Improved Set-Size Labeling Mediates the Effect of a Counting Intervention on Children's Understanding of Cardinality

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Research Highlights

- Increases in the ability to recognize and label set sizes without counting mediated the effect of intervention on the development of children's understanding of cardinality
- Mediation was full for an intervention where children learned to pair cardinal labels with sets before receiving a counting book intervention
- Mediation was partial for children who only received the standard counting book intervention, suggesting this intervention works via improved set labeling and some other mechanism
- Results highlight the role of labeling sets without counting and possible equifinality in the development of children's understanding of cardinality

Abstract

How does improving children's ability to label set sizes without counting affect the development of understanding of the cardinality principle? It may accelerate development by facilitating subsequent alignment and comparison of the cardinal label for a given set and the last word counted when counting that set (Mix et al., 2012). Alternatively, it may delay development by decreasing the need for a comprehensive abstract principle to understand and label exact numerosities (Piantadosi et al., 2012). In the present study, preschoolers ($N = 106$, $M_{age} = 4;8$) were randomly assigned to one of three conditions: (a) *count-and-label*, wherein children spent six weeks both counting and labeling sets arranged in canonical patterns like pips on a die; (b) *label-first,* wherein children spent the first three weeks learning to label the set sizes without counting before spending three weeks identical to the count-and-label condition; (c) *print referencing control*. Both counting conditions improved understanding of cardinality through increases in children's ability to label set sizes without counting. In addition to this indirect effect, there was a direct effect of the count-and-label condition on progress toward understanding of cardinality. Results highlight the roles of set labeling and equifinality in the development of children's understanding of number concepts.

Keywords: cardinality, counting, preschool mathematics, cognitive development, early learning

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The development of children's number word understanding follows a predictable trajectory (e.g., Wynn, 1992). Children first understand that "one" refers to exactly one item and are referred to as "one knowers." After a few months, they become two- and then three-knowers. Eventually, they reach an understanding that "four" refers to exactly four items. Around this time children figure out that the last word counted refers to the number of items in the set and become cardinality principle (CP) knowers, and understand any number in their count list (Carey, 2009). This key insight, which typically happens prior to the start of kindergarten, provides the foundation upon which more formal mathematics knowledge is constructed (Chu, vanMarle Rouder, & Geary, 2018). Here we experimentally compared two versions of a counting intervention to probe the mechanisms involved in the development of this foundational concept.

Preschoolers' understanding of the cardinality principle is associated with positive mathematics achievement outcomes. The age at which children become CP-knowers in preschool predicts first grade mathematics outcomes, such as number systems knowledge (Geary et al., 2018) and the sophistication of arithmetic strategies (Chu et al., 2018). Additionally, the growth of children's symbolic number knowledge accelerates after they become CP-knowers (Geary & vanMarle, 2018). Unfortunately, many children from lower-SES backgrounds are behind their peers from higher-SES backgrounds in the development of this foundational concept, and they fall further behind in mathematics after starting formal schooling (e.g., Jordan, Kaplan, Ramineni, & Locuniak, 2009). Thus, early intervention is needed. One roadblock in the design of effective interventions is our poor understanding of the mechanisms involved in the development of this knowledge. The research literature provides a fairly consistent picture of what the development of children's number word knowledge looks like and how it progresses along the path toward becoming a CP-knower (e.g., Le Corre, Van de Walle, Brannon, & Carey, 2006; Sarnecka & Lee, 2009; Shusterman, Slusser, Halberda, & Odic, 2016; Wynn, 1992); however, it is unclear how best to promote development. Below we outline two accounts of how children develop an understanding of the cardinality principle and use them to make predictions about what type of intervention might promote development.

Theories of how children develop understanding of cardinality

Conceptual bootstrapping. The development of children's understanding of cardinality may be an example of "Quinian bootstrapping" wherein children create a new representational system that is qualitatively different from, and more powerful than, the system that preceded it (Carey, 2009, 2014). Initially, children possess a "primitive" system capable of exactly representing small set sizes (up to three or four), referred to as the parallel individuation system. Once children have discovered the relation between the position of the number words on the count list and their set size (i.e., one more on the count list means the set size increases by exactly one item), they become capable of exactly representing *all* set sizes on their count list. Thus, the key for conceptual bootstrapping is linking an understanding of counting to an understanding of set size.

Under the original bootstrapping account, progression through the knower-levels is due to item-specific mappings between small set-size representations and the number words for those set sizes (e.g., Carey, 2009). Because children's parallel individuation system is capable of representing set sizes up to four, children can form associations between each of these representations and the corresponding number words one at a time. This initial understanding does not explicitly represent the relations between number words (e.g., children understand that "three" refers to a set of exactly three but not that "three" is exactly one more than "two" on the count list). As these item-specific mappings are forming, children develop a procedural understanding of counting that allows them to recite the number words in order. This structure is used to bootstrap an understanding of set sizes. The main insight occurs when children notice that one more on the count list means the set size increases by exactly one item. Once children make this connection, they understand the *successor principle*, which according to Carey (2004, 2009, 2014) allows them to become CP-knowers and use counting to represent larger set sizes (but see Davidson, Eng, & Barner [2012], Cheung, Rubenson, & Barner [2017], Le Corre [2014], and Spaepen, Gunderson, Gibson, Goldin-Meadow, & Levine [2018] for an alternative idea about the relation between the successor and cardinality principles).

