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The effect of multimodal information on children's numerical judgments

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ABSTRACT

Although much research suggests that adults, infants, and nonhuman primates process number (among other properties) across distinct modalities, limited studies have explored children's abilities to integrate multisensory information when making judgments about number. In the current study, 3- to 6-year-old children performed numerical matching or numerical discrimination tasks in which numerical information was presented either unimodally (visual only), cross-modally (comparing audio with visual), or bimodally (simultaneously presenting audio and visual input). In three experiments, we investigated children's multimodal numerical processing across distinct task demands and difficulty levels. In contrast to previous work, results indicate that even the youngest children (3 and 4 years) performed above chance across all three modality presentations. In addition, the current study contributes two other novel findings, namely that (a) children exhibit a cross-modal disadvantage when numerical comparisons are easy and that (b) accuracy on bimodal trial types led to even more accurate numerical judgments under more difficult circumstances, particularly for the youngest participants and when precise numerical matching was required. Importantly, findings from this study extend the literature on children's numerical cross-modal abilities to reveal that, like their adult counterparts, children readily track and compare visual and auditory numerical information, although their abilities to do so are not perfect and are affected by task demands and trial difficulty.

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Introduction

Substantial evidence suggests that our ability to track number interacts with the perceptual properties of the set (e.g., Clearfield & Mix, 1999, 2001; Leibovich, Katzin, Harel, & Henik A, 2017; Mix, Huttenlocher, & Levine, 2002; Piaget, 1942; Posid, Mills, & Sloutsky, 2017), particularly in early developing numerical abilities. Numerous studies have revealed that perceptual features can facilitate (or hinder) children's abilities to attend to number (e.g., Cantlon, Fink, Safford, & Brannon, 2007; Feron, Gentaz, & Streri, 2006; Jordan & Brannon, 2006; Jordan, Clark, & Mitroff, 2010; Jordan, Suanda, et al. 2008; Kaminski & Sloutsky, 2009, 2013; Kobayashi, Hiraki, & Hasegawa, 2005; Mix, Huttenlocher, & Levine, 1996; Posid & Cordes, 2015; Posid, Mills, & Sloutsky, 2017; Starkey, Spelke, & Gelman, 1983, 1990); however, the boundary limits of how perceptual cues may affect numerical processing, particularly early in development, are currently undefined.

The current study aimed to provide a systematic test of children's cross-modal numerical abilities, specifically as they compare with unimodal abilities and the role of bimodal input in this development. Prior work investigating multimodal numerical abilities has suggested that two distinct phenomena may affect numerical abilities early in development: a cross-modal deficit (an impairment in processing numerical stimuli across modalities) and a bimodal advantage (improved numerical processing in the context of simultaneous multimodal stimuli). However, when—and if—these phenomena are at play differs from study to study. Notably, substantial variability in methodology and developmental samples across studies has prevented a true examination of those contexts that give rise to cross-modal deficits and bimodal advantages. The current study fills this gap in the literature by systematically investigating numerical matching and discrimination abilities across visual and auditory modalities in 3- to 6-year-old children.

Cross-modal perception

What we understand about cross-sensory numerical processing has primarily come from research with human infants and adults and nonhuman animals (e.g., Alards-Tomalin, Walker, Shaw, & Leboe-McGowan, 2015; Cappelletti et al., 2013; Chick, 2014; Cote, 2015; Gallace, Tan, & Spence, 2007; Hayashi et al., 2013; Jordan, Maclean, et al. 2008; Mix, Levine, & Huttenlocher, 1997; Tokita, Ashitani, & Ishiguchi, 2013). This literature has shown that young infants can track number cross-modally, with most evidence demonstrated so far for small sets and limited evidence suggesting that this can also be done for large set sizes (small sets: Starkey, Spelke, & Gelman, 1983, 1990; see also Feron et al., 2006; Jordan & Brannon, 2006; Jordan, Suanda, et al. 2008.; Kobayashi et al., 2005; Mix et al., 1996; large sets: Izard, Sann, Spelke, & Streri, 2009). Unsurprisingly, adults can make numerical judgments abstractly and independent of modality (Barth et al., 2006; Jordan et al., 2010).

Children's abilities to track number cross-modally, however, have been studied in a limited and nonsystematic fashion, revealing mixed results. Barth and colleagues reported that 5-year-olds perform cross-modal numerical comparisons and arithmetic with the same level of accuracy as they perform exclusively visual numerical judgments (unimodal) (Barth, La Mont, Lipton, & Spelke, 2005; Barth, Spelke, & Beckmann, 2007), suggesting no cross-modal performance cost. However, other studies involving numerical match-to-sample tasks (i.e., where participants indicate which of two arrays exactly matches the number of items heard) found that preschoolers fail to accurately match auditory arrays with visual ones (Jordan & Baker, 2010; Mix et al., 1996; see also DeLoss, Pierce, & Andersen, 2013). This failure to match number cross-modally is found for both large sets (Jordan & Baker, 2010) and small sets (Mix et al., 1996) alike. Importantly, children fail to match auditory number with visual number despite succeeding on visual–visual (unimodal) matching under the same circumstances (e.g., Mix et al., 1996). Given that prior studies have employed different paradigms (numerical discrimination vs. numerical matching) to evaluate children's abilities to make cross-modal numerical judgments, it is unclear whether children's numerical abilities are compromised in the context of cross-modal numerical stimuli or whether, instead, performance costs are dependent on specific task demands. That is, are cross-modal deficits found only when children are asked to match number exactly? The current study aimed to clarify how children's numerical abilities are affected by the presentation of cross-modal stimuli across distinct task demands. We asked these questions: Are young children's cross-modal numerical abilities compromised relative to those within a single modality? If so, what contexts give rise to cross-modal impairments?

Bimodal perception

In contrast to the variable cross-modal literature, research suggests that the integration of synchronous redundant intersensory information (bimodal) may help to guide children's attention toward relevant learning experiences. This *intersensory redundancy hypothesis* (Bahrick & Lickliter, 2000, 2002; Bahrick, Lickliter, & Flom, 2004) has been supported by evidence revealing heightened learning when presented with information across modalities, more so than when input is limited to a single sensory source (e.g., unimodal) (Laurienti, Burdette, Maldjian, & Wallace, 2006; Laurienti et al., 2003). Intersensory redundancy has been found to be particularly relevant when participants are presented with very difficult tasks (Bahrick, Lickliter, Castellanos, & Vaillant-Molina, 2010) and has been shown to promote earlier detection of many properties—such as infant affect discrimination, face discrimination, sequence detection, abstract rule learning, and word comprehension and segmentation—compared with unimodal exposure to these same properties (Lickliter & Bahrick, 2013).

Some evidence points to the facilitating effects of intersensory redundancy in numerical tasks. Using a habituation–dishabituation paradigm, Jordan, Suanda, et al. (2008) found that bimodal stimuli (both auditory and visual, e.g., a ball bouncing and producing sound on each impact) resulted in improved numerical discrimination in infants relative to unimodal stimuli. Moreover, another study revealed bimodal information to promote numerical matching abilities in preschoolers (Jordan & Baker, 2010). Thus, intersensory redundancy seems to facilitate numerical discrimination and matching early in development by directing attention to the relevant aspects of the stimuli being learned. Yet, the constraints on this bimodal advantage are undefined. Previous work has explored only synchronous bimodal presentation of sequential auditory and visual stimuli—that is, sounds presented for the presentation of each and every visual stimulus. Is this observed bimodal advantage limited to sequential stimuli, or might auditory information similarly promote attention to number in the case of the presentation of simultaneous visual arrays? The current study aimed to clarify how children's numerical abilities are affected by the presentation of bimodal stimuli across distinct contexts. We asked this question: Does the reported bimodal advantage emerge across contexts, or is this advantage task dependent?

The current study

In three experiments, 3- to 6-year-old children performed unimodal, bimodal, and cross-modal numerical matching (Experiment 1) or discrimination (Experiments 2 and 3) tasks. To explore how task difficulty may affect the presence or absence of cross-modal deficits or bimodal advantages, we manipulated the ratio of the two numbers being compared (because numerical discrimination is well known to be ratio dependent). This age range was chosen because it matched that of previous investigations of preschoolers' cross-modal and bimodal matching abilities (Barth et al., 2005, 2007; Jordan & Baker, 2010; Mix et al., 1996). Importantly, however, to ensure that children of this age were capable of tracking the number of items presented and would be able to understand the instructions, we made sure to include only children who were proficient counters in our task (i.e., identified as cardinal principle knowers via the Give-*N* task; Le Corre & Carey, 2007). Building on previous literature, the current study addressed these open questions: (a) Are young children's cross-modal numerical abilities compromised relative to those within a single modality? If so, are there particular contexts that exacerbate cross-modal impairments? (b) Does the observed bimodal advantage emerge across contexts, or is this advantage task dependent?

