other studies of preschool-aged children, such that participants were asked to compare a greater number of pairs (32), and the presentation time decreased (stimuli presented for 2.3 seconds). The dot quantities ranged from 4-15 and included numerical comparisons with ratios of 2.0 (e.g., 4|8, 25% of trials); 1.5 (e.g., 4|6, 25% of trials); 1.3 – 1.4 (e.g., 8|11, 25% of trials); and 1.1 – 1.2 (e.g., 8|9, 25% of trials). The dependent measure was the percentage of accurate comparisons. As in Experiment 1, Weber fractions were not used as a dependent measure. The inter-item reliability was α = .69 at the first administration.

Numerical Card Games

Two numerical card games were used to provide low-income participants with experience related to magnitude comparison and memory of numerical information. The numerical magnitude comparison card game (*War*) and the numerical matching card game (*Memory*) are described in turn.

Numerical magnitude comparison card game (War) — The materials for the magnitude comparison card game were a set of 40 cards in the dimensions of standard playing cards (3.5 inches X 2.5 inches). The set included four subsets of cards representing quantities 1 through 10. Each card had both red Arabic numerals (0.5 inches in height) in the upper left and lower right corners and red dots (0.5 inches in diameter) representing the quantity (Figure 1).

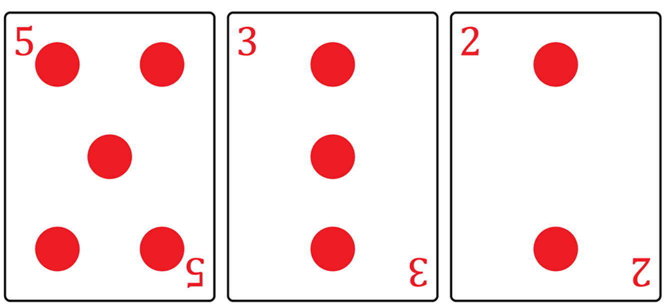

Figure 1. Numerical cards used in *War* and *Memory* games; quantities ranged from 1 to 10.

For each game, the experimenter first divided the cards equally so that the child and the experimenter each had 20 cards stacked in a pile face down. To play, each person turned over his/her top card, said the number on the card, and the child was asked to say which number was greater. If children struggled to identify the numeral on the card, the experimenter encouraged them to count the circles on the card to determine the number, having previously established that the numeral and quantity of circles were always the same. If children could not compare the two quantities, or did so incorrectly, the experimenter encouraged them to look at the quantities of circles visually presented on each card to help them decide. The experimenter always corrected inaccurate counting, numeral identification, and magnitude comparison decisions, typically by asking the child to try again and scaffolding their arrival at the correct answer. The player with the card of greater magnitude (“the card with more”) took both cards. If two cards were the same, both players put three additional cards down, then turned a fourth card to determine who took all of the cards. At the end of the game, the players counted their cards to see who had more. During each session, the experimenter and child played as many rounds as possible until 15 minutes elapsed.

Numerical matching card game (Memory) — Children who played the numerical memory and matching card game used the same playing cards described above, organized into two sets of 10 cards each. Each set of 10 cards contained five pairs of matching numbers between one and ten, and the experimenter alternated the use of each set so that children were exposed to all pairs equally. This allowed for similar exposure to all of the numbers from 1 through 10 for children in both numerical card games.

For each game, the 10 cards were placed face down in two rows of five columns. Each player took turns flipping over two cards and saying the number on each card, trying to find two cards with the same number. As in the game *War*, if children struggled to identify the numeral on the card, the experimenter encouraged them to count the circles on the card to determine the number. The experimenter always corrected inaccurate counting, numeral identification, and matching decisions. If the two cards matched, the player kept both, but if they did not match, the player returned the cards to their face down position. The players counted the cards at the end of the game to determine who had more. During each session, the experimenter and child played as many rounds as possible until 15 minutes elapsed.

Procedure

Low-income participants met individually with an experimenter in a quiet area of the hallway or room nearby their classroom for six 15-20 minute sessions over a 3-week period on average. During Sessions 1 and 6, the children completed five pretest and posttest assessments of their numerical knowledge in the order listed above, including multiple measures assessing non-symbolic and symbolic representations. Following Session 1, children were randomly assigned at the sample level stratified by gender to play either the numerical magnitude comparison card game condition (*War*; n = 24) or to the numerical matching card game condition (*Memory*; n = 22) during Sessions 2-5. Previous intervention research targeting low-income children's numerical skills found significant improvements to children's knowledge after four 15-minute training sessions (e.g., Ramani & Siegler, 2008, 2011; Siegler & Ramani, 2008, 2009). Each child played the same game with the same experimenter for all of the card game training (Sessions 2-5), while another experimenter blind to their condition conducted 48% of the posttest assessments. After each session, children were given a sticker to thank them for their participation. The experimenters were four females: two Caucasian graduate students, one Caucasian and one Asian American undergraduate student.

