**When the word "more" doesn't matter:
Measuring toddlers non-symbolic number processing using a novel task**

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Abstract

Much research has investigated children's non-symbolic number processing and its relation to mathematical ability. However, surprisingly few studies have investigated performance in 18-36 month-olds, where symbolic number concepts begin to emerge, and the extent results indicate poor performance. We tested 74 2 - 3.5 year-olds recruited from two sites (Ulster and Uppsala). They completed a novel dot-comparison task where children were shown, but not verbally instructed, how pushing a more numerous array resulted in reward and a Give-N task. Overall, participants performed above chance on the dot comparison task, indicating that non-symbolic number processing skills can be measured in toddlers without verbal instructions. We found no relation between performance on the non-symbolic number processing task and knower-level. Our results warrant two conclusions. First, verbal instructions involving the concept of *more* are not necessary to measure non-symbolic number processing skills in young children. Second, the development of a symbolic number concept seems independent of the development of non-symbolic comparison skills but may become artificially related when researchers use quantifiers such as "more" to measure the former.

Children exhibit numerical abilities from an early age. Even at a few hours after birth, infants respond to the cardinality of sets (Izard et al., 2009). The ability to extract the cardinality of a set continues to develop through infancy and early childhood. At six months-of-age, infants can discriminate between two sets when the ratio of their numerosity is 1:2 (Xu, 2003; Xu & Spelke, 2000), while 9-month-olds can discriminate a 2:3 ratio (Libertus & Brannon, 2010; Lipton & Spelke, 2003). Already during infancy, individual differences emerge in the ability to process non-symbolic numerosity (Libertus & Brannon, 2010), which remain into adulthood (Halberda et al., 2012; Pica et al., 2004). Several studies, including recent meta-analyses, have shown that such individual differences are associated with mathematics ability in both adults (Chen & Li, 2014; Halberda et al., 2012) and children (Halberda & Feigenson, 2008; Schneider et al., 2017). Studies have even indicated that mathematical ability at three years of age can be predicted from individual differences in non-symbolic number processing at 10-months (Starr et al., 2013). Furthermore, it has been proposed that mathematical abilities in general (Gilmore et al., 2007), and in particular children's knowledge about natural numbers (Gallistel & Gelman, 1992; Leslie et al., 2008), have their foundation in these primitive abilities.

A systematic review by Schneider et al. (2017) identified 45 studies investigating the relationship between performance on non-symbolic number processing tasks and broader mathematical processing skills. Surprisingly few of these studies investigated non-symbolic number processing skills during the period in toddlerhood where children start to form on the earliest mathematical concepts, i.e. natural numbers, with only 3 of the included studies investigating these skills in children under the age of 4 years-old. Thus, an important piece of knowledge about the development of non-symbolic number processing skills and its possible influence on the development of mathematical abilities is missing.

Natural number concept

Around the age of 2, children begin to learn the natural numbers by first learning to memorize the number words “one” to “nine” (Carey, 2009; Gallistel & Gelman, 1992). At this point, the number words have no cardinal meaning to the child. Rather, they are arbitrary labels similar to other counting rhymes the child learns to memorize (e.g., eeny, meeny, miny, moe; or the Alphabet). Next, the child begins to attach cardinal meaning to the number words by first realizing that the word *one* refers to a set containing precisely one object. A child's *knower level* is often evaluated using the “Give-N” task introduced by Wynn (1990, 1992). According to the logic of this task, the child knows the cardinality of *1* if it can give the correct number of objects when asked for one object, but not when asked for, for example, two or three objects. A child who knows the cardinality of one is called a *one-knower*. Over a period of several months, children go from being one-knowers to becoming two-knowers, three-knowers, four-knowers, and, eventually, cardinal principal knowers (CP-knowers). The transition from being a four-knower to being a CP-knower is marked by an important conceptual change (Carey, 2009). When a child is a four-knower, they know the cardinal meaning of the number words “one” to “four”, even though their count list (i.e., the sequence of numbers they are able to correctly recite) might be larger. In contrast, when the child becomes a CP-knower, the knowledge of cardinal meaning is extended to all the numbers in the child’s count list.