This theory precipitated two more recent accounts that try to explain how children connect the count list to their understanding of set sizes: the primitives account (Piantadosi, Tenenbaum, & Goodman, 2012) and the analogical reasoning account (e.g., Mix, Sandhofer, Moore, & Russell, 2012). These accounts differ in their explanation for what ultimately drives children to understand the cardinality principle. The primitives account suggests children are driven to understand cardinality by the *need* for a new system for representing number. The analogical reasoning account suggests children develop an understanding of cardinality because they align and compare two similar entities. These accounts make opposing predictions about the role of set-size labeling without counting in the acquisition of the cardinality principle.

Primitives model. Piantadosi and colleagues (2012) modeled how children may shift from understanding a few small set sizes to understanding the cardinality principle. In this computational model, as in the original bootstrapping theory, children start with a few cognitive primitives from which they can construct more advanced concepts (but note that according to Carey [2014] and Rips, Asmuth, & Bloomfield [2012] the model does not perform Quinian bootstrapping per se). These primitives include, among other things, the ability to understand the order of the words on the count list and an ability to understand the cardinal labels for a few small set sizes. These set-size primitives are directly related to the cardinal labels that children are capable of understanding without needing a full understanding of the cardinality principle. If children are able to see a set of three, and determine, without counting, that "three" correctly applies to the set, then they would be considered to have a primitive for set size three.

In this model, children start off by learning to pair the cardinal labels they hear ("one," "two") with their cognitive primitives (set-size representations for singleton, doubleton). The progression through the knower-levels can be explained, in part, by the statistical structure of the number word input children receive. Each knower-level reflects a more complex and informative mapping. For example, a two-knower will have mapped their system containing primitive representations for sets of one or two items (more complex than a system that only represents exactly one item) to the cardinal labels "one" and "two" (more informative than a system that only maps "one").

As children encounter additional number words, they must balance the simplest system of explanation with a system that is capable of adequately explaining the input. This balance is achieved by an initial preference for simple over complex hypotheses. That is, a child must have sufficient exposure to number words that cannot be explained by the current representational system before the system will generate more complex hypotheses about number word mappings.

In typical parent-child interactions each number word tends to occur less frequently than the word before it, such that children hear small number words (one, two, and three) most often (see Figure 1). The primitives model explains development by combining children's initial understanding of a few small set sizes with this input. Being a one-knower initially provides adequate explanation of the cardinal labels children encounter because over half of the number-word input is “one.” Over time, children hear an increasing number of instances of “two,” and therefore “one” versus “not one” no longer accurately explains the data, so they extend their understanding to include “one,” “two,” and “not one or two.” By making this small extension and mapping on to their primitive representation for sets of two items, children can adequately explain the input they receive without needing a qualitatively different representational system.

Once children have mapped number words onto every existing primitive representation, the “need” to form a new representational system outweighs the effort it takes to do so. That is, the hypothesis that every cardinal label will map to a cognitive primitive provides a poor enough fit to the data that a new representational system will be constructed. The new system is implemented in the model by a recursive process that mimics the counting procedure and can be used to determine the exact number of items in any set, representing understanding of the cardinality principle. However, because recursion is complex, its use is penalized at the start of learning and only becomes worthwhile once all simpler functions have proven unsatisfactory.

This model explains how children might construct an understanding of the successor and cardinality principles. However, it is important to note that the model is not a direct translation of the original bootstrapping theory (e.g., Carey, 2014). Although both draw on the idea that children’s discovery of the successor principle is the key to being able to represent the numbers in their count list, they differ in the assumptions about children’s initial understanding of set sizes. The original theory posits that children rely on the ability to represent small set sizes using enriched parallel individuation (i.e., long-term representations for small sets 1-4; Carey, 2009). The newer primitives model, however, does not assume that children rely on a parallel individuation system. Rather, set-size primitives here are defined as any way children can identify that a cardinal label is being correctly mapped to a given set, and the number of primitives may differ from child to child.

This expanded definition of set-size primitives points to the possibility that improvements in children’s *conceptual subitizing* may increase the capacity of the primitive system. Conceptual subitizing refers to the ability to quickly and accurately determine a set’s size without counting (e.g., identifying the pattern of items on a die; see Clements & Sarama, 2014). Given that the set-size primitives are any way that children can accurately determine whether a cardinal label is correct for a given set size, a measure of conceptual subitizing can help to determine the capacity of the primitive. Research has shown that preschool children can improve their ability to quickly and accurately conceptually subitize sets beyond four (e.g., Clements & Sarama, 2007), so interventions that improve conceptual subitizing offer a possible way to expand the capacity of the primitive representational system.

According to the primitives model, the capacity of the primitive system partially determines when children become CP-knowers because the need to construct understanding of cardinality only happens once the mappings to all set size primitives have been exhausted. The greater the number of set-size primitives, the more input necessary to become a CP-knower. Children’s set-size primitives allow them to incrementally increase their understanding of number words without needing a new representational system. Thus, children with two set size primitives will reach the capacity of their primitive system with less input than children with four set size primitives. Note that some researchers have already argued that the primitives model does not capture how children’s learning occurs in the real world (e.g., Rips et al., 2013), but to date there has been no empirical test of the account’s key prediction. The current study fills this gap by trying to manipulate children’s ability to identify and label set sizes without counting (i.e., increasing children’s set-size primitives) prior to exposing them to a counting intervention.

If the primitives account is correct, then increasing set labeling should delay the need for the cardinality principle. This is because the primitives account suggests that increasing a child's set-size primitives takes pressure off the need to construct a new representational system. It predicts there will be a negative relation between the number of set-size primitives in children's repertoire (the mediator) and understanding of cardinality (the outcome) after a counting intervention. Thus, an experimental intervention designed to increase the number of set-size primitives should improve children's set labeling but delay children's understanding of cardinality. This prediction stands in contrast to another prominent account of how children develop understanding of the cardinality principle—the analogical reasoning account.