The middle-income children completed one session of assessments of numerical knowledge and working memory abilities individually with an experimenter, including the symbolic magnitude comparison assessment described in Experiment 1. The experimenters were three females: one Caucasian graduate student, one Caucasian undergraduate student, and one Asian American undergraduate student. These experimenters were blind to the specific hypotheses of this study.

Results

To address our first set of hypotheses, we began by investigating the effectiveness of the two intervention conditions (magnitude comparison and matching) on low-income preschoolers' numerical knowledge. Given the related nature of the five measures of numerical knowledge, we chose to conduct a doubly multivariate repeated measures analysis to examine the effects of participant age, condition, and session, and then conduct univariate analyses to examine the effects on each individual task. We report Pillai's Trace as an F-statistic because it is more robust with smaller sample sizes. For each of the numerical knowledge tasks, a single measure of accuracy was used. To account for the age range of low-income participants in the study, a median split (59 months) was applied to create a group of younger children (n = 20, M = 4 years, 2 months, SD = 0.42, range = 3 years, 6 months to 4 years, 8 months) and a group of older children (n = 26, M = 5 years, 2 months, SD = 0.25, range = 4 years, 11 months to 5 years, 7 months). The median split served as a proxy for participants' number of years in preschool (i.e., one versus two years).

Preliminary Analyses

To ensure that low-income children in the two conditions were equivalent at pretest, and to check for potential effects of classrooms on pretest knowledge, a 2 (condition: *War* or *Memory* card game) x 4 (classroom: Head Start classroom membership) MANOVA was first conducted on the five pretest measures of numerical knowledge. There were no significant main effects on the pretest numerical knowledge measures of condition, $F(5, 34) = 1.35$, $p = .267$, $\omega^2 = .04$, or class, $F(15, 108) = 1.46$, $p = .135$, $\omega^2 = .05$. Given that there were no differences, classroom was not controlled for in the following analyses. Similarly, as there was no main effect of condition, the two groups are considered equivalent on pretest numerical knowledge measures.

The difference in the amount of time children spent playing the card games in the two conditions fell just short of conventional significance levels (M_{War} = 59 minutes vs. M_{Memory} = 57 minutes, $t(44) = 1.98$, $p = .054$). On average, participants spent 58 minutes total playing the games across sessions. However, given the nature of the two card games, there was a difference in the number of games played across sessions between the two conditions. Children in the *War* condition on average played a total of 8.5 games, while children in the *Memory* condition on average played a total of 22.3 games. This reflects the fact that across participants, completing a single game of *War* took approximately 8 minutes, while a single game of *Memory* took approximately 3 minutes. As described previously, games of *Memory* alternated between two decks of cards that each included half of the quantities between 1 and 10, thus playing approximately twice as many games as children who played *War* resulted in a similar amount of overall exposure to the quantities 1 to 10.

Multivariate Analyses

A 2 (age: above or below median) x 2 (condition: *War* or *Memory* numerical card game) x 2 (session: pretest or posttest) repeated measures MANOVA was conducted on the five measures of numerical knowledge: rote counting, numeral identification, non-symbolic ordinality, symbolic magnitude comparison, and non-symbolic magnitude comparison. There were significant main effects for age, $F(5, 38) = 2.52$, $p = .046$, $\omega^2 = .15$; session, $F(5, 38) = 3.47$, $p = .011$, $\omega^2 = .22$; and the condition x session interaction, $F(5, 38) = 2.81$, $p = .029$, $\omega^2 = .17$. Table 1 presents descriptive statistics and comparisons for the pretest and posttest measures. Additional univariate analyses for each task are presented below to establish the sources of the abovementioned differences.

Table 1

Descriptive Statistics by Condition

	Pretest				Posttest				Pre vs. Post		
Measure	***M***	***SD***	**Min**	**Max**	***M***	***SD***	**Min**	**Max**	***p***	***r***	**ES**
Numerical magnitude comparison card game, *War* (*n* = 24)											
Rote counting	0.88	0.26	0.20	1.00	0.93	0.17	0.40	1.00	†	.82	0.39
Numeral identification	0.80	0.31	0.10	1.00	0.82	0.32	0.00	1.00		.92	0.16
Non-symbolic ordinality	0.63	0.22	0.17	1.00	0.67	0.26	0.00	1.00		.47	0.16
Symbolic magnitude comparison	0.72	0.23	0.28	1.00	0.80	0.20	0.39	1.00	***	.91	0.88
Non-symbolic magnitude comparison	0.63	0.13	0.41	0.88	0.64	0.15	0.41	0.88		.61	0.08
Numerical matching card game, *Memory* (*n* = 22)											
Rote counting	0.95	0.18	0.30	1.00	0.98	0.11	0.50	1.00		.56	0.22
Numeral identification	0.88	0.23	0.30	1.00	0.91	0.20	0.30	1.00	†	.96	0.49
Non-symbolic ordinality	0.71	0.21	0.33	1.00	0.61	0.17	0.33	1.00	†	.07	-0.39
Symbolic magnitude comparison	0.82	0.18	0.44	1.00	0.83	0.16	0.56	1.00		.72	0.08
Non-symbolic magnitude comparison	0.71	0.14	0.50	0.94	0.66	0.14	0.44	0.94	†	.46	-0.34