Experiment 1

In Experiment 1, 3- to 6-year-old children performed a numerical matching task in which they initially saw (unimodal), heard (cross-modal), or saw *and* heard (bimodal) a number of pictures or sounds (sample array) and then were subsequently asked to select which of two visual arrays contained the same number of items as the sample array. Importantly, all items within a visual array were presented simultaneously in a single image and not sequentially over time. Accuracy levels on these three trial types were compared in order to determine (a) whether cross-modal numerical matching involves a performance cost relative to unimodal matching; (b) whether redundant sensory information (i.e., bimodal trials), even when not presented in synchrony, provides children with an advantage over single sensory (unimodal or cross-modal) trials; and (c) whether cross-modal performance disadvantages *or* bimodal performance advantages vary over the course of early childhood.

Method

Participants

A total of 93 3- to 6-year-old children took part in this experiment (M_{age} = 58.3 months, *SD* = 9.68; 41 girls). Children were divided into younger (3- and 4-year-olds; *n* = 46, M_{age} = 50.7 months, *SD* = 4.65; 19 girls) and older (5- and 6-year-olds; *n* = 47, M_{age} = 65.8 months, *SD* = 7.15; 22 girls) age groups for purposes of all analyses. To ensure that all children were able to follow directions to attend to number—indicating that they were numerically competent—only children identified as proficient counters (cardinal principle knowers [CP-knowers]) through the Give-*N* task (correctly producing a set of 6 items when asked; Le Corre & Carey, 2007; Wynn, 1990, 1992) were included in this experiment. Children were first administered the Give-*N* task, and only those who correctly produced a set of up to 6 items (and thus were classified as CP-knowers or proficient counters) were run in the current study[1]; children who were not proficient counters were run in a different study. Data from 18 additional children were excluded due to computer error (*n* = 4), failure to complete all test trials (*n* = 12), or failure to follow the rules of the game (*n* = 2).

Across all three experiments, children were recruited while visiting one of two local Boston-area museums (the Boston Children's Museum or the Museum of Science, Boston), via public birth records for a single visit to the Infant and Child Cognition Lab on Boston College's main campus, or at local preschools/after-school programs. Due to the auditory nature of the stimuli, all testing took place in a quiet location where children could hear the experimenter's instructions and listen to the auditory stimuli from the computer. Children received a sticker and/or small prize for participating, depending on regulations at each testing location.

Due to time constraints when testing children off-site, demographic information was not systematically collected for children tested outside of the laboratory. Racial and ethnic demographics of our participants at museums were likely to match those of museum visitors as reported by the museum itself, which were roughly 88.7% White (not of Hispanic origin), 2.9% Hispanic/Latino, 4.2% Asian American, 2.7% African American, 1.2% American Indian or Alaskan Native, and 3.4% "other." For children whose parents reported demographic information within the laboratory, the sample was predominantly White and educated, approximately as follows: 73% White, 7% Asian, 13% Black or African American, and 6% mixed race. In addition, about 15% reported being Hispanic. Of those who reported their education, all mothers had at least some college and 80% had a bachelor's degree or

[1] Unlike CP-knowers, "subset-knowers" are those children who are still in the process of figuring out the verbal count procedure (Le Corre & Carey, 2007). These nonproficient counters lack the mapping necessary to compare sets (e.g., they do not understand that two items is the same as the word "two" and, thus, may be more reliant on perceptual properties of a display when making numerical judgments (Huang, Spelke, & Snedeker, 2010; Posid & Cordes, 2015). Thus, only proficient counters were included in the current study, such that an inability to use numerical language may hinder numerical abstraction abilities. In the course of running the study, any children categorized as subset-knowers using the Give-*N* task were allocated to another study (*N* = 258; Posid & Cordes, 2018) whose research question specifically examined the development of verbal language and an understanding of cardinality prior to a proficient ability.

higher. It is expected that the demographics of children tested at off-site school locations were similar to those of children tested in the laboratory.

Stimuli

For visual sample arrays (unimodal and bimodal trials), children saw a single array displayed on a white box (12 × 6.5 inches) centered on a black background (e.g., five dogs). The size and identity of individual items within an array was constant (e.g., all same-sized dogs), but item size and identity varied across arrays (e.g., dogs, trains, pianos). Elements within each array were randomly placed.

For cross-modal trials, the sample array was a series of sounds (e.g., five dog barks) with no corresponding visual array. Instead, an image of a speaker was placed in the center of the screen, indicating that children should listen for the auditory presentation. Within each auditory array the sounds were homogeneous (e.g., all dog barks), but across arrays the type of sounds presented varied (e.g., dog barks, train whistles, beeps). The presentation length of the arrays was approximately 1 s, such that the duration of a 5-item auditory array lasted approximately 5 s. Auditory stimuli were played through the speaker of the laptop computer on which children were tested.

Across trial types, auditory and visual sample presentations of the same numerosity were matched for duration; for example, if five dog barks were presented for 5 s on cross-modal trials, the visual array of five dogs was also displayed for 5 s on unimodal trials).

After the presentation of the sample array (visual, auditory, or bimodal), children were presented with two side-by-side visual arrays (e.g., 5 dogs vs. 10 dogs), each displayed inside a white box (6.35 × 5.75 inches) centered against a black background (12.78 × 8.92 inches) (see Fig. 1). The secondary arrays did not differ across trial types; they were always two visual arrays presented side by side. The cumulative areas of the items in the secondary arrays were matched, such that the total area taken up by the elements was the same (element sizes ranged from 63.7 × 63.7 pixels to 122.47 × 122.47 pixels). The side of the array containing the same number of items as the sample array (i.e., the correct numerical match) and the side of the more numerous array varied randomly across trials, such that the correct match or the more numerous match appeared on the right side for half of the trials. Stimuli were presented on a 13-inch MacBook laptop and were controlled through a RealBasic program, which also recorded responses. See Fig. 1 (top panel) for an example of the stimuli used.[2]

Practice trials

In practice, children were presented with six randomly intermixed trials: 2 unimodal trials (visual to visual match), two cross-modal trials (auditory to visual match), and two bimodal trials (visual + auditory to visual match). The size of each distractor array (i.e., the incorrect array) in practice varied from the size of the correct array (i.e., the target array) by a 1:4 ratio, a difference that should be easily discriminable even for the youngest children (e.g., Libertus & Brannon, 2010; Lipton & Spelke, 2003, 2004; Wood & Spelke, 2005; Xu & Spelke, 2000). On half of the trials the distractor array was more numerous than the target array, and on the other half the distractor array was less numerous than the target array.

Test trials

During testing, all three trial types were randomly intermixed throughout. The number of items in the distractor array differed from the number of items in the sample array by one of two numerical ratios (1:2 or 2:3), again with half of the trials involving a distractor that was numerically larger than the sample array and the other half involving a distractor that was numerically smaller than the sample array. Each ratio was composed of three distinct numerical pairs (1:2 ratio: 2 vs. 4, 4 vs. 8, and 5 vs. 10; 2:3 ratio: 2 vs. 3, 4 vs. 6, and 8 vs. 12), for a total of 36 test trials. Given that previous research has

[2] In addition, categorical congruency of the stimuli was manipulated across all three experiments, such that on half of the trials the sample array conceptually matched the two choice stimuli (e.g., dogs or dog barks were paired with dogs), and on the other half of the trials the sample array did not conceptually match the choice stimuli (e.g., piano sounds or beeps were paired with dogs). Preliminary analyses across all three experiments revealed no main effects or interactions involving the congruency variable; thus, this variable was not included in final analyses.