Analogical reasoning account. Children may use their understanding of a few numbers to understand cardinality through analogical reasoning (Mix et al., 2012). According to this account, children learn the cardinality principle by recognizing the overlap between the cardinal label of a set (***3***) and the last word said when counting that set (e.g., 1-2-***3***). The crucial insight here is that counting can be used to determine the size of any set. Similar to the original bootstrapping account, once children connect counting to set size, they become CP-knowers. Note that analogical reasoning also has been cited as important for the initial mapping of number words to their relevant set sizes (e.g., comparing "three" with the set size representation for three items; Carey, 2014), but our focus here is on its role in the discovery of the relation between set size and the count list as described by Mix et al (2012) (see Carey [2004, 2009, 2014] and Gentner & Christie [2010] for related but different ideas about how this analogical reasoning process works).

The primary evidence for the role of analogical reasoning in the development of understanding of cardinality comes from Mix et al.'s (2012) experiment comparing several possible interventions, including counting sets only, labeling the set sizes only, alternating between counting on one page and labeling the next, or both labeling and counting every set. Only children who both labeled and counted every set improved their understanding of cardinality (see also Paliwal & Baroody, 2017). According to the researchers, counting and labeling the same set promotes alignment and comparison of the set size and last word stated when counting, and this analogical reasoning process allows children to realize that counting can be used to determine the exact size of sets, which in turn leads them to understand the cardinality principle.

If analogical reasoning helps children discover the cardinality principle, then children may benefit from learning to map cardinal labels to set sizes without counting prior to receiving a count-and-label intervention. This is because analogical reasoning is easiest for individuals who have a high knowledge of at least one of the two entities being compared (Gentner & Ratterman, 1991; Novick, 1988; Rittle-Johnson, Star, Durkin, 2009). Young counters are still in the process of learning how to count and how to attach the appropriate labels to small set sizes, so they start out with low knowledge of both entities they must compare. Thus, one way to increase children's ability to learn about the cardinality principle through analogy is to first increase their knowledge of cardinal labels. Current recommendations for educators are consistent with this view, as they specifically encourage teaching children to label small sets as the first step in the developmental progression for learning early mathematics concepts (Frye et al., 2013). The more cardinal labels a child can apply without counting, the more opportunities—and the more effective those opportunities—for comparing the cardinal label to the last word used when counting. An analogical reasoning account suggests that the ease with which these two entities can be aligned and compared partially determines when a child becomes a CP-knower because that is the process by which children come to recognize that counting can be used to determine the size of any set.

When put in terms of the meditational model mentioned above, the analogical reasoning account predicts a positive relation between the number of set-size primitives in children's repertoire (the mediator) and understanding of cardinality (the outcome). Thus, an experimental intervention designed to increase the number of set-size primitives should increase children's set labeling and facilitate the development of children's understanding of cardinality. This positive indirect effect predicted by the analogical reasoning account runs counter to the negative indirect effect predicted by the primitives account. One goal of our study was to conduct an experiment that could reconcile these opposing predictions.

Goals of the Present Study

We conducted a six-week long pretest-intervention-posttest experiment where children were randomly assigned to one of two experimental conditions or to a control. In one experimental condition children received the count-and-label practice found to be effective by Mix et al. (2012) for all six weeks; this condition allowed us to compare a previously successful counting intervention from Mix et al. to our new experimental condition. In the other experimental condition, the label-first condition, children first spent three weeks learning to label set-sizes without counting before receiving three weeks of count-and-label practice. We predicted that the two experimental conditions would be better than control at promoting set labeling and understanding of cardinality. We also predicted that the label-first condition would be best at improving children's set labeling ability. However, we had competing predictions about which experimental condition would be best for improving understanding of cardinality because the primitives account and the analogical reasoning account disagree about how improvements in set labeling affect subsequent learning from a counting intervention. The primitives account predicts that the more cardinal labels children can apply without counting, the less pressure there will be to become CP-knowers (Piantadosi et al., 2012). The analogical reasoning account predicts the more cardinal labels children can apply without counting, the easier it will be to make the connection between the labeled set size and the last word stated when counting.

To test the indirect effects through which the interventions affected the development of understanding of cardinality, we constructed a mediational model with intervention condition as the predictor variable, understanding of cardinality at posttest as the outcome, and set labeling without counting after three weeks as the mediator. The analogical reasoning account predicted a positive indirect effect of set labeling, while the primitives account predicted a negative indirect effect.

Method

Participants

Participants were recruited from Title I and Head Start programs from a midsized city in the Midwestern United States. Head Start serves preschoolers (ages 3-5) from households below the poverty level ($24,300 for a family of four in 2016). Title I preschools cover the pre-K year (ages 4-5) and serve children who were waitlisted for Head Start and those from households up to 125% of the poverty level. Our university's institutional review board approved the study.

We pretested 130 preschoolers. Children were excluded from the analyses if they missed more than three weeks of the intervention (*n* = 13), had trouble understanding English (*n* = 4), refused to continue participating (*n* = 3), refused to complete all the tasks at midtest (*n* = 1), had a developmental delay (*n* = 1), or if there was an error in intervention administration (*n* = 2). The final sample included 106 preschoolers (*M* age = 4;8; 57 boys, 49 girls; 64% Black or African American, 27% Hispanic, 9% White).