Note. $^{\dagger}p < .10$. $^{***}p < .001$.

Symbolic magnitude comparison — There were significant main effects on the symbolic magnitude comparison measure for age, $F(1, 42) = 6.88$, $p = .012$, $\omega^2 = .11$; session, $F(1, 42) = 5.84$, $p = .020$, $\omega^2 = .10$; and the condition x session interaction, $F(1, 42) = 5.70$, $p = .022$, $\omega^2 = .10$. Across sessions and conditions, older children tended to be more accurate in their symbolic magnitude comparisons than younger children (average of 85% comparisons answered correctly versus 72% comparisons). Across conditions and age groups, children tended to improve on symbolic magnitude comparison between pretest and posttest sessions (an average of 76% of comparisons answered correctly at pretest versus an average of 81% of comparisons at posttest).

As predicted, the significant condition x session interaction revealed that the children who played the *War* card game improved more on the symbolic magnitude comparison measure than their peers who played the *Memory* card game. Children in the *War* condition improved from correctly comparing 72% of the pairs at pretest to 80% of the pairs at posttest, $t(23) = 4.27$, $p < .001$, $d = 0.88$, whereas children in the *Memory* condition showed no significant improvement in performance, answering 82% correct at pretest and 83% correct at posttest.

Rote counting — Children's ability to count correctly from 1-10 varied by session, $F(1, 42) = 4.68$, $p = .036$, $\omega^2 = .08$; though there was not a significant condition x session interaction, $F(1, 42) = .05$, $p = .819$, $\omega^2 = -.02$. The main effect of session indicated that children in both conditions improved on average in their counting accuracy between the pre- and posttest sessions, with accuracy improving from an average of 91% at pretest to an average of 95% at posttest.

Numeral identification — Children's ability to correctly identify each Arabic numeral from 1 to 10 showed no statistically significant effects of age or the condition x session interaction, however the main effect of session approached significance, $F(1, 42) = 2.93$, $p = .094$, $\omega^2 = .04$. This suggested that some children in both card game conditions showed improvement in their numeral identification skills between the pretest and posttest sessions. Indeed, the percentage of the sample that correctly identified all ten Arabic numerals was 63% at the pretest and 67% at the posttest.

Non-symbolic ordinality — Performance on the non-symbolic ordinality measure approached statistically significant effects for age, $F(1, 42) = 3.19$, $p = .081$, $\omega^2 = .05$, and the condition x session interaction, $F(1, 42) = 3.76$, $p = .059$, $\omega^2 = .06$, however there were no effects that were statistically significant at the $\alpha = .05$ level.

Non-symbolic magnitude comparison — On the non-symbolic magnitude comparison measure, there was a significant effect of age, $F(1, 42) = 9.51$, $p = .004$, $\omega^2 = .16$, but no effects of session nor a condition x session interaction. Older children across sessions and conditions were more accurate in their non-symbolic magnitude judgments than younger children, with 70% of comparisons made correctly by older children compared to 60% of comparisons made correctly by younger children.

Low- and Middle-Income Comparison

To address our second set of hypotheses, we examined the extent to which playing the magnitude comparison card game improved the low-income children's symbolic magnitude skills relative to a matched sample of middle-income participants, which was the area of numerical knowledge with the greatest improvements among low-income preschoolers. The low-income children's symbolic magnitude comparison performance at pretest and posttest was compared to the performance of the matched middle-income children. Independent samples *t*-tests showed that there were differences between the lower- and middle-income samples at pretest (M = 72% vs. M = 88%; $t(46) = 2.97$, $p = .005$, $d = 0.86$). However, after playing the *War* game the posttest scores of the low-income children were no longer significantly different than those of the middle-income sample (M = 80% vs. M = 88%; $t(46) = 1.67$, $p = .103$, $d = 0.48$). Although the symbolic magnitude comparison accuracy of low-income children after playing the *War* game was not significantly less than the accuracy of the middle-income children, the estimated effect size of the difference decreased from a 0.86 standard deviation gap (large) to a 0.48 standard deviation gap (moderate).