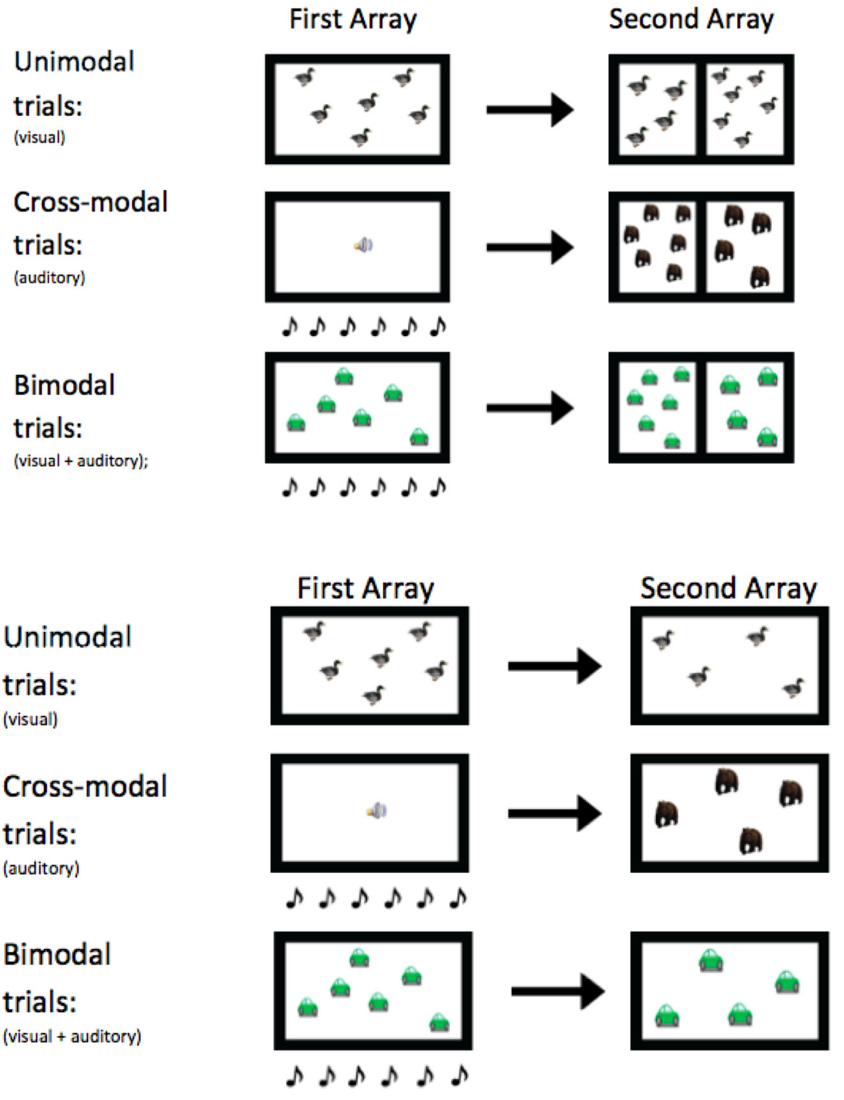

Fig. 1. Example stimuli from Experiment 1 (top panel) and Experiment 2 (bottom panel).

explored multimodal numerical matching abilities in children using both small (e.g., Mix et al., 1996) and large (Jordan & Baker, 2010) values, we had no expectations for difference performance patterns across these ranges. Thus, we included both small and large set sizes in our tasks.

Procedure

The entire experimental session (including the initial Give-*N* task) lasted approximately 15 to 20 min.

Give-N screening assessment

Because only proficient counters were included in this study, children were first presented with the Give-*N* task (modeled after Le Corre & Carey, 2007; Posid & Cordes, 2014, 2018; Wynn, 1990, 1992) to determine their level of counting proficiency. A total of 15 small rubber ducks were placed on the table in front of children, who were instructed to make a certain number of ducks jump into a blue basket ("Can you make *N* ducks jump in the pond?"). The experimenter first asked children to produce one item ("Can you make one duck jump in the pond?"). If children successfully produced one item, the experimenter removed the item from the basket and then proceeded to ask for $N + 1$ items. If children failed to produce the correct quantity, the experimenter asked them, "Is that *N* duck(s)?" Children were given the opportunity to correct the size of the set. If children failed to correct the size of the set, the experimenter then started a new trial and asked for $N - 1$ items. If children successfully produced $N - 1$ items, the experimenter continued to ask for *N* items, with the requested set size increasing with each correct response; however, if children failed to produce a requested quantity twice, the experimenter ended the game. Only those children who successfully produced sets containing six items (identified as CP-knowers) were administered the computer task as part of the study.

Match-to-Sample task

Following the Give-*N* task, children participated in the computerized numerical matching task. On each trial, children were first presented with a sample array and were asked to pick which of two following arrays matched the numerosity of the sample array. There were three types of trials (randomly intermixed): (a) unimodal, where the sample array was presented as a simultaneous visual array (e.g., an array of five dogs); (b) cross-modal, where the sample array was presented as a sequence of sounds (e.g., a series of five dog barks); and (c) bimodal, where the sample array was presented as a simultaneous visual array coupled with a sequence of sounds matching the numerosity of the visual array (e.g., a visual array of five dogs accompanied by a sequence of five dog barks).

Regardless of trial type, following the sample array, children were presented with two side-by-side visual arrays (e.g., 5 dogs and 10 dogs) and were asked to select the array that matched the numerosity of the sample array.

Children first participated in six practice trials to acclimate them to the computer task and familiarize them with the different trial types. Children were given an unlimited amount of time to make their selection. During practice, children were given feedback on their performance. During testing, however, children were not provided with any feedback based on their performance, but they did receive positive encouragement (e.g., "Great job!"). Children's responses were recorded on the computer. Although rare, if a child took more than 10 s to respond to a specific trial, the trial was excluded from final analyses.

Results

A mixed-measures analysis of variance (ANOVA) examining the impact of the within-participants factors of ratio (1:2 or 2:3) and trial type (unimodal, bimodal, or cross-modal) and the between-participants factor of age group (3- and 4-year-olds or 5- and 6-year-olds) was conducted. Analyses revealed a main effect of age group, $F(1, 92) = 57.9$, $p < .001$, $\eta_p^2 = .326$, such that children were more accurate as they aged (3- and 4-year-olds: $M = 65.2\%$; 5- and 6-year-olds: $M = 79.7\%$). Importantly, however, both age groups performed significantly above chance overall (single-sample *t* tests vs. 50% [chance], both *p*s < .001).

The ANOVA also revealed a main effect of ratio, $F(1, 92) = 68.9$, $p < .001$, $\eta_p^2 = .428$, such that children performed significantly better on the 1:2 ratio trials ($M = 78.6\%$) than on the 2:3 ratio trials ($M = 66.2\%$), consistent with the Weber characteristic of numerical discriminations (ratio effects; e.g., Cantlon & Brannon, 2006). There was also a Ratio × Age Group interaction, $F(1, 92) = 25.3$, $p < .001$, $\eta_p^2 = .216$, revealing that although ratio effects were evident across both age groups, numerical ratio had a greater impact on performance with age [3- and 4-year-olds: 1:2 ratio, $M = 67.6\%$ vs. 2:3 ratio, $M = 62.7\%$, $t(46) = 2.1$, $p = .042$, Cohen's $d = 0.33$; 5- and 6-year-olds: 1:2 ratio, $M = 89.7\%$ vs. 2:3 ratio, $M = 69.7\%$, $t(46) = 10.8$, $p < .001$, Cohen's $d = 1.90$]. Again, single-sample *t* tests (vs. 50% [chance]) confirmed that performance in each Age Group × Ratio cell was significantly above chance (all *p*s < .001).

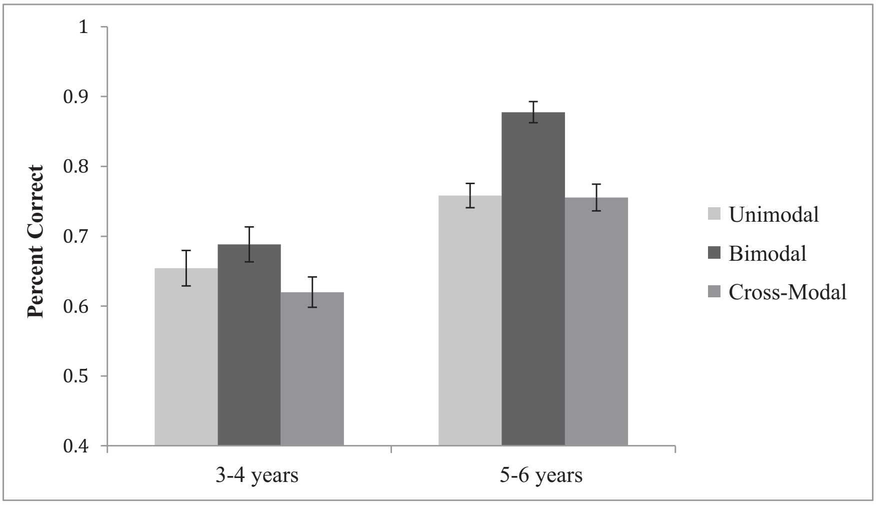

Fig. 2. Accuracy in Experiment 1 as a function of age group and trial type. Error bars reflect standard error of the mean.

Relevant to our primary research questions, results revealed a main effect of trial type, $F(1, 92) = 15.6$, $p < .001$, $n_p^2 = .145$, such that children performed most accurately on bimodal trials ($M = 78.0\%$) compared with unimodal trials ($M = 70.7\%$), $t(93) = 4.5$, $p < .001$, Cohen's $d = 0.93$, and cross-modal trials ($M = 68.6\%$), $t(93) = 5.5$, $p < .001$, Cohen's $d = 1.10$. Notably, a cross-modal performance cost was not evident given that children performed comparably on unimodal and cross-modal trials ($p > .30$) (see Fig. 2). In addition, in contrast to previous studies in which preschool-age children performed at chance levels matching auditory to visual stimuli (Jordan & Baker, 2010; Mix et al., 1996), children in both age groups performed significantly better than chance (50%) on cross-modal trials [3- and 4-year-olds: $M = 65.4\%$, $t(46) = 5.5$, $p < .001$, Cohen's $d = 1.60$; 5- and 6-year-olds: $M = 75.5\%$, $t(46) = 13.4$, $p < .001$, Cohen's $d = 3.90$]. Thus, results replicate findings of a bimodal advantage in young children (Jordan & Baker, 2010) while also being the first to reveal young children can perform cross-modal numerical matching at above chance.