Measures

Count Disks (assesses counting skill; Mix et al., 2012). Children were shown a board containing 20, one-inch disks spaced one-inch apart arranged in a straight line alternating in color. The experimenter asked the child to count the disks. The largest number the child could count to while counting in the correct order and counting each disk only once was coded as their highest count. Children completed this task twice, and their best count was used for analyses.

Give-N (assesses where children are on the developmental progression toward understanding cardinality; Wynn, 1990). Children were asked to help a stuffed zebra make a fruit salad. For each trial, children were given a pile of 15 fruits. Children were first asked for one item. Once they placed the item(s) on the plate, they were asked "Is that *one*?" If the child said yes, then the set was put into Zebra's bucket. If they said no, then the experimenter said "Zebra wanted *one*. Can you give Zebra *one?"* Similar prompts were repeated after each trial. Administration followed a titration method (e.g., Wynn, 1992), such that if children were correct, they were asked for $n + 1$; if they were incorrect, they were asked for $n - 1$. This pattern continued until children consistently gave the correct number for a given set size (on at least two of three opportunities) as well as for all lower set sizes. The highest set size children consistently provided, while also being able to provide all lower set sizes, was coded as their knower level. Children with knower levels of five or six were considered CP-knowers (Carey, 2009; Sarnecka, 2015). Children were never asked to count but were allowed to do so.

What's on this card? (WOC; assesses where children are on the developmental progression toward understanding cardinality; adapted from Le Corre et al., 2006). Children were introduced to a stuffed zebra that had forgotten its number words and needed help. Children and zebra were then shown cards, each containing a homogenous set (carrots, ladybugs, or helicopters) arranged in a straight line. There were three decks, each containing set sizes 1-6. The first two cards were sets of one and two, respectively, and were used to give feedback meant to encourage a numerical response (e.g., "This *is* a carrot. But remember, Zebra forgot his *number* words. So, what *number* word should we tell Zebra?"). Once children correctly responded to these example trials, they moved on to the test trials. Each deck was pseudo-randomly arranged where children always saw a set of one to begin the deck. On the next two trials, children saw either two or three; sets of four, five, or six were randomly assigned for the second half of each deck. Children received a score from 0-16 based on the number of trials they correctly provided the cardinal label. Children were considered CP-knowers if they were able to correctly label sets of five or six on two of three attempts. Children were never asked to count but were allowed to do so.

Set labeling (assesses set labeling without counting). This task was designed to be a manipulation check of the first three weeks of the intervention, so it was similar, but not identical, to the label-first condition (described below). Children were shown a card with a set of between 1-6 black squares arranged canonically, like pips on a die, and asked "what number word goes with the card?" Cards were held out of arm's reach, and children were told to answer as quickly as possible and were not allowed to count. Any time the child attempted to count the card, the experimenter removed the card from view, repeated the instructions, and restarted the trial. At pretest, children saw each set size (1-6) one time and received a score from 0-5 (the card with one item served as the example trial). After the third session (i.e., the midtest), children were given a total of 13 trials with set sizes one and two presented once, sets of three, four, and five presented three times, and six presented twice. This allowed for a closer investigation of changes at the edge of children's typical subitizable range (three or four), where intervention effects were likely to emerge.

Print awareness (assesses alphabet knowledge and concept of word; adapted from Justice & Ezell, 2002). Children were read *If You Give a Mouse a Cookie* and asked 17 questions (9 alphabet knowledge and 8 concept of word) over the course of the book. Alphabet knowledge questions focused on children's ability to identify individual letters within a word (e.g., "Where is the letter *w* on this page?"). Concept of word questions focused on children's ability to identify individual words (e.g., "Where is the first word on this page?"). Children received a score from 0-17.

Intervention Conditions

Label-first. Children spent the first three weeks using flashcards to learn to apply the proper labels to set sizes one through six. The cards contained familiar, colorful items arranged canonically, like pips on a die (see Figure 2); all canonical patterns remained the same over the course of the decks. The cards were similar to those used in the set labeling assessment, but differed in that they displayed colorful objects rather than black boxes, and they were contextualized as a game involving Zebra (described below). The order and presentation of the decks was based on the incremental rehearsal (IR) drill model in which participants see a minority of unknown material included with a majority of known material (e.g., 30% unknown vs 70% known). Research has shown this to be an effective way to increase retention (e.g., MacQuerrie, Tucker, Burns, & Hartman, 2002). Before the start of each deck, cards were shuffled, but the deck was stacked so the smallest set size was presented first. Children started with decks of one and two items and moved on to a deck that included the next set size once they had mastered the current deck. There were nine total decks of flashcards (see Table 2).

Cards were presented as a game in which a stuffed zebra was learning its number words. Children were shown the flashcard (e.g., three fish) and asked about the number word (e.g., "what number word should Zebra say for these fish?"). If children attempted to count they were told, "remember, this isn't a counting game! Zebra just wants to know the number word that goes with this card." If correct, children were given positive feedback (e.g., "That's right! This card has three fish!"). If incorrect, children were told the correct answer and were asked to repeat the correct number word (e.g., "Whoops! This card actually has three fish! So, what number word should we tell Zebra for this card?"). After three weeks of label-only practice, children received three weeks of the count-and-label practice (described next). Recall that Mix et al. (2012) included a similar set labeling condition (where children only had to provide the cardinal label, but not count) and found that six weeks of label-only was not enough to improve understanding of cardinality. Their condition where children labeled each set size *and* counted the same set did improve cardinality after only three weeks. In the present label-first condition, we used three weeks of set labeling practice followed by three weeks of count-and-label practice to test how improving set size labeling without counting affects learning from count-and-label practice.