Discussion

In Experiment 2, we found that playing both card games improved children's counting skills. However, as predicted, only playing *War* improved children's symbolic magnitude comparison performance. There were no gains found for children on either of the non-symbolic measures of numerical knowledge, which was somewhat surprising in light of the improvements in symbolic magnitude comparison demonstrated by children in the magnitude comparison card game condition. Possible explanations for the lack of improvement could be the competing salience of symbolic number representations on the cards (stressed by the experimenter), and generally poor performance on the ordinal choice non-symbolic magnitude comparison task. In particular, the ordinal choice task required a nontrivial working memory load in order to represent the quantities obscured by the opaque cups, as well as a fairly sophisticated tracking strategy (e.g., counting the objects placed into one cup, then remembering the first count while simultaneously keeping an accurate count of the objects in the second cup, then comparing the two counts). These potential explanations are discussed in more detail in the General Discussion.

Early gaps in numerical knowledge tend to widen over the course of schooling (Alexander & Entwisle, 1988; Geary, 1994, 2006), therefore, it is important to examine whether the intervention helped children to "catch-up" to their peers from higher-income backgrounds, ideally preventing small gaps in numerical knowledge from growing into larger ones. The results of the low-income and middle-income comparison analysis suggest that playing the numerical magnitude comparison card game improved the low-income children's performance to a point of statistical equivalence with the middle-income children, thus narrowing the observed achievement gap in early numerical knowledge.

General Discussion

In the present study, we examined the specificity of SES-related performance gaps on measures of magnitude representation, designed and implemented a numerical card game intervention for low-income preschoolers, and compared children's improved performance to a matched sample of middle-income preschoolers. We found that low-income preschoolers did not show a significant performance gap on a measure of non-symbolic magnitude comparison, although they did significantly lag behind middle-income preschoolers on a matched measure of symbolic magnitude comparison. We then examined whether we could capitalize on these differences by providing experience playing numerical card games with both symbolic and non-symbolic representations to improve low-income preschoolers' early number skills. We found that playing the numerical magnitude comparison card game improved the low-income children's symbolic numerical magnitude knowledge.

Card Games and Numerical Magnitude Knowledge

Given that magnitude comparison skill predicts broader mathematics achievement (Jordan et al., 2006; Mazzocco, Feigenson, & Halberda, 2011), we were particularly interested in whether targeted practice playing a magnitude comparison card game would boost preschoolers' numerical magnitude understanding. As hypothesized, children who played the numerical magnitude comparison card game for approximately one hour also showed improvements in their symbolic magnitude comparison skills. We found that their skills improved to the point of statistical equivalence with a matched sample of middle-income preschoolers. Additionally, we found that children in both conditions, having similar opportunities to count circles and label Arabic numerals, improved similarly on those skills as hypothesized.

However, as discussed in Experiment 2, playing the numerical magnitude comparison (*War*) card game did not improve children's performance on either of the two measures of non-symbolic magnitude comparison. One explanation may be that including both numerals and non-symbolic quantities (circles) on the cards led children who played the *War* card game to focus more on the symbolic numeral information while making comparisons, largely ignoring the non-symbolic information. Theories of numerical development suggest that between 4- and 5-years old children begin to fully integrate their symbolic number knowledge with non-symbolic magnitude information (Siegler, 2016; Siegler & Lortie-Forgues, 2014; Siegler, Thompson, & Schneider, 2011), which may mean the symbolic magnitude information was particularly salient to our sample of predominately 4- and 5-year old children. In addition, the non-symbolic ordinality task showed only marginally significant pretest-posttest reliability and low inter-item reliability (Pearson's $r(44) = .29$, $p = .051$; inter-item reliability at first administration $\alpha = .24$), which may be an indication that the children had trouble focusing on or understanding that specific task.

Nevertheless, at pretest some of the children in our experimental sample were unable to recognize written numerals, and many children performed poorly when asked to make symbolic magnitude comparisons, which suggests they may have needed to rely on the non-symbolic magnitude information to make accurate comparisons during the card game. Although the present study suggests that children may scaffold symbolic magnitude understanding from their non-symbolic magnitude comparison skills, future work could further tease apart this hypothesis by contrasting the effectiveness of intervention conditions with purely non-symbolic, symbolic, and dual (non-symbolic and symbolic) magnitude representations.

These results add additional support to the growing literature of play-based mathematics interventions for low-income and struggling early learners (Laski & Siegler, 2014; Ramani & Siegler, 2008; Ramani, Siegler, & Hitti, 2012; Räsänen, Salminen, Wilson, Aunio, & Dehaene, 2009; Whyte & Bull, 2008). Although many previous studies with low-income preschoolers have focused on linear number board game interventions designed to promote children's mental number line (e.g., Ramani & Siegler, 2008; Siegler & Ramani, 2008; Siegler & Ramani, 2009), a representation of their magnitude understanding, the current study suggests that numerical card games may lead to similar improvements in children's early math skills. There are several existing curricula targeting early childhood education that similarly incorporate informal mathematics activities such as games, both commercially available and experimental (e.g., Building Blocks; Big Math, Little Kids; Number Sense Interventions). Understanding the impact of playing card games on children's numerical knowledge can help to determine when and how numerical card games could be used as an activity independently in classrooms or coupled with existing curricular programs in preschools.