Trial type also interacted marginally with age, $F(2, 184) = 3.0$, $p = .051$, $n_p^2 = .032$, revealing a trend toward greater benefits of bimodal stimulus presentation with age. Specifically, 3- and 4-year-olds showed a bimodal advantage compared with cross-modal trials, $t(46) = 2.5$, $p = .018$, Cohen's $d = .74$, but showed equal performance between bimodal and unimodal trials, $t(46) = 1.3$, $p > .10$, Cohen's $d = 0.39$. However, 5- and 6-year-olds showed a clearer bimodal advantage over both unimodal trials, $t(46) = 5.7$, $p < .001$, Cohen's $d = 1.70$, and cross-modal trials, $t(46) = 6.1$, $p < .001$, Cohen's $d = 1.80$.

Trial type also interacted with ratio, $F(2, 184) = 27.9$, $p < .001$, $n_p^2 = .233$ (Fig. 3), revealing that although performance across all three trial types was affected by numerical ratio ($ps < .05$), ratio effects were notably stronger for the unimodal trials compared with the two other trial types [difference in performance between 1:2 and 2:3 ratios: $M_{uni} = .28$, $M_{bi} = .084$, and $M_{cross} = .042$, $F(2, 184) = 50.01$, $p < .001$; unimodal vs. other trial types, $p < .001$; bimodal vs. cross-modal, $p > .05$].

Lastly, a three-way interaction among trial type, ratio, and age group, $F(2, 184) = 3.8$, $p = .023$, $n_p^2 = .04$ (Table 1), was attributed to the finding that, inexplicably, the youngest age group performed slightly better on 2:3 ratio trials compared with 1:2 ratio trials (the opposite direction than that predicted by Weber's law), but only on cross-modal trials.

Discussion

In contrast to previous studies in which preschool-age children performed at chance when matching auditory to visual stimuli (Jordan & Baker, 2010; Mix et al., 1996), children in Experiment

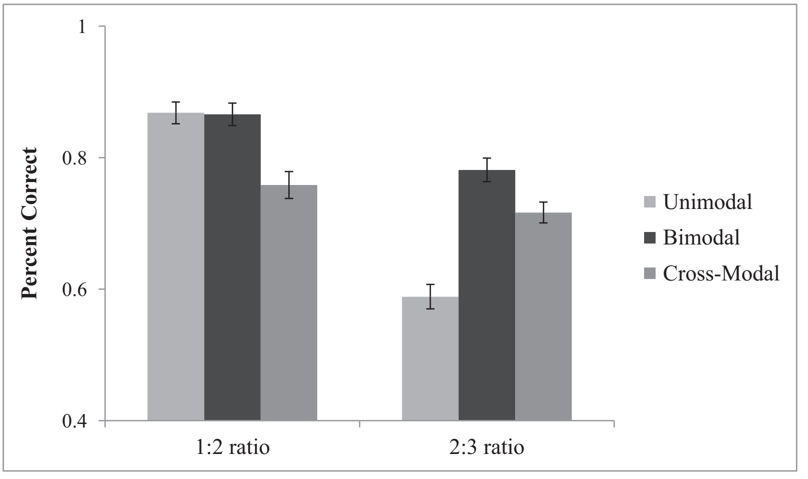

Fig. 3. Accuracy in Experiment 1 as a function of ratio and trial type. Error bars reflect standard error of the mean.

Table 1
Experiment 1: trial type × ratio × age.

Trial type	Age group (years)	1:2 ratio (mean %)	2:3 ratio (mean %)
Unimodal	3–4	73.2	57.6
	5–6	93.1	58.7
Cross-modal	3–4	57.6	65.6
	5–6	82.1	69.0
Bimodal	3–4	72.0	64.9
	5–6	93.8	81.4

1 performed *above* chance across the board on these trials. Even the youngest age group (3- and 4-year-olds) performed significantly more accurately than chance, extending findings from Barth et al. (2006) to reveal that young children not only can make approximate numerical comparisons across modalities but also can match number across modalities.

Consistent with the intersensory redundancy hypothesis (Bahrick & Lickliter, 2000, 2002), Experiment 1 also revealed a bimodal advantage in an exact numerical matching task (see also Jordan & Baker, 2010; Jordan, Maclean, et al., 2008). Whereas previous studies have demonstrated a bimodal advantage with sequential sets, these data are the first to reveal that numerical representations formed over simultaneous visual arrays may also profit from the presentation of redundant auditory stimuli.

Previous studies have used both numerical matching and numerical discrimination tasks to assess cross-modal numerical abilities in children. Exact number matching tasks are generally more difficult than approximate number discriminations (e.g., Cantlon et al., 2007; Halberda & Feigenson, 2008; Posid & Cordes, 2015) because numerical matching requires more than simply discriminating set sizes, instead requiring children to identify which of two sets represented a specific cardinal value held in working memory. Thus, in Experiment 2, we examined children's numerical *discrimination* abilities for stimuli presented unimodally, cross-modally, and bimodally. Importantly, numerical discrimination tasks do not require an ability to track number exactly, only to determine the approximate ordinality of two sets (i.e., which is more?). We asked this question: Does the developmental profile of cross-modal and bimodal numerical judgments differ under different task demands?

Experiment 2

In Experiment 2, 3- to 6-year-old children performed a numerical discrimination task in which they were asked to discriminate the relative numerosity of two sets. As in Experiment 1, the first set was presented as a visual array (unimodal trials), an auditory sequence of sounds (cross-modal trials), or a visual array paired with an auditory sequence (bimodal trials).

Method

Participants

A total of 94 3- to 6-year-old children took part in this experiment (M_{age} = 57.3 months, *SD* = 11.9; 46 girls). Children were divided into younger (3- and 4-year-olds; *n* = 50, M_{age} = 48.4 months, *SD* = 6.75; 27 girls) and older (5- and 6-year-olds; *n* = 44, M_{age} = 67.5 months, *SD* = 7.40; 19 girls) age groups for purposes of all analyses. As in Experiment 1, only children identified as proficient counters (CP-knowers per the Give-*N* task; Le Corre & Carey, 2007; Wynn, 1990, 1992) were included in this experiment. An additional 31 children were excluded due to: computer error (*n* = 3), failure to complete all test trials (*n* = 27),[3] or failure to follow the rules of the game (*n* = 1). Children were tested at one of two local museums or during a single visit to the laboratory.

Stimuli

The stimuli were identical to those in Experiment 1 with the following differences. On every trial, the sample array was identical to that of Experiment 1; however, after the sample array, children saw a single visual array (comparison array) displayed on a white box (12 × 6.5 inches) centered on a black background (Fig. 1). Secondary comparison arrays were the distractor arrays used in Experiment 1. Again, elements in the comparison arrays were homogeneous in element size within each array but varied between arrays. The first and second arrays were matched in cumulative area. Elements within each array were randomly placed. As in Experiment 1, all three trial types (unimodal, cross-modal, and bimodal) were randomly intermixed throughout the task. During testing, the number of items in the distractor array differed from the number of items in the sample array by one of two numerical ratios (1:2 or 2:3). Each ratio was composed of three distinct numerical pairs, with the number of items in each array varying from 2 to 12. Thus, there were 3 trial types (unimodal, cross-modal, or bimodal) × 2 ratios (1:2 or 2:3) × 3 distinct numerical pairs (for 1:2: 2 vs. 4, 4 vs. 8, or 5 vs. 10; for 2:3: 2 vs. 3, 4 vs. 6, or 8 vs. 12) × 4 presentations each, for a total of 72 test trials.

Procedure

The entire experimental session lasted approximately 25 to 30 min. The procedure was similar to that of Experiment 1. Following the Give-*N* task, children participated in the discrimination task on a laptop computer. Children were instructed to indicate which of the two sets (the sample or the subsequent comparison array) contained a greater number of items. Children were again presented with unimodal, cross-modal, and bimodal trials intermixed. Children participated in six practice trials, involving a 1:4 ratio change, to acclimate them to the computer task and the types of modalities with which they were to be presented. In contrast to Experiment 1, children had a limited time (3 s) after the presentation of the comparison array to indicate which array they believed contained more items. This was done to ensure that the task gauged *approximate* numerical judgments.

[3] Due to the theoretically predicted "easier" nature of this approximate numerical task (e.g., Cantlon et al., 2007), the number of trials was doubled from that of Experiment 1 in an effort to increase the power of our data set. However, this also resulted in more children failing to complete all trials because this task took longer than Experiment 1 (approximately 25–30 min). When the partial data from these children are included in analyses, the overall pattern of results holds.