Count-and-label (adapted from Mix et al., 2012). Children in this condition worked with experimenters to label and count every set for the entire six weeks. All items to be counted were homogenous sets presented in a canonical pattern like pips on a die. The first three weeks were spent with two, 18-page books containing pictures of the same items children in the label-first condition viewed on their flashcards (e.g., Figure 2). After three weeks, children switched to a second set of counting books that contained a brief story about an animal learning to count the items on the page (e.g., Figure 3).

On each page, children were first told the cardinal label and asked to repeat it (e.g., "Look! There are three fish! Can you say that with me? Three fish!"). Then children were asked to count the set with the experimenter (e.g., "Let's count them together! One [point to object], two [point to object], three [point to object]"). Then, children were asked to count independently (e.g., "Now it's your turn. So, how many are there?"). If a child correctly labeled but miscounted, the experimenter corrected their count and confirmed their label was correct (e.g., "Right, there are three fish. But let's count them again: one [point to object], two [point to object], three [point to object]"). If a child counted correctly but did not provide the cardinal label the experimenter recounted and asked again (e.g., "Right! 1, 2, 3. So, how many are there?").

Control (adapted from Justice & Ezell, 2002). Children in this condition completed a print-awareness intervention previously shown to improve children's alphabet knowledge and concept of print. Children read one of four story books with an experimenter. For each story there were 12 questions, with an emphasis on questions that promote early alphabet knowledge.

Procedure

After being randomly assigned to conditions, children worked one-on-one with an experimenter once a week for six weeks (see Table 1). During the first session, children completed the pretest measures followed by an abbreviated intervention session. Sessions 2-5 were full intervention sessions. To equate the time spent in each condition, full intervention sessions were timed to last 15 minutes. After session 3, children completed a brief midtest. Session 6 included an abbreviated intervention session followed by the posttest measures.

Results

The groups were well matched at pretest (see Table 3), suggesting random assignment worked as intended. Performance on the measures of counting skill, understanding of cardinality, and set labeling were all correlated (see Table 4), with the largest correlation between the two measures of children's understanding of cardinality (give-N and WOC). Because these two measures are designed to measure the same construct, and are highly correlated, we created a composite measure of understanding of cardinality at pretest and posttest by summing each child's z-score for give-N and z-score for WOC. Composite measures allow for more efficient presentation (Cohen, 1990) and decreased measurement error (Jenkins & Taber, 1977).

Recall, the analogical reasoning account predicts a positive indirect effect between condition and understanding of cardinality through increased set labeling (i.e., improved set labeling is associated with larger increases in an understanding of cardinality), while the primitives model predicts a negative indirect effect between condition and understanding of cardinality (i.e., improved set labeling is associated with smaller increases in an understanding of cardinality).

We first considered children's set labeling during the label-first flashcard intervention to see if intervention improved performance. After two sessions, children had mastered, on average, 4.94 decks (SD = 2.95). For reference, deck five introduces sets of five for the first time. After three sessions, children had mastered, on average, 6.29 decks (SD = 2.87). Deck seven introduces children to sets of six for the first time. Roughly half (n =18) of the 35 children had mastered decks that involved sets of six items by the end of session three. A paired-samples t-test indicated that children passed a more advanced deck after three sessions than they did after two sessions, $t(34) = 5.318$, $p < .001$, suggesting set labeling improved with intervention.

Table 5 presents performance on all midtest and posttest outcomes by condition controlling for the relevant pretest variables. As shown in the table, there was a significant effect of condition on performance on the set labeling task at midtest. Planned comparisons revealed that children in the label-first condition outperformed those in the count-and-label condition (p = .006) who outperformed those in the control condition (p = .021). Thus, the label-first condition was most effective at promoting children's ability to label sets without counting, though the count-and-label condition also improved set labeling relative to the control condition. There was not a significant effect of condition on give-N performance at midtest, $F(2, 99) = .331$, $p = .719$, $\eta_p^2 = .007$. Neither experimental condition improved children's understanding of cardinality after only three weeks; thus, for both experimental conditions improvements in set-labeling preceded improvements in understanding of cardinality.

Next, we turned to the primary objective—analyzing the indirect effect of condition on posttest understanding of cardinality through set labeling. A mediational model was constructed (see Figure 4) to test the direction and magnitude of the indirect effect of condition on posttest performance through the hypothesized mediator (set labeling performance at midtest). In order to create a mediational model with a multi-categorical predictor, the experimental conditions were dummy-coded with the control condition used as the comparison group (Hayes & Preacher, 2014). The PROCESS macro was used to construct the mediational model (Hayes, 2013). The PROCESS procedure provides estimates of the total, indirect, and direct effects of the model. A 95% confidence interval for the pathways with 10,000 bootstrap samples was used. The following pretest measures were entered as covariates: age, counting skill, set labeling, and composite cardinality understanding. Performance on the set labeling task at midtest was entered as the mediator.

The *a* terms provide the effect of the experimental conditions on the mediator (Figure 4). Mirroring the ANCOVA, both experimental conditions outperformed the control on the midtest set labeling task. The *b* coefficient provides an estimate of the effect of the mediator on composite cardinality understanding at posttest, controlling for the other variables. This estimate shows that improved performance on the set labeling task by midtest predicts improved understanding of cardinality at posttest.