Limitations

There are several limitations of the current study that should be noted. First, although participants were randomly assigned to the card game condition and preliminary analyses confirmed there were no statistically significant effects of condition at pretest, the sample average symbolic magnitude comparison performance of children in the *Memory* condition at pretest was greater than that of the children in the *War* condition. Thus, while children in the *War* condition improved their symbolic magnitude comparison performance to the point of equivalence at posttest to an age and gender-matched middle-income sample (Experiment 2), the scores of low-income children in the *Memory* condition were statistically equivalent to the same middle-income sample at pretest. Since children were randomly assigned to the two groups, it is likely that this was simply due to variation in the magnitude comparison skills of the greater population of low-income preschoolers. Future work will seek to replicate these effects with larger sample sizes, which should help reduce the variability in estimating children's abilities.

Second, the relatively high performance at pretest of many preschoolers on the rote counting and numeral identification meant there was limited room for improvement. All measures were selected based on previous studies that found sufficient variability in samples of low-income preschoolers (e.g., Chu et al., 2013; Jordan et al., 2006; Ramani & Siegler, 2008; Siegler & Ramani, 2008), however our results suggest that they may no longer be appropriate in today's academically focused preschool settings. Future studies could adapt tasks to be more challenging for the children (e.g., have children count as high as they can as opposed to stopping at 10), or target children with lower initial knowledge for the training.

Third, all participants were involved in an active condition with exposure to numerical card games. Including a passive control condition or card game condition that did not involve numerical cards may provide a more accurate picture of the improvements in children's early number skills that can be attributed to their experience playing the numerical magnitude comparison card game. In a similar vein, incorporating more distal measures of magnitude understanding such as the number line task (Siegler & Booth, 2004), which assesses magnitude understanding without directly referencing magnitude comparison, may help explain if the training effects from the magnitude comparison card game are specific to magnitude knowledge.

Fourth, although the two card games were matched in terms of total duration of playing time and exposure to non-symbolic and symbolic representations of quantities from 1-10, the two games did differ in average duration per card game. This may in turn have led children to tire more quickly of playing the memory and matching game (as opposed to the longer numerical magnitude comparison game). Anecdotally, children appeared to be equally engaged in both types of games despite the variation in game duration. Children in both conditions rarely asked to end the game-playing sessions prior to the 15-minute time limit (less than 5 percent of intervention training sessions ended early at the child's request). However, the present study did not collect a formal measure of children's attention to or engagement in the card games, which could be added to future studies to control for potential variability between the two conditions.

Finally, the current study assessed learning by means of a posttest assessment conducted within several days of the final training condition. It remains an open question whether or not the improvements observed using a short-term posttest assessment are maintained in the long-term, several weeks or months after the intervention training.

Conclusions

The current study expands the early mathematics intervention literature to include numerical card games: a readily accessible and affordable resource. The results revealed significant effects of playing numerical card games on improving low-income children's basic numerical skills, an area in which many low-income children are behind relative to middle- and upper-income peers (Jordan et al., 2006; Starkey et al., 2004). Although the theoretical links between non-symbolic and symbolic representations are debated, our study suggests exposure to both types of representation simultaneously may support low-income children's symbolic number skills by capitalizing on their more accurate non-symbolic magnitude discriminations among quantities less than ten. Numerical card games provide the aforementioned opportunity for dual numerical representations, and future work should further explore their potential as intervention materials in classrooms and homes.

Promoting early mathematical understanding prior to the start of formal schooling has the potential to boost low-income students' long-term academic performance and combat perpetual STEM performance gaps. Basic numerical skills such as counting and the ability to make comparisons between numbers are foundational to the development of later mathematics skills such as addition and subtraction (Geary et al., 1999; Siegler & Lortie-Forgues, 2014). Thus, improvements in these skills may support children's success in elementary school and later mathematics experiences, narrowing the early mathematics gap.

Funding

This work was supported by the Heising-Simons Foundation [Grant number 2014-142] and the Spencer Foundation [Grant number 201600002] to Geetha B. Ramani; the National Science Foundation [DGE 1322106] to Nicole R. Scalise; and the National Institutes of Health [NICHD Training Grant 1T32 HD07542-9] to Emily N. Daubert.

Competing Interests

The authors have declared that no competing interests exist.