Results

As predicted, children performed better on the approximate numerical discrimination task (Experiment 2) than on the exact numerical discrimination task (Experiment 1) (M_{E2} = 83.0% vs. M_{E1} = 72.6%), $t(188) = 5.2$, $p < .001$, Cohen's $d = 0.76$.

A mixed-measures ANOVA on the within-participants variables of ratio (2) and trial type (3) and the between-participants variable of age group (2) was conducted. As in Experiment 1, there was a main effect of age group, $F(1, 94) = 35.6$, $p < .001$, $\eta_p^2 = .275$, such that older children performed more accurately (M = 91.0%) than younger children (M = 75.7%). Again, however, even the youngest children performed well above chance (50%) [3- and 4-year-olds: $t(50) = 11.5$, $p < .001$, Cohen's $d = 3.30$; 5- and 6-year-olds: $t(44) = 37.5$, $p < .001$, Cohen's $d = 11.30$]. Possibly on account of the higher performance overall, there was no main effect of ratio in the current experiment, $F(1, 94) = 0.036$, $p > .80$, $\eta_p^2 < .001$, or any interactions ($ps > .10$).

Critically, there was again a significant main effect of trial type, $F(2, 188) = 28.2$, $p < .001$, $\eta_p^2 = .231$ (Fig. 4), such that children performed comparably on unimodal and bimodal trials [unimodal: M = 86.7% vs. bimodal: M = 86.1%, $t(94) = 0.432$, $p > .60$, Cohen's $d = 0.03$] but performed significantly worse on cross-modal trials [cross-modal: M = 77.2% vs. unimodal: $t(94) = 6.4$, $p < .001$, Cohen's $d = 0.55$; vs. bimodal: $t(94) = 5.8$, $p < .001$, Cohen's $d = 0.55$]. Again, children performed above chance on all trial types (all $ps < .001$ vs. chance), including the youngest age group (unimodal: M = 78.2%; bimodal: M = 79.2%; cross-modal: M = 68.1%; all $ps < .001$ vs. chance).

Discussion

Results from Experiment 2 extend findings from Experiment 1's numerical matching task to reveal that children can compare approximate representations of number across sensory modalities. As in Experiment 1, preschoolers were able to successfully compare arrays across all trial types. Moreover, confirming our hypothesis, analyses indicate that children found the numerical discrimination task of Experiment 2 to be less challenging than the numerical matching task of Experiment 1. Although not surprising, this finding is important in that it confirms that the specific demands of exact matching tasks may be more challenging than those of approximate discrimination tasks.

In addition to differences in overall performance between the first two experiments, the pattern of results obtained in Experiment 2 differed in important ways. In contrast to Experiment 1 (and Jordan & Baker, 2010), data from our numerical discrimination task in Experiment 2 revealed a cross-modal deficit (poorer performance on cross-modal trials vs. unimodal trials) but no support for a bimodal advantage across our sample (i.e., children performed comparably on unimodal and bimodal trials). These findings suggest that both phenomena (bimodal advantage and cross-modal deficit) may be context dependent. Under more difficult and exact conditions in Experiment 1, children demonstrated a clear bimodal advantage, particularly on the more difficult 2:3 ratio trials. In contrast, in Experiment 2's easier and approximate conditions, children performed comparably on unimodal and bimodal trials, instead exhibiting a disadvantage for cross-modal trials.

Although the approximate numerical discrimination task used in Experiment 2 provides a nice contrast to the match-to-sample task in Experiment 1, differences exist between this task and those used in previous studies. Specifically, Barth et al. (2005) and Jordan and Baker (2010) presented items within each array sequentially, whereas in Experiments 1 and 2, all visual sets were presented as simultaneous arrays. It is unclear whether an identical pattern may be found when visual stimuli are presented sequentially. Therefore, in Experiment 3, we presented children with a numerical discrimination task identical to that in Experiment 2 but with both visual and auditory sample stimuli presented sequentially rather than simultaneously, thereby also increasing the difficulty of the task itself.

Experiment 3

In Experiment 3, children performed a numerical discrimination task identical to that in Experiment 2 except that the sample array was presented in a sequential fashion.

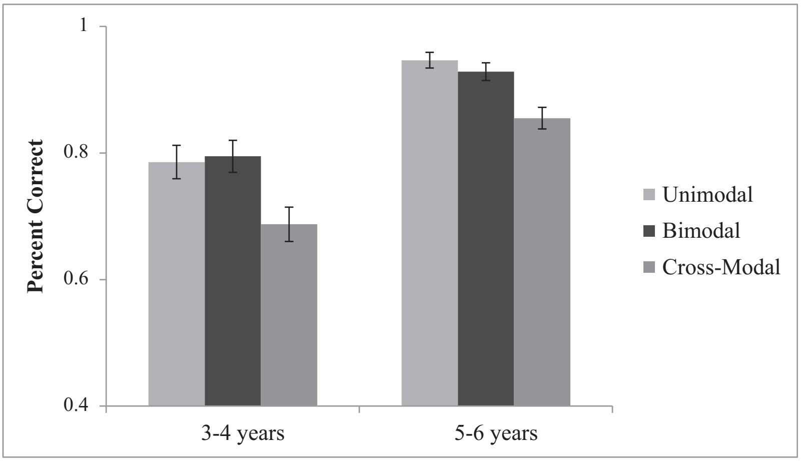

Fig. 4. Accuracy in Experiment 2 as a function of age and trial type. Error bars reflect standard error of the mean.

Method

Participants

A total of 94 different 3- to 6-year-old children participated in this experiment (M_{age} = 58.4 months, *SD* = 11.8; 51 girls). Children were again divided into younger (3- and 4-year-olds; *n* = 48, M_{age} = 49.4 - months, *SD* = 6.77; 32 girls) and older (5- and 6-year-olds; *n* = 46, M_{age} = 67.8 months, *SD* = 7.94; 19 girls) age groups for purposes of all analyses. As in Experiments 1 and 2, only children identified as proficient counters (CP-knowers per the Give-*N* task; Le Corre & Carey, 2007; Wynn 1990, 1992) participated in the experiment. An additional 29 children were excluded due to: computer error (*n* = 7), failure to complete all test trials (*n* = 16),[4] or failure to follow the rules of the game (*n* = 6; e.g., they randomly clicked buttons or told the experimenter they were purposely not following the instructions given to them). Children were again tested at one of two local children's museums or during a single visit to the laboratory.

Stimuli and procedure

The stimuli were identical to those used in Experiment 2 with the following differences. The elements in the comparison array were identical to those used in Experiment 2 except that the white box was centered on a red background.[5] Across trials, all visual items in the sample array (the first set presented) were presented sequentially (e.g., one dog, one dog, one dog) in the center of the screen. The timing of presentation of the sequential array was identical to the timing of auditory stimuli in Experiments 1 and 2, such that each item was presented for approximately 1 s with the same interstimulus interval (500 ms) as used previously. Again, the duration of presentation of the auditory arrays (cross-modal trials, sample array) was precisely matched to the presentation duration of visual items (unimodal trials, sample array). As in Experiment 2, the comparison array was always presented as a simultaneous visual array. See Fig. 1 (bottom panel) for an example of the stimuli used. The items in

[4] As in Experiment 2, the number of trials was doubled from that of Experiment 1, resulting in a greater number of children failing to finish the entire task. As in Experiment 2, the inclusion of these children (partial data) does not change the findings presented below.

[5] This was done to highlight the difference between the first and second sets because pilot testing indicated that children had trouble in distinguishing between the two sets of arrays when both contained a black background (i.e., children did not realize that the first sequence of items had ended and the second sequence of items had begun).

the distractor arrays were identical to those in Experiment 2. They differed from the number of items in the sample array by one of two numerical ratios (1:2 or 2:3). Each ratio was composed of three distinct numerical set sizes, with the number of items in each array varying from 2 to 12 presented four times each, for a total of 72 test trials. The entire experimental session lasted approximately 25 to 30 min.

Results

Initial analyses confirmed that performance on Experiment 3 was significantly lower than that on Experiment 2 (M_{Exp2} = 83.0% vs. M_{Exp3} = 74.3%), $F(1, 187) = 23.8$, $p < .001$, $n_p^2 = .113$. Unsurprisingly, this difference was driven by performance on the unimodal and bimodal trials [main effect trial type: $F(2, 374) = 14.0$, $p < .001$, $n_p^2 = .07$; Trial Type × Experiment: $F(2, 374) = 17.5$, $p < .001$, $n_p^2 = .086$; unimodal: M_{Exp2} = 86.3% vs. M_{Exp3} = 72.1%, $p < .001$; bimodal: M_{Exp2} = 85.8% vs. M_{Exp3} = 76.3%, $p < .001$], with performance on cross-modal trials across the two experiments being comparable (M_{Exp2} = 76.6% vs. M_{Exp3} = 74.6%, $p > .40$). No other significant main effects or interactions were found (*ps* > .05).