The *c* and *c'* coefficients provide estimates of the total and direct effects, respectively, of condition on composite understanding of cardinality at posttest, controlling for the pretest measures (Figure 4). Both conditions have a significant, positive effect on understanding of cardinality at posttest, relative to the control condition. We re-ran the model with condition coded as Helmert coefficients and found that neither of the *c* pathways for the experimental conditions differed from each other, providing no evidence that the experimental conditions differed in terms of improving understanding of cardinality (p = .48). Of primary interest are the *c'* estimates, which reveal the direct effect of the intervention condition once the indirect effect has been accounted for. The significant c'_1 estimate shows that a direct effect of the count-and-label condition on understanding of cardinality remains even after accounting for its indirect effect via set labeling. The non-significant c'_2 estimate suggests that there is not a direct effect of the label-first condition on understanding of cardinality. Thus, the effect of the label-first condition on understanding of cardinality can be entirely explained by improvements in set labeling performance. To see whether the direct effect of the count-and-label condition was due to increased counting skill (posthoc) we included posttest counting skill as a covariate, but the direct pathway remained significant (estimate = .482, p = .035).

Looking at the 95% confidence intervals (CIs) for the indirect effect, neither the count-and-label (estimate = .205, [.027, .524]) nor label-first (estimate = .457 [.181, .844]) contain zero.[1,2] The difference between

[1] The pattern of results for the indirect effect held when looking only at give-N or WOC performance at posttest. The direct effect of the count-and-label condition was significant for the posttest WOC performance (estimate = 1.212, p = .019) and positive but non-significant for posttest give-N performance (estimate = .475, p = .181).

[2] Including midtest give-N performance as a covariate produced the same pattern of significant results (significant p-values remain < .05; CIs for the indirect effects do not contain zero).

these two experimental conditions was significant here, with the label-first condition having the stronger indirect effect (estimate = .252 [.090, .543]).[3]

The above analyses show that improvements in set labeling predict advances along the trajectory of cardinality understanding; however, results thus far have not shown that improvements in set labeling predict CP-knower status per se. Thus, we considered whether children were CP-knowers or not on each cardinality task and gave them a score of 0-2 based on whether they were CP-knowers on neither, one, or both tasks.

We constructed a new model (see Figure 5) identical to the previous model but now with CP-knower status as the outcome. Set labeling at midtest positively predicted CP-knower status at posttest (estimate = .042, $p = .013$). The 95% CIs for the indirect effects for both the count-and-label (estimate = .081 [.0088, .226]) and label-first (estimate = .164, [.036, .342]) conditions did not contain zero.[4] Thus, improved set labeling facilitated not just children's development along the trajectory of understanding cardinality, but also their CP-knower status. Unlike the previous model the direct effect of the count-and-label condition was non-significant (estimate = .158, $p = .227$).[5]

Finally, to evaluate discriminant validity, we tested whether the direct or indirect effects were specific to children's understanding of cardinality by analyzing posttest counting skill and print awareness. We constructed identical mediational models as above but with these new outcomes. When counting skill was the outcome, neither the direct nor indirect pathways were statistically significant (p-values > .10; CIs contained zero). When print awareness was the outcome, direct effects were statistically significant for both the count-and-label (estimate = -3.492, $p < .001$) and label-first conditions (estimate = -2.801, $p < .001$). These negative estimates suggest that the control condition was better than both experimental conditions at improving children's print awareness. The CIs for the indirect effects of both conditions contained zero, suggesting that this effect was not mediated by differences in set labeling.

Discussion

What role does children's ability to label set sizes without counting play in the development of understanding of cardinality? The primitives model (Piantadosi et al., 2012) predicts improvements in children's ability to recognize and label set sizes will increase the time it takes to construct understanding of cardinality. The analogical reasoning account (Mix et al., 2012) predicts that improvements in set labeling will accelerate development of understanding of cardinality. Results of the present study favored the analogical reasoning account.

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[3] The indirect effects remained significant when we removed children who were CP-knowers on both tasks at pretest.

[4] Removing children who were CP-knowers on both tasks at pretest did not alter the pattern of results for the indirect effect (i.e., 90% CI for the model with conditions coded as Helmert coefficients showed positive indirect effects for the two experimental conditions compared to the control condition and a stronger effect of the label-first condition compared to the count-and-label.).

[5] A logistic regression predicting being a CP-knower on both tasks at posttest, controlling for the dummy coded conditions, pretest set labeling, pretest counting skill, age, being a CP-knower on both tasks at pretest, and midtest set labeling also showed a significant effect of midtest set labeling ($p = .007$). This effect held when removing the children who were CP-knowers on both tasks at pretest ($p = .048$).

Figures 4 and 5 illustrate how set labeling relates to later development of understanding of cardinality once exposed to count-and-label practice. Set labeling improved greatly from pretest to midtest in the label-first condition, yet there was no evidence this delayed having an understanding of cardinality at posttest. Instead, better set-labeling predicted better understanding of cardinality. This effect was found not only for moving along the developmental trajectory toward understanding cardinality (Figure 4), but also for CP-knower status (Figure 5). These findings conflict with the prediction derived from the primitives model (Piantadosi et al., 2012). This model suggests that if children can explain most of their input with their primitive system, such as by being able to immediately recognize and label a given set size, then they will not be pushed to construct a qualitatively different representational system. If input can be explained by the current representational system, then the model has no reason to construct a more advanced system. Therefore, the more children can initially explain, the more input it will take to become a CP-knower. In the present study, we manipulated the amount of information children could explain by teaching them to label set sizes without counting, but instead of decreasing the need for a new system, the increases in explanatory power positively predicted later understanding.