Acknowledgments

The authors give special thanks to the students and teachers at the Howard County and Prince George's County Head Start classrooms for their participation in this research. The authors also thank Talia Rosenstrauch, Naomi Silverman, and Joanne Vu for their assistance with data collection and entry.

References

Administration for Children and Families (ACF), Office of Head Start. (2016, August). *Head Start Programs.* Retrieved from https://www.acf.hhs.gov/ohs/about/head-start

Alexander, K. L., & Entwisle, D. R. (1988). Achievement in the first 2 years of school: Patterns and processes. *Monographs of the Society for Research in Child Development, 53*(2), 1-157. doi:10.2307/1166081

Chen, Q., & Li, J. (2014). Association between individual differences in non-symbolic number acuity and math performance: A meta-analysis. *Acta Psychologica, 148*, 163-172. doi:10.1016/j.actpsy.2014.01.016

Chu, F. W., Van Marle, K., & Geary, D. C. (2013). Quantitative deficits of preschool children at risk for mathematical learning disability. *Frontiers in Psychology, 4*(195), Article 195. doi:10.3389/fpsyg.2013.00195

Clements, D. H., & Sarama, J. (2007). Effects of a preschool mathematics curriculum: Summative research on the *Building Blocks* project. *Journal for Research in Mathematics Education, 38*(2), 136-163.

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). Hillsdale, NJ, USA: Lawrence Erlbaum Associates.

De Smedt, B., Noël, M.-P., Gilmore, C., & Ansari, D. (2013). How do symbolic and non-symbolic numerical magnitude processing skills relate to individual differences in children's mathematical skills? A review of evidence from brain and behavior. *Trends in Neuroscience and Education, 2*(2), 48-55. doi:10.1016/j.tine.2013.06.001

Duncan, G. J., Dowsett, C. J., Claessens, A., Magnuson, K., Huston, A. C., Klebanov, P., . . . Japel, C. (2007). School readiness and later achievement. *Developmental Psychology, 43*(6), 1428-1446. doi:10.1037/0012-1649.43.6.1428

Dyson, N. I., Jordan, N. C., & Glutting, J. (2013). A number sense intervention for low-income kindergarteners at risk for mathematics difficulties. *Journal of Learning Disabilities, 46*(2), 166-181. doi:10.1177/0022219411410233

Fazio, L. K., Bailey, D. H., Thompson, C. A., & Siegler, R. S. (2014). Relations of different types of numerical magnitude representations to each other and to mathematics achievement. *Journal of Experimental Child Psychology, 123*, 53-72. doi:10.1016/j.jecp.2014.01.013

Ferrara, K., Hirsh-Pasek, K., Newcombe, N. S., Golinkoff, R. M., & Lam, W. S. (2011). Block talk: Spatial language during block play. *Mind, Brain and Education: The Official Journal of the International Mind, Brain, and Education Society, 5*(3), 143-151. doi:10.1111/j.1751-228X.2011.01122.x

Fuhs, M. W., & McNeil, N. M. (2013). ANS acuity and mathematics ability in preschoolers from low-income homes: Contributions of inhibitory control. *Developmental Science, 16*(1), 136-148. doi:10.1111/desc.12013

Geary, D. C. (1994). *Children's mathematics development: Research and practical applications.* Washington, DC, USA: American Psychological Association.

Geary, D. C. (2006). Development of mathematical understanding. In W. Damon & R. M. Lerner (Series Eds.) & D. Kuhn & R. S. Siegler (Vol. Eds.), *Handbook of Child Psychology: Vol 2. Cognition, perception, and language* (6th ed., pp. 777-810). New York, NY, USA: Wiley.

Geary, D. C., Hoard, M. K., & Hamson, C. O. (1999). Numerical and arithmetical cognition: Patterns of functions and deficits in children at risk for a mathematical disability. *Journal of Experimental Child Psychology, 74*(3), 213-239. doi:10.1006/jecp.1999.2515

Gilmore, C. K., McCarthy, S. E., & Spelke, E. S. (2010). Non-symbolic arithmetic abilities and mathematics achievement in the first year of formal schooling. *Cognition, 115*(3), 394-406. doi:10.1016/j.cognition.2010.02.002

Hassinger-Das, B., Toub, T. S., Zosh, J. M., Michnick, J., Golinkoff, R., & Hirsh-Pasek, K. (2017). More than just fun: A place for games in playful learning / Más que diversión: El lugar de los juegos reglados en el aprendizaje lúdico. *Infancia y Aprendizaje: Journal for the Study of Education and Development, 40*(2), 191-218. doi:10.1080/02103702.2017.1292684

Jordan, N. C., Huttenlocher, J., & Levine, S. C. (1992). Differential calculation abilities in young children from middle- and low-income families. *Developmental Psychology, 28*(4), 644-653. doi:10.1037/0012-1649.28.4.644