A mixed-measures ANOVA was run to determine the effects of the within-participants factors of ratio (2) and trial type (3) and the between-participants factor of age group (2) on accuracy on the discrimination task in Experiment 3. Analyses revealed a main effect of age group, indicating that older children were more accurate overall than the younger age group [3- and 4-year-olds: M = 64.4% vs. 5- and 6-year-olds: M = 84.1%, $F(1, 93) = 52.8$, $p < .001$, $n_p^2 = .362$]; however, again both age groups still performed above chance, $t(46) = 7.4$, $p < .001$, Cohen's $d = 2.20$, and $t(47) = 18.1$, $p < .001$, Cohen's $d = 5.30$.

As in Experiment 2, there was no main effect of ratio, $F(1, 93) = 0.01$, $p > .90$, $n_p^2 < .001$, or any interactions involving this variable (*ps* > .10). Critically, results did again reveal a main effect of trial type, $F(2, 186) = 4.3$, $p = .014$, $n_p^2 = .044$ (Fig. 5). Follow-up analyses revealed that children performed more accurately on bimodal trials than on unimodal trials [unimodal: M = 71.9% vs. bimodal: M = 76.2%, $t(94) = 2.6$, $p = .01$, Cohen's $d = 0.23$], with performance on cross-modal trials falling between the two [cross-modal: M = 74.5% vs. bimodal trials: $t(94) = 1.3$, $p = .191$, Cohen's $d = 0.09$; vs. unimodal trials, $t(94) = 1.7$, $p = .097$, Cohen's $d = .14$].

This main effect was qualified by a marginal Trial Type × Age Group interaction, $F(2, 186) = 2.9$, $p = .054$, $n_p^2 = .031$, such that a different pattern was observed across age groups. The youngest age group demonstrated a bimodal advantage (M = 67.4%) over both unimodal trials (M = 63.1%), $t(46) = 1.7$, $p = .101$, Cohen's $d = 0.27$ (trending), and cross-modal trials (M = 62.6%), $t(46) = 2.3$, $p = .025$, Cohen's $d = 0.29$, with no difference in performance between unimodal and cross-modal trials, $t(46)$

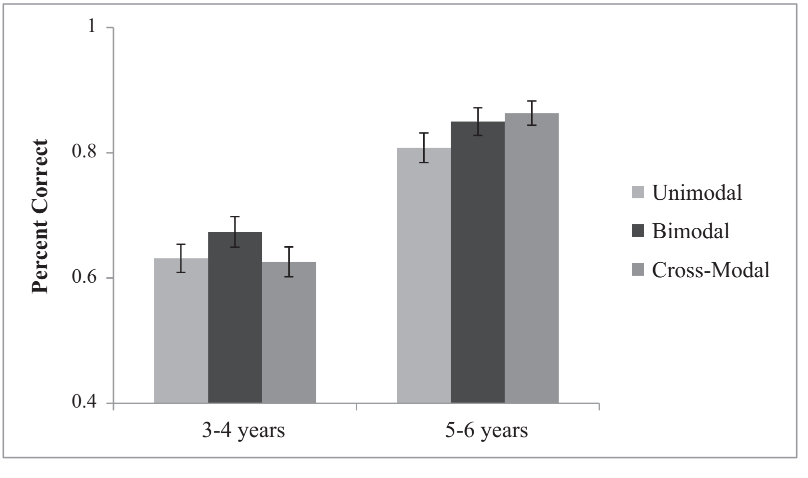

Fig. 5. Accuracy in Experiment 3 as a function of age group and trial type. Error bars reflect standard error of the mean.

= 0.237, $p > .80$, Cohen's $d = 0.03$. In contrast, older children performed comparably on bimodal and cross-modal trials [bimodal: $M = 85.1\%$ vs. cross-modal: $M = 86.4\%$, $t(47) = 0.901$, $p > .30$, Cohen's $d = 0.09$], with performance on both of these trial types significantly more accurate than that on unimodal trials [$M = 80.8\%$ vs. bimodal: $t(47) = 2.1$, $p = .042$, Cohen's $d = 0.27$; vs. cross-modal: $t(47) = 2.8$, $p = .007$, Cohen's $d = 0.37$].

Again, children in the youngest age range performed significantly above chance in all three trial types [3- and 4-year-olds: unimodal: $t(46) = 5.8$, $p < .001$, Cohen's $d = 1.72$; bimodal: $t(46) = 7.2$, $p < .001$, Cohen's $d = 2.12$; cross-modal: $t(46) = 5.3$, $p < .001$, Cohen's $d = 1.60$], in contrast to previous reports that children in this age range do not succeed at cross-modal numerical *matching* (Jordan & Baker, 2010; Mix, 2008a, 2008b). No other significant main effects or interactions were found ($ps > .30$).

Cross-experiment analysis

Cross-experiment analyses were conducted in order to evaluate the strength of our observed main findings (Table 2). To do this, we computed a magnitude score for our bimodal advantage (accuracy on bimodal trials − unimodal trials) and our cross-modal disadvantage (accuracy on unimodal trials − -cross-modal trials) and compared that with accuracy on unimodal trials alone. Using data across all three experiments, we found two significant trends. First, analyses indicate a significant negative correlation between the bimodal advantage and performance on the unimodal trials ($r = -.462$, $p < .001$) (Fig. 6). Given that performance on unimodal trials could be considered to be our purest indicator of difficulty of the numerical task (because these trials did not involve multimodal processing), this finding indicates that when the numerical task was hard (as assessed by performance on the unimodal trials), children benefited the most from bimodal presentation of stimuli. Importantly, when a partial correlation controlling for age (in months) was run comparing the bimodal advantage and performance on unimodal trials, this correlation was still significant ($r = -.503$, $p < .001$). That is, the relation between unimodal performance and the extent of the bimodal advantage held even when controlling for age.

Second, analyses revealed a significant positive correlation between the cross-modal disadvantage and performance on unimodal trials ($r = .491$, $p < .001$) (Fig. 6), indicating that when numerical tasks were easy (again, using unimodal performance as our best measure of the difficulty of the numerical task), the cross-modal disadvantage was stronger. Again, when controlling for age (in months), this correlation was still significant ($r = .604$, $p < .001$). In fact, these two findings held across each experiment (partial correlations controlling for age: Experiment 1: bimodal advantage, $r = -.569$, $p < .001$; cross-modal disadvantage, $r = .678$, $p < .001$; Experiment 2: bimodal advantage, $r = -.450$, $p < .001$; cross-modal disadvantage, $r = .446$, $p < .001$; Experiment 3: bimodal advantage, $r = -.560$, $p < .001$; cross-modal disadvantage, $r = .575$, $p = .001$).

Post hoc analyses excluding small set sizes

Post hoc analyses explored whether there were any differences in performance between small (sets < 4; e.g., 2 vs. 3) and large sets (sets > 3; e.g., 8 vs. 12) given that ample literature suggests clear differences in how we process small versus large sets (e.g., Ansari, Lyons, van Eimeren, & Xu, 2007; Buhusi & Cordes, 2011; Cordes & Brannon, 2009; Hyde & Spelke, 2009, 2011, 2012). Given that our study was not designed to intentionally explore small–large numerical differences, and thus the number of trials involving small sets was too low to allow for analyses of these trials, our analyses were restricted to exploring whether a similar pattern of results was found for large sets as was reported

Table 2
Accuracy (%) across trial types for each experiment (3–6 years).