Note, however, that a stricter interpretation of what constitutes a primitive might hold that the number of set size primitives is not easily altered by experience (e.g., parallel individuation a la Carey, 2009). That is, the increased set labeling performance shown in the present study may not reflect altered capacity of what children can explain with their primitive system. Rather, it may reflect a temporary improvement in the ability to pair number words with specific visual patterns, or it may reflect improvement in another aspect of children's cognition. The data here cannot rule out this stricter interpretation.

Piantadosi et al.'s (2012) primitives model does not make strict assumptions about the nature of primitives. It makes very few assumptions about the cognitive mechanisms involved in development to demonstrate that statistical learning can underlie a complex understanding of natural number. However, it does not specifically rule out analogical reasoning processes (e.g., Carey, 2009; Gentner & Christie, 2010; Mix et al., 2012), and Piantadosi et al. acknowledge that children's learning of number words likely involves additional cognitive processes and numerical input (e.g., quantifier language). Future models may benefit from the inclusion of such processes.

The analogical reasoning account predicted that growth in set labeling would positively predict growth in understanding of cardinality. People's ability to form an analogy between two entities depends on several factors, one of which is the existing knowledge of the two entities being compared (e.g., Rittle-Johnson & Star, 2009). As learners increase their level of knowledge of one of the entities being compared, they are able to focus less on the superficial details and more on the relations between entities (e.g., Richland, Morrison, & Holyoak, 2006). The current results support this account, as children benefited from increasing their knowledge of set-size labels prior to receiving counting input that allowed them to compare the last word counted and the labeled set size.

Although our results are consistent with the idea that analogical reasoning helps propel the development of children's understanding of cardinality, they also suggest a complex pattern of development. If all that mattered was improving children's set labeling abilities before administering a counting intervention, then children in the label-first condition would have had the greatest improvement in their understanding of cardinality. However, we did not find evidence that the two groups differed in their posttest understanding of cardinality. One possible explanation is the direct effect of the count-and-label condition on posttest understanding. That is, although the hypothesized mechanism (set labeling) had the greatest effect for the condition that was specifically designed to improve it (the label-first condition), there may be some other unidentified mechanism also leading to improved understanding of cardinality (represented by the direct effect of the count-and-label condition).

However, the direct effect of the count-and-label condition was not significant when considering CP-knower status as the outcome. This suggests that whatever the direct effect is, it may only be involved in helping children advance along the trajectory of understanding cardinality, but not in the ultimate abstraction of the cardinality principle. Caution should be taken when interpreting null effects though, as CP-knower status may just be a less sensitive outcome. In a larger sample, or over a longer period of time where more children reach CP-knower status, the direct effect may emerge for CP-knower status. Moreover, coding CP-knower status is currently not standardized. We scored it here based on the number of tasks on which it was exhibited, but it is unclear what it means to be a CP-knower on one task but not another. Our coding system led to roughly one third of the sample (35%) being CP-knowers on both tasks. Having a sample with a large number of CP-knowers may limit the generalizability of intervention findings, but findings here were similar when predicting CP-knower status on both tasks and when children who were CP-knowers on both tasks were removed from the mediational models. Still, constructing a standardized, normed measure of CP-knower status is an important goal for future research.

The idea that multiple processes can contribute to the same outcome (i.e., equifinality; e.g., Cicchetti & Rogosch, 1996) has important implications for thinking about how to help children develop understanding of cardinality, as it suggests that many different types of interventions may be able to promote development. In terms of theory, it illustrates a need to conceptualize the development of children's number word knowledge more broadly. However, additional work needs to be done to establish the specific processes involved here. It could be that the present findings illustrate two ways in which analogical reasoning can influence the development of an understanding of cardinality. Children in the count-and-label condition may have benefitted not just from increases in set labeling ability but also from receiving more opportunities to make the relevant comparisons. They received three more weeks of the count-and-label practice than did children in the label-first condition. This may have driven the direct effect by providing twice as many opportunities to compare the last word counted to the labeled set size.

Alternatively, some other aspect of the count-and-label practice (outside of any analogical reasoning process) could be responsible for the direct effect. One possibility is that the counting practice improved children's counting skill. However, the direct effect of the count-and-label condition remained even after controlling for count disks performance, suggesting that this is unlikely, assuming the count disk task is a valid measure of counting skill. Another possibility is that the count-and-label condition provided more experience with "large" numbers (i.e., five and six). Children in the count-and-label condition used counting books containing between 1-6 items in all sessions, while the exposure of children in the label-first condition to various set sizes was based on their performance labeling sets in the first three sessions. They did not reach decks with 5-6 items, on average, until the end of the second session. Greater exposure to larger numbers in the count-and-label condition may be behind the direct effect (cf. Gunderson & Levine, 2011). Future research manipulating the set sizes children are exposed to and the overall number of times children are exposed to the count-and-label input can begin to disentangle the processes involved.

Regardless, these findings add to a small but growing literature suggesting it is beneficial for children to gain experience with counting and labeling the same sets (Mix et al., 2012; Paliwal & Baroody, 2017). Simply counting sets is not as effective as both counting and labeling those sets, and a few weeks of labeling set sizes alone is not enough to promote children's understanding of cardinality (current study; Mix et al., 2012). Thus, labeling and counting the same set may be necessary to make the connection between counting and set size.