Measuring non-symbolic number skills in toddlers

One reason for the surprisingly low number of studies investigating non-symbolic number processing skills in toddlers is due to the lack of developmentally appropriate tasks. With infants, researchers have predominantly used looking time paradigms, either habituation

paradigms (Xu, 2003; Xu & Spelke, 2000) or change detection paradigms (Libertus & Brannon, 2010; Schröder et al., 2019). Looking time paradigms use attention to features in the environment to infer knowledge or understanding and are well suited for infant subjects, since they cannot easily give verbal or manual responses. However, they have limitations. For example, is difficult to collect multiple responses for varying difficulty levels of a task (Libertus & Brannon, 2010; Schröder et al., 2019). When studying older children and adults, researchers most often use a two-alternative forced-choice (2AFC) paradigm (Chen & Li, 2014; Schneider et al., 2017). In such a paradigm, participants are shown two arrays of objects, and are asked to determine which array is more (or less) numerous. This method makes it possible to test participants' ability to discriminate between two arrays over many difficulty levels and using many trials, which allows for more reliable and fine grained estimates of the capacity to compare non-symbolic number than does looking-time paradigms. However, although looking-time- and 2AFC-paradigms are well suited for the populations they were developed, neither of them are satisfactory during a couple of years of toddlerhood. Looking time paradigms are generally ill-suited for this age group, since toddlers are mobile and lack the needed attention span. Furthermore, 2AFC paradigms are difficult since they require children to understand verbal instruction in general and more specifically verbal quantifiers (e.g., "most"). Previous research has indicated that children do not come to understand verbal quantifiers until about the age of 3.5 (Halberda et al., 2008). Thus, low performance on a 2AFC task for a child under the age of 3.5 is likely due to not understanding instructions rather than poor non-symbolic number comparison skills per se.

Studies that have attempted to use non-symbolic number comparison tasks in 3-4 year-olds have relied on the typical approach used with older children and adults. Using 2AFC tasks,

participants are asked to identify between two sets “what box has more bubbles?” (Bonny & Lourenco, 2013) “who has more?” (Starr et al., 2013; Wagner & Johnson, 2011) or “who has more bars?” (Rousselle & Noël, 2008). Overall, these studies often report a large proportion of children performing at or below chance, especially in more difficult ratio conditions (e.g., with 3 year-olds: Bonny & Lourenco, 2013; Starr et al., 2013; Wagner & Johnson, 2011). In a multi-experiment paper, Rousselle and Noel (2008) reported that the youngest children (Experiment 2: 4 years-old; Experiment 3: 3 years 7 months old) in two out of three of their experiments had low accuracy rates (Experiment 2: 55.5%) or performed at chance (Experiment 3). In addition, a significant minority of children have been commonly excluded from analyses due to their inability to complete the non-symbolic comparison task (11%: Starr et al., 2013; 33%: Wagner & Johnson, 2011) or because Weber fractions cannot be calculated using individuals data (17%: Starr et al., 2013).

The current study

In the current study, we developed a novel approach for measuring non-symbolic number comparison skills in toddlers. Previous research has indicated that children can learn associations between events in the environment from a young age (Richardson & Kirkham, 2004). Furthermore, they can categorize stimuli on a number of perceptual features (Mareschal & Quinn, 2001). With this in mind, we developed a paradigm where toddlers were taught through a demonstration that pressing the more numerous of two arrays of objects results in a reward. Importantly, the demonstration contained no reference to verbal quantifiers such as “more” or “less” or reference to the number of the arrays. We evaluated our measure by investigating if children could learn the demonstrated contingency and if their pattern of responses when the

reward was removed showed the signature ratio effect of non-symbolic number comparison tasks (Feigenson et al., 2004). Furthermore, in an effort to further evaluate the hypothesis that non-symbolic number comparison is foundational to the development of a concept of natural numbers we measured participants' knower levels.

Methods

Participants

Participants were 74 2-3.5 year-olds ($M = 32$ months, $SD = 3.6$ months; Range = [26, 40]; 49 % girls) recruited at two sites: Uppsala, Sweden ($N = 40$) and Ulster, Northern Ireland ($N = 34$). The study protocol was approved by the local ethics committees at the respective sites (Uppsala: Regional Etikprövningsnämnden, Ulster: Ulster University Research Ethics Committee) in line with the 1964 Declaration of Helsinki. All methods were performed in accordance with relevant ethical guidelines and regulations. Written informed consent was obtained from the caregivers of all participants.

Materials and Procedure

Toddlers were tested in a single, 30 min session, either in the lab or in a quiet room at their preschool, during which they carried out a non-symbolic comparison task and a Give-N task (e.g., Wynn, 1990; 1992).