Jordan, N. C., Kaplan, D., Olah, L. N., & Locuniak, M. N. (2006). Number sense growth in kindergarten: A longitudinal investigation of children at risk for mathematics difficulties. *Child Development, 77*(1), 153-175. doi:10.1111/j.1467-8624.2006.00862.x

Jordan, N. C., & Levine, S. C. (2009). Socioeconomic variation, number competence, and mathematics learning difficulties in young children. *Developmental Disabilities Research Reviews, 15*, 60-68. doi:10.1002/ddrr.46

Kolkman, M. E., Kroesbergen, E. H., & Leseman, P. M. (2013). Early numerical development and the role of non-symbolic and symbolic skills. *Learning and Instruction, 25*, 95-103. doi:10.1016/j.learninstruc.2012.12.001

Laski, E. V., & Siegler, R. S. (2014). Learning from number board games: You learn what you encode. *Developmental Psychology, 50*, 853-864. doi:10.1037/a0034321

LeFevre, J., Skwarchuk, S., Smith-Chant, B., Fast, L., Kamawar, D., & Bisanz, J. (2009). Home numeracy experiences and children's math performance in the early school years. *Canadian Journal of Behavioural Science, 41*, 55-66. doi:10.1037/a0014532

Libertus, M. E., & Brannon, E. M. (2009). Behavioral and neural basis of number sense in infancy. *Current Directions in Psychological Science, 18*(6), 346-351. doi:10.1111/j.1467-8721.2009.01665.x

Libertus, M. E., Feigenson, L., & Halberda, J. (2011). Preschooler acuity of the approximate number system correlates with school math ability. *Developmental Science, 14*(6), 1292-1300. doi:10.1111/j.1467-7687.2011.01080.x

Libertus, M. E., Feigenson, L., & Halberda, J. (2013). Is approximate number precision a stable predictor of math ability? *Learning and Individual Differences, 25*, 126-133. doi:10.1016/j.lindif.2013.02.001

Lipton, J. S., & Spelke, E. S. (2003). Origins of number sense: Large-number discrimination in human infants. *Psychological Science, 14*(5), 396-401. doi:10.1111/1467-9280.01453

Mazzocco, M. M., Feigenson, L., & Halberda, J. (2011). Preschoolers' precision of the approximate number system predicts later school mathematics performance. *PLOS ONE, 6*(9), Article e23749. doi:10.1371/journal.pone.0023749

Mejias, S., & Schiltz, C. (2013). Estimation abilities of large numerosities in kindergartners. *Frontiers in Psychology, 4*(518), Article 518. doi:10.3389/fpsyg.2013.00518

Melhuish, E. C., Sylva, K., Sammons, P., Siraj-Blatchford, I., Taggart, B., Phan, M. B., & Malin, A. (2008). Preschool influences on mathematics achievement. *Science, 321*(5893), 1161-1162. doi:10.1126/science.1158808

Pew Research Center. (2016). *Are you in the American middle class?* Retrieved from http://www.pewresearch.org/fact-tank/2016/05/11/are-you-in-the-american-middle-class/

President's Council of Advisors on Science and Technology (PCAST). (2012). *Engage to excel: Producing one million additional college graduates with degrees in science, technology, engineering, and mathematics*. Retrieved from https://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast-engage-to-excel-final_feb.pdf

Ramani, G. B., & Eason, S. H. (2015). It all adds up: Learning early math through play and games. *Phi Delta Kappan, 96*(8), 27-32. doi:10.1177/0031721715583959

Ramani, G. B., Rowe, M. L., Eason, S. H., & Leech, K. A. (2015). Math talk during informal learning activities in Head Start families. *Cognitive Development, 35*, 15-33. doi:10.1016/j.cogdev.2014.11.002

Ramani, G. B., & Siegler, R. S. (2008). Promoting broad and stable improvements in low-income children's numerical knowledge through playing number board games. *Child Development, 79*(2), 375-394. doi:10.1111/j.1467-8624.2007.01131.x

Ramani, G. B., & Siegler, R. S. (2011). Reducing the gap in numerical knowledge between low- and middle-income preschoolers. *Journal of Applied Developmental Psychology, 32*, 146-159. doi:10.1016/j.appdev.2011.02.005

Ramani, G. B., Siegler, R. S., & Hitti, A. (2012). Taking it to the classroom: Number board games as a small group learning activity. *Journal of Educational Psychology, 104*(3), 661-672. doi:10.1037/a0028995

Räsänen, P., Salminen, J., Wilson, A. J., Aunio, P., & Dehaene, S. (2009). Computer-assisted intervention for children with low numeracy skills. *Cognitive Development, 24*, 450-472. doi:10.1016/j.cogdev.2009.09.003

Sadler, P. M., & Tai, R. H. (2007). The two high-school pillars supporting college science. *Science, 317*(5837), 457-458. doi:10.1126/science.1144214