Although our study replicated Mix et al.'s (2012) findings that children's understanding of cardinality can be improved in a relatively short period of time with the right input, improvements for understanding cardinality were not as dramatic as those in Mix et al., and the effect size was not as large. When interpreted along with other recent findings, this may offer at least two suggestions for how to improve future interventions. First, our study focused on sets between one and six during the intervention, whereas Mix et al. used sets up to nine. Given the potential importance of number talk beyond four (Gunderson & Levine, 2011), Mix et al. may have provided a more potent source of input. Second, the books in our study contained objects that were arranged in canonical patterns, and children's understanding of cardinality may improve more after counting objects randomly placed on the page than after counting objects arranged in canonical patterns (O'Rear, Bohnsack, & McNeil, 2017).

Notably, most counting books on the market do not contain sets arranged in canonical patterns (Ward, Mazzocco, Bock, & Prokes, 2017). Thus, pairing cardinal labels with canonically arranged patterns and then subsequently labeling and counting sets in those same canonical arrangements may not be what children typically encounter in the world. Further research is needed to see if increased knowledge of how cardinal labels apply to canonically arranged set sizes would help children construct understanding of cardinality from counting sets arranged in unfamiliar patterns.

Finally, it should be noted that recommendations for educators (Frye et al., 2013) suggests that children should be taught to label small set sizes before moving on to counting. We did not find strong evidence that an intervention structured in this way yields superior outcomes to one in which children start by counting and labeling every set from the outset. Still, it remains possible that one sequence has an advantage for longer-term development. Given that children's understanding of cardinality is an important predictor of later mathematics achievement (e.g. Geary et al., 2017), finding simple tasks that can accelerate children's understanding of cardinality, such as labeling set sizes using flashcards or counting and labeling sets in counting books, may help children who are behind on the developmental trajectory toward understanding the cardinality principle.

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Table 1

Overview of Tasks Completed During Each Session for Each Condition

	Pretest and Session 1	Session 2	Session 3 and Midtest	Session 4	Session 5	Session 6 and Posttest
Control	Count disks Give-N and WOC Set labeling Brief print awareness intervention	Full print awareness intervention	Full print awareness intervention Give-N Set labeling	Full print awareness intervention	Full print awareness intervention	Brief print awareness intervention Count disks Give-N and WOC Print awareness assessment
Label-first	Count disks Give-N and WOC Set labeling Brief cardinal label intervention	Full cardinal label intervention	Full cardinal label intervention Give-N Set labeling	Full count-and-label intervention	Full count-and-label intervention	Brief count-and-label intervention Count Disks Give-N and WOC Print awareness assessment
Count-and-label	Count disks Give-N and WOC Set labeling Brief count-and-label intervention	Full count-and-label intervention	Full count-and-label intervention Give-N Set labeling	Full count-and-label intervention	Full count-and-label intervention	Brief count-and-label intervention Count Disks Give-N and WOC Print awareness assessment

Table 2

Composition of the Decks Used for the First Three Weeks of the Label-First Condition

Deck	Set Sizes Presented
1	1-2
2	1-3
3	3-4
4	1-4
5	4-5
6	1-5
7	5-6
8	4-6
9	1-6

Table 3

Characteristics of Each Condition at Pretest (N = 106)

	Gender *% Girls*	Race/Ethnicity *% Person of Color*	Age *M* (*SD*)	Set Labeling *M* (*SD*)	Give-N *M* (*SD*)	WOC *M* (*SD*)	CP-knower % 0, 1, 2	Count Disk *M* (*SD*)
Control	51.35	91.89	55.73 (6.29)	2.30 (1.39)	3.35 (2.04)	10.08 (4.59)	41, 32, 27	11.14 (5.53)
Count-and-label	41.18	94.12	55.63 (5.29)	2.32 (1.20)	3.79 (1.93)	9.79 (4.76)	44, 21, 35	11.09 (5.87)
Label first	45.71	85.71	56.50 (6.74)	2.14 (1.29)	3.37 (2.02)	9.29 (3.79)	48, 29, 23	11.46 (6.48)

Table 4

Correlations Among Pretest Measures

	1	2	3	4	5
1. Age (In Months)	-				
2. Count Disks	.53**	-			
3. Give-N	.51**	.68**	-		
4. WOC	.41**	.57**	.75**	-	
5. Set Labeling	.27*	.58**	.58**	.69**	-

*$p < .01$, **$p < .001$

Table 5

Estimated Marginal Means and Standard Errors for Each Outcome by Condition Controlling for the Following Pretest Variables: Age (in Months), Counting Skill, Set Labeling, and Composite Cardinality Understanding

	Control			Count-and-label			Label-first			Estimated effect		
	n	*M*	*SE*	*n*	*M*	*SE*	*n*	*M*	*SE*	*F*	*p*	η_p^2
Set labeling mid	37	5.63	0.42	34	7.06	0.44	35	8.81	0.44	13.63	<.001	0.22
Give-N mid	37	3.71	0.19	34	3.49	0.20	35	3.55	0.20	0.33	.72	0.01
Composite cardinality post	37	-0.41	0.16	34	0.31	0.17	35	0.14	0.17	5.24	.007	0.10
Give-N post	37	3.14	0.25	34	3.89	0.26	35	3.56	0.26	2.20	.12	0.04
WOC post	37	9.15	0.35	34	10.68	0.37	35	10.61	0.37	5.84	.004	0.11
Count disk post	37	10.99	0.64	34	12.64	0.67	35	12.25	0.66	1.76	.18	0.03
Print awareness post	37	5.76	0.44	34	2.08	0.46	34*	2.53	0.46	20.45	<.001	0.29

* One child refused to complete the print awareness assessment