Experiment	Unimodal	Bimodal	Cross-Modal
Experiment 1	70.6	78.3	68.8
Experiment 2	86.3	85.8	76.6
Experiment 3	72.1	76.3	74.6

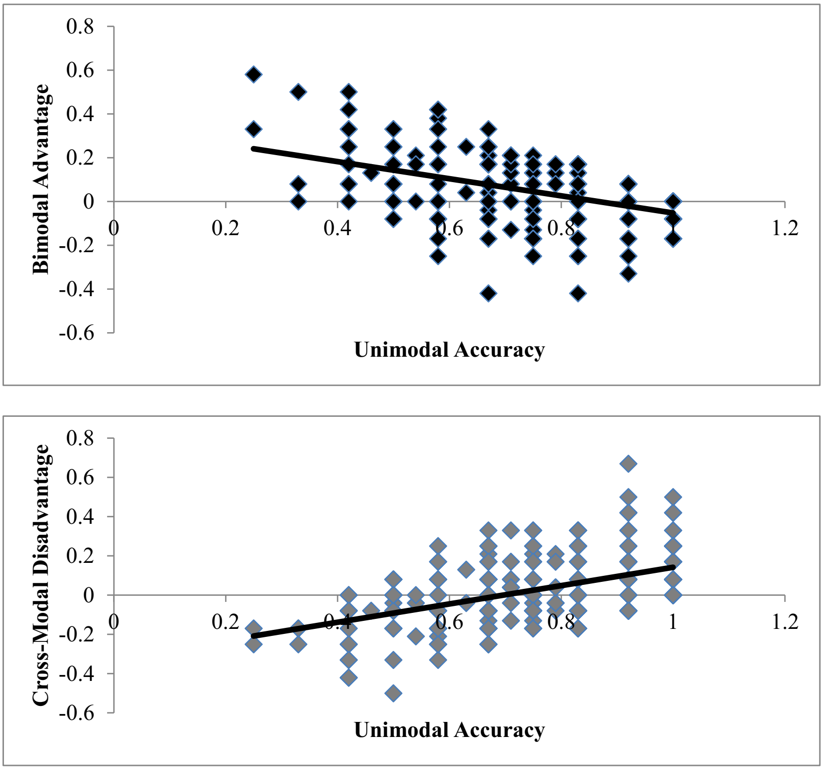

Fig. 6. Cross-experiment analysis: Aggregate data of the observed bimodal advantage (top panel) and cross-modal disadvantage (bottom panel) versus accuracy on unimodal trials. This trend holds across experiments and numerical set sizes.

in the main text of the article. One caveat to these post hoc analyses is that breaking down our data set into large number-only trials leads to the inclusion of only 2 experimental trials for each participant's data point, so conclusions should be interpreted with caution. Results of these analyses are reported in Table 3. As can be seen in this table, the pattern of results was identical across Experiments 1 and 2 for those analyses involving only large set size trials, suggesting that our results were not driven by small set trials. For Experiment 3, however, the main effect of trial type was no longer significant in our large set size analyses. Follow-up simple comparisons, however, revealed that even though the main effect was not significant, the same pattern of better performance on bimodal trials, compared with unimodal trials, held (M_{uni} = 72.7% vs. M_{bi} = 76.3%), $t(93) = 1.9$, $p = .061$, Cohen's $d = 0.18$ (marginal), again suggesting that our pattern of results was not exclusive to small set trials.

Discussion

Children in Experiment 3 performed less accurately overall in our numerical discrimination task when visual sets were presented sequentially (as compared with simultaneously in Experiment 2). Together, data from Experiment 3 extend findings from Experiments 1 and 2, indicating that children (a) can successfully process numerical information cross-modally, even as young as 3 and 4 years of age; (b) demonstrate a cross-modal disadvantage when numerical comparisons are easy (Experiment 2), but not under more difficult task demands (Experiments 1 and 3); and (c) benefit from the bimodal presentation of stimuli when presented with a challenging numerical task (in an exact matching task—Experiment 1) or when participants have working memory taxed via sequential presentations (in a numerical discrimination task—Experiment 3).

Table 3
Cross-experiment analyses of all trials (presented in this article) and the same analyses omitting small-number trials (i.e., large-number trials only).

Experiment	All trials		Large numbers only
Experiment 1	Age group	($p < .001$, $\eta_p^2 = .326$)	($p < .001$, $\eta_p^2 = .289$)
Ratio × Trial Type × Age	Ratio	($p < .001$, $\eta_p^2 = .428$)	($p < .001$, $\eta_p^2 = .517$)
	Ratio × Age	($p < .001$, $\eta_p^2 = .216$)	($p < .001$, $\eta_p^2 = .194$)
	Trial type	($p < .001$, $\eta_p^2 = .145$)	($p < .001$, $\eta_p^2 = .100$)
	Trial Type × Age	($p = .051$, $\eta_p^2 = .032$)	($p = .106$, $\eta_p^2 = .024$)
	Trial Type × Ratio	($p < .001$, $\eta_p^2 = .233$)	($p < .001$, $\eta_p^2 = .092$)
	Trial Type × Ratio × Age	($p = .023$, $\eta_p^2 = .040$)	($p = .016$, $\eta_p^2 = .044$)
Correlation analysis	Bimodal advantage	($r = -.445$, $p < .001$)	($r = -.345$, $p = .001$)
	Cross-modal disadvantage	($r = .602$, $p < .001$)	($r = .595$, $p < .001$)
Experiment 2	Age group	($p < .001$, $\eta_p^2 = .275$)	($p < .001$, $\eta_p^2 = .296$)
Ratio × Trial Type × Age	Trial type	($p < .001$, $\eta_p^2 = .231$)	($p < .001$, $\eta_p^2 = .165$)
	Trial Type × Age	($p = .051$, $\eta_p^2 = .032$)	($p = .07$, $\eta_p^2 = .028$)
Correlation analysis	Bimodal advantage	($r = -.408$, $p < .001$)	($r = -.393$, $p < .001$)
	Cross-modal disadvantage	($r = .376$, $p < .001$)	($r = .352$, $p < .001$)
Experiment 3	Age group	($p < .001$, $\eta_p^2 = .362$)	($p < .001$, $\eta_p^2 = .367$)
Ratio × Trial Type × Age	Trial type	($p = .014$, $\eta_p^2 = .044$)	($p = .146$, $\eta_p^2 = .021$)
	Trial Type × Age	($p = .054$, $\eta_p^2 = .031$)	($p = .169$, $\eta_p^2 = .019$)
Correlation analysis	Bimodal advantage	($r = -.430$, $p < .001$)	($r = -.471$, $p < .001$)
	Cross-modal disadvantage	($r = .347$, $p = .001$)	($r = .363$, $p < .001$)
Cross-Experiment			
Correlation analysis	Bimodal advantage	($r = -.462$, $p < .001$)	($r = -.430$, $p < .001$)
Linear regression	Model	($R^2 = .293$, $p < .001$)	($R^2 = .255$, $p < .001$)
	Age	($\beta = .314$, $p < .001$)	($\beta = .564$, $p < .001$)
	Unimodal accuracy	($\beta = .610$, $p < .001$)	($\beta = .297$, $p < .001$)
Correlation analysis	Cross-modal disadvantage	($r = .491$, $p < .001$)	($r = .455$, $p < .001$)
Linear regression	Model	($R^2 = .353$, $p < .001$)	($R^2 = .306$, $p < .001$)
	Age	($\beta = .365$, $p < .001$)	($\beta = .614$, $p < .001$)
	Unimodal accuracy	($\beta = .662$, $p < .001$)	($\beta = .353$, $p < .001$)

General discussion

Although research to date suggests that nonhuman animals, human infants, and human adults can represent number cross-modally, very little work has explored this ability in children. Across three experiments, this study addressed two critical research questions. First, are young children's cross-modal numerical abilities compromised relative to those within a single modality? If so, what contexts give rise to cross-modal impairments? Second, does the observed bimodal advantage emerge across contexts, or is this advantage task dependent? We find a cross-modal disadvantage when numerical comparisons are easy (Experiment 2) and a bimodal advantage when numerical comparisons are difficult (Experiments 1 and 3). These findings are discussed in more detail below but are the first to present a coherent and systematic exploration of children's multimodal numerical processing across task demands and difficulty levels.

Most research to date on cross-modal numerical processing has come from infants, adults, and nonhuman primates (Feron et al., 2006; Gallace et al., 2007; Jordan & Brannon, 2006; Jordan et al., 2010; Jordan, Maclean, et al., 2008; Kobayashi et al., 2005; Mix et al., 1996; Starkey et al., 1983, 1990). This work demonstrates that young infants can track small sets cross-modally, whereas adults can make numerical judgments abstractly and independent of modality. However, developmental studies focusing on cross-modal numerical abilities during childhood have produced mixed results (Badets & Pesenti, 2010; Barth et al., 2005, 2007; Cote, 2015; Jordan & Baker, 2010; Mix et al., 1996). These studies have used critically different paradigms, resulting in noninterpretable findings leaving it unclear whether children's numerical abilities are actually compromised in the context of cross-modal numerical stimuli or whether these performance costs are task specific. In the current study, results indicate that a cross-modal disadvantage does emerge, but only when numerical comparisons are relatively easy. Specifically, a cross-modal disadvantage was observed only in Experiment 2's easier and approximate numerical discrimination task, but not in Experiment 1 or 3, where task demands were more difficult (Experiment 1: exact match to sample; Experiment 3: sequential numerical discrimination).