Saxe, G. B., Guberman, S. R., & Gearhart, M. (1987). Social processes in early number development. *Monographs of the Society for Research in Child Development, 52*(2, Serial No. 216). doi:10.2307/1166071

Schneider, M., Beeres, K., Coban, L., Merz, S., Schmidt, S. S., Stricker, J., & De Smedt, B. (2016). Associations of non-symbolic and symbolic numerical magnitude processing with mathematical competence: A meta-analysis. *Developmental Science, 20*(3), Article e12372. doi:10.1111/desc.12372

Siegler, R. S. (2009). Improving the numerical understanding of children from low-income families. *Child Development Perspectives, 3*, 118-124. doi:10.1111/j.1750-8606.2009.00090.x

Siegler, R. S. (2016). Magnitude knowledge: the common core of numerical development. *Developmental Science, 19*(3), 341-361. doi:10.1111/desc.12395

Siegler, R. S., & Booth, J. L. (2004). Development of numerical estimation in young children. *Child Development, 75*(2), 428-444. doi:10.1111/j.1467-8624.2004.00684.x

Siegler, R. S., & Lortie-Forgues, H. (2014). An integrative theory of numerical development. *Child Development Perspectives, 8*(3), 144-150. doi:10.1111/cdep.12077

Siegler, R. S., & Ramani, G. B. (2008). Playing linear numerical board games promotes low-income children's numerical development. *Developmental Science, 11*, 655-661. doi:10.1111/j.1467-7687.2008.00714.x

Siegler, R. S., & Ramani, G. B. (2009). Playing linear number board games – but not circular ones – improves low-income preschoolers' numerical understanding. *Journal of Educational Psychology, 101*(3), 545-560. doi:10.1037/a0014239

Siegler, R. S., Thompson, C. A., & Schneider, M. (2011). An integrated theory of whole number and fractions development. *Cognitive Psychology, 62*, 273-296. doi:10.1016/j.cogpsych.2011.03.001

Singer, D. G., Golinkoff, R. M., & Hirsh-Pasek, K. (2006). *Play = Learning: How play motivates and enhances children's cognitive and social-emotional growth*. New York, NY, USA: Oxford University Press.

Starkey, P., Klein, A., & Wakeley, P. (2004). Enhancing young children's mathematical knowledge through a pre-kindergarten mathematics intervention. *Early Childhood Research Quarterly, 19*(1), 99-120. doi:10.1016/j.ecresq.2004.01.002

U.S. Department of Education, Institute of Education Sciences, National Center for Education Statistics. (2015). *2015 Mathematics & Reading Assessments: Achievement levels by student groups.* Retrieved from http://www.nationsreportcard.gov/reading_math_2015/#mathematics/acl?grade=8

van Marle, K., Chu, F. W., Li, Y., & Geary, D. C. (2014). Acuity of the approximate number system and preschoolers' quantitative development. *Developmental Science, 17*(4), 492-505. doi:10.1111/desc.12143

Wang, J. J., Odic, D., Halberda, J., & Feigenson, L. (2016). Changing the precision of preschoolers' approximate number system representations changes their symbolic math performance. *Journal of Experimental Child Psychology, 147*, 82-99. doi:10.1016/j.jecp.2016.03.002

Watts, T. W., Duncan, G. J., Siegler, R. S., & Davis-Kean, P. E. (2014). What's past is prologue: Relations between early mathematics knowledge and high school achievement. *Educational Researcher, 43*, 352-360. doi:10.3102/0013189X14553660

Weisberg, D. S., Hirsh-Pasek, K., & Golinkoff, R. M. (2013). Guided play: Where curricular goals meet a playful pedagogy. *Mind, Brain and Education: The Official Journal of the International Mind, Brain, and Education Society, 7*(2), 104-112. doi:10.1111/mbe.12015

Whyte, J. C., & Bull, R. (2008). Number games, magnitude representation, and basic number skills in preschoolers. *Developmental Psychology, 44*, 588-596. doi:10.1037/0012-1649.44.2.588

Wilson, A. J., Dehaene, S., Dubois, O., & Fayol, M. (2009). Effects of an adaptive game intervention on accessing number sense in low-socioeconomic-status kindergarten children. *Mind, Brain and Education: The Official Journal of the International Mind, Brain, and Education Society, 3*(4), 224-234. doi:10.1111/j.1751-228X.2009.01075.x

Xu, F., & Spelke, E. S. (2000). Large number discrimination in 6-month-old infants. *Cognition, 74*(1), B1-B11. doi:10.1016/S0010-0277(99)00066-9

PsychOpen is a publishing service by Leibniz Institute
for Psychology Information (ZPID), Trier, Germany.
www.zpid.de/en

PsychOpen
publishing psychology