Broadly, results from the current study suggest that children may be slowly developing strategies for making unimodal comparisons (e.g., through the use of perceptual cues; Jordan & Baker, 2010). These visual (unimodal) strategies are presumably practiced in everyday life—with even young infants able to make visual numerical discriminations at these ratios (e.g., see Cordes & Brannon, 2008, for a review)—leading to improved performance on our unimodal trials as compared with cross-modal trials, which are presumably less practiced by children of this developmental age range. Support for this comes from the fact that we see that these practiced unimodal numerical tracking strategies do not transfer to cross-modal trials, such that children occasionally perform worse on cross-modal trials compared with unimodal trials—or demonstrate a cross-modal disadvantage. Thus, our findings suggest that cross-modal and unimodal numerical abilities might not develop in parallel. Instead, this pattern of findings suggests that unimodal comparison abilities develop first (and/or faster) and cross-modal numerical tracking may fall behind at this stage of development. This is likely due to children having more experience (i.e., practice) in comparing number within the same modality (often visual) and having less experience in tracking number cross-modally. Thus, when children are challenged, both unimodal and cross-modal abilities are low because of the increase in difficulty (i.e., unimodal performance drops). However, when numerical tracking is relatively easier (i.e., less difficult), children use their unimodal numerical tracking skills in light of a less developed ability to track cross-modally, a skill that they need to continue to practice and develop.

On this note, it is perhaps surprising that even the youngest age group in this study performed above chance across modalities and experiments despite previous reports of chance-level cross-modal numerical performance in children of this age (e.g., Jordan & Baker, 2010; Mix et al., 1996). Importantly, although we tested an age range similar to that tested in other studies (3- to 6-year-olds), we ensured that all participants were proficient counters (i.e., CP-knowers). Although we do not think it is likely that children in our study explicitly counted the items, it is likely that they were more able to follow instructions, were more able to understand the numeric language used (e.g., "same number"), and were overall better able to discriminate number with increasing precision (e.g., Shusterman, Slusser, Halberda, & Odic, 2016). A non-mutually exclusive second possibility is that the ratios included in the current study were easier (1:2 and 2:3, shown to be easily discriminable by young infants; see Cordes & Brannon, 2008, for a review) compared with numerical ratios tested in previous studies (e.g., 8:9; Jordan & Baker, 2010), thereby leading to higher overall accuracy in our task. Thus, the numerical comparisons we tested were easier, and our preschool sample was likely more numerically proficient, than those of previous studies. For both of these reasons, it is not surprising that we found our participants to succeed on our cross-modal numerical trials.

The current study critically reveals a second important finding—a bimodal advantage for trials involving difficult numerical comparisons. These findings align with predictions of the intersensory redundancy hypothesis set forth by Bahrick, Lickliter, and colleagues (Bahrick & Lickliter, 2000, 2002; Bahrick et al., 2004), suggesting that redundant stimuli (e.g. visual + auditory) promote learning. In line with previous findings (Jordan & Baker, 2010), our results reveal that children's numerical processing may benefit from the bimodal presentation of numerical stimuli. Moreover, our findings extend previous work by revealing that a bimodal advantage is found for both synchronous sequential presentation (i.e., presenting auditory stimuli synchronous with sequential visual stimuli—Experiment 3) *and* synchronous simultaneous visual stimuli (i.e., presenting sequential auditory stimuli while presenting a simultaneous visual array).

Despite ample evidence that learning is heightened when participants are presented with redundant information across modalities rather than a single sensory modality (Laurienti et al., 2003, 2006), much less work has been conducted on this phenomenon in the context of numerical tasks and has truly done so only very early in development (infancy and preschool age; see Jordan & Baker, 2010; Jordan, Suanda, et al., 2008). Thus, the current study clarified how children's numerical abilities are affected by the presentation of bimodal stimuli across distinct contexts and difficulty levels. Extending work from early in development and from non-numerical domains, data from the current study reveal the existence of a bimodal advantage, specifically when numerical comparisons are most difficult (Experiments 1 and 3). These results suggest that children may benefit from the additional help when attending to difficult or novel numerical information. However, when numerical judgments (or comparisons) were easy, this information was not necessary, as observed in the equal performance across unimodal and bimodal trial types in Experiment 2.

These findings implicate selective attention as a possible mechanism supporting children's ability to make multimodal numerical judgments. It is well known that children and adults allocate attention differently, such that the flexible and abstract ability to selectively attend—as seen during adulthood—develops with age (Best, Yim, & Sloutsky, 2013; Plebanek & Sloutsky, 2017; Plude, Enns, & Brodeur, 1994; Rivera & Sloutsky, 2015; Robinson, Best, & Sloutsky, 2011). That is, immaturities in top-down attentional control during infancy (e.g., Best et al., 2013; Plude et al., 1994) develop during early childhood, resulting in increased selectivity with age (see also Rueda, Posner, & Rothbart, 2005). Selective attention undergoes substantial development during the preschool years (Hanania & Smith, 2010; Plebanek & Sloutsky, 2017; Plude et al., 1994), increasing substantially between 4 and 7 years of age (Deng & Sloutsky, 2016; Plebanek & Sloutsky, 2017; Rueda et al., 2005). Thus, early in development, children tend to distribute attention across multiple dimensions unless a single dimension captures attention automatically, leading to unsurprisingly higher performance in unimodal numerical comparisons where children are more easily able to extract the relevant numerical properties to be judged. However, we suggest that the use of bimodal information *boosts* children's numerical performance in difficult tasks by amplifying their attention to the relevant numerical properties of the set rather than to the less relevant perceptual features.

What do our findings tell us about children's numerical representations? We believe that there are two main points to be learned from our findings. First, given that children across all three experiments performed above chance in their ability to match and discriminate number across modalities, this finding supports claims that children represent number in an abstract fashion, independent of the modality in which it was presented, as adults do. That is, children were able to track the number of auditory stimuli heard and compare it with the number of visual stimuli presented, suggesting that they were able to encode number via a single common currency regardless of the modality in which it was encoded. However, children's performance on cross-modal trials was not always as strong as their performance on unimodal trials, suggesting that the modality in which number is encoded does bias their ability to track number. This finding strongly suggests that children's numerical tracking may be biased by the perceptual features of the stimulus, including modality. Thus, whereas their numerical representations may be abstract, their numerical tracking—that is, their ability to perceive number in the real world—is inherently linked to perceptual qualities of the stimulus, much like how the color, shape, and/or size of objects may bias children's ability to track number (e.g., Chan & Mazzocco, 2017; Mix, 1999; Posid & Cordes, 2014).

It should be noted that all experiments in our study required children to match a sample stimulus to two visual choice stimuli. Our reason for doing so was for simplicity; it would substantially lengthen the experiment and make the task more taxing for young children if we occasionally presented two auditory sequences as our choice stimuli. However, it is not clear whether performance patterns would differ if children were given the opportunity to match numerical representations formed in a visual modality to auditory stimuli. Although we think it is unlikely that this order effect would have a substantial impact on the pattern of results, future work may explore whether the order of the stimulus presentation affects the presentation of either a cross-modal disadvantage or a bimodal advantage.

In addition, in the creation of our visual stimuli, we controlled for cumulative area across primary and secondary arrays across all three experiments. For example, 10 items in the first image contained the same total cumulative area as the corresponding array containing 5 items in the second image. Although we were careful to control for cumulative area, it is true that difference in perimeter, density, and convex hull may have been correlated with number. However, these cues were confounded across all trial types. Thus, even if children chose to use these cues, it is unclear how these cues may have contributed to our distinct pattern of results across trial types, specifically because we observed a bimodal advantage over unimodal accuracy in Experiment 1. If these visual cues provided additional confounding information that benefited children's performance, we might expect to see either a unimodal advantage (over bimodal accuracy) or statistically similar accuracy across unimodal and bimodal trials, which we did not.

Results from the current study have potential implications for curriculum design, instructional techniques, and teacher training. For example, it may be helpful for educational platforms and environments—particularly given the fact that early mathematical concepts continue to build on themselves well into middle school and high school—to present multimodal numerical tasks bimodally, particularly if the content is novel and/or difficult. This falls in line with research from Mayer and Moreno (2003), whose work suggests that children are actively required to integrate multiple types of information, which may lead to information overload or "cognitive overload." In an effort to reduce this cognitive load, the use of bimodal input may be helpful. For example, when children interact with educational materials, the components are often vibrant and perceptually rich visual displays that use real-world contextualized examples (e.g., Van de Walle, 2007), presumably because these high-contrast items and displays are attention-grabbing, motivating, and often found in children's natural environment (National Center for Education Statistics, 2010; National Council of Teachers of Mathematics, 2000; National Mathematics Advisory Panel, 2008). Our findings suggest that bimodal presentation of multimodal numerical concepts and judgments could help children to selectively attend to the relevant number concepts amid varying perceptual attributes readily available in their learning environment.

In conclusion, the current study systematically examined children's multimodal numerical judgments across ratio, set size, modality, and developmental age range. The study contributes two novel findings to the limited multimodal research conducted with preschool-age children. First, children exhibit a cross-modal disadvantage when numerical comparisons are easy. Second, accuracy on bimodal trial types leads to even more accurate numerical judgments, particularly when task demands are most difficult. Importantly, findings from this study extend the literature on children's numerical cross-modal abilities to reveal that children, like their adult counterparts, readily track and compare visual and auditory numerical information, although their abilities to do so are not perfect and are affected by task demands and task difficulty.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jecp.2019.01.003.

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