Non-symbolic dot-comparison task. The dot-comparison task was carried out on an iPad (9.7-inch screen) and consisted of three phases; a demonstration phase, a contingency learning phase, and a test phase. On every trial, regardless of phase, participants were presented with two arrays of black circular discs on a white background presented on the left and right side of the screen, respectively. The two arrays were spatially separated by a thick black line. On each of the six (6) trials of the *demonstration* phase, children were demonstrated by an experimenter

how pushing the more numerous array resulted in a fun movie clip with an animated animal and an interesting sound being played. Importantly, the experimenter did not mention any numerical aspect of the arrays when demonstrating how to activate the reward to the child, but said: “Look, if I push here the animal will appear!”. Half of the trials had the more numerous array on the right and half had it on the left. Furthermore, half of the trials had a 1:4 ratio between the number of discs in the arrays, while the other half had a 1:2 ratio. In the *contingency learning* phase, participants completed eight (8) trials. On each trial, the experimenter encouraged the child to find the fun animals by pushing one of the two arrays by saying: “Can you find the fun animal?” or “Can you make the fun animal appear?”. During this phase, the child was rewarded on all trials by the fun movie being played if they pushed the side with the more numerous array. As in the demonstration phase, the side with the more numerous array was counterbalanced over trials, and the ratios 1:4 and 1:2 were used. Finally, the *test* phase consisted of 18 trials. As in the previous phase, participants were on each trial encouraged to find the fun animal by pressing one of the two arrays. However, no feedback was given, except on three randomly chosen catch trials, following a correct answer. The introduction of three catch trials was motivated by an attempt to keep children’s interest in the task throughout the entire test phase. As in the other two phases, the side with the more numerous array was counterbalanced over trials, but the ratios 1:4, 1:2, and 2:3 were used. The number of dots in each array varied between 6 and 24. Following Halberda et al. (2008), we controlled the two arrays for cumulative area on half of the trials and average area on the other half.

Give-N. In the Give-N task, participants were first introduced to a toy animal and a set of 15 small objects. The child was told that the toy animal liked the small objects and was asked to help the experimenter give the animal a specific number of objects by taking them out of their

container, placing them on a small platter, and sliding the platter to the animal. The experimenter demonstrated this procedure to the child prior to the first trial. During each trial, the child was first asked to give the animal a specific number of objects: “Can you give the animal N objects?”. Once the child had slid the platter over to the animal, the experimenter asked “Is that N objects?”. In contrast to previous studies using the Give-N task (e.g., Wynn, 1990; 1992) we did not use a titration procedure to determine the child’s knower level. Instead, a fixed set of 13 items were administered to all participants in the same order.

Results

Knower levels

A child’s knower level was determined using the method described by Lee and Sarnecka (2011, Negen et al., 2012). This method determines the knower level by estimating the posterior probability of a child belonging to each of the six knower levels (pre-knower, one-knower, two-knower, three-knower, four-knower, CP-knower) given their responses. We used the knower level with the highest posterior probability as our dependent measure. Table 1 summarizes the distribution of knower levels in our sample. There was no difference between the distribution of knower levels at the two sites, $\chi^2(4) = 6.49, p < .17$.

Table 1. *Distribution of knower levels.*

Site	Knower level					
	Pre	One	Two	Three	Four	CP
Uppsala	14	16	2	3	0	2

Ulster	9	16	6	0	0	1
Total	22	32	8	3	0	3

Non-symbolic dot-comparison task

We analyzed the contingency learning and test phase of the non-symbolic number processing task separately. For the contingency learning phase, we wanted to ascertain if the participants had learned the task and could correctly identify the array that produced the reward (i.e., the more numerous array). To this end, we collapsed over the two ratios (1:4 and 1:2) and evaluated the proportion of correct answers using a single sample t-test. For the test phase we were interested both in the overall performance of participants and if their responses exhibited a ratio effect (i.e., that performance decreases with more difficult ratios $1:4 > 1:2 > 2:3$).

Furthermore, we were also interested in controlling for the age of participants and the site at which data was collected. To these ends, we analyzed the data using within-subjects ANOVAs.

Contingency learning phase. In the contingency learning phase, participants completed eight trials with a 1:4 (four trials) or a 1:2 (four trials) ratio. Feedback was given on every trial. The mean proportion of correct trials was .55 ($SD = .14$), which was significantly higher than what could be expected from random responding, single sample t-test with $H_0 = .5$, $t(65) = 2.92$, $p = .005$, $d = .36$. There was no difference in performance between the two sites ($t(64) = 1.2$, $p = .23$, $d = .30$; Ulster: $M = .58$, $SD = .17$ vs. Uppsala: $M = .53$, $SD = .12$). Thus, in the demonstration phase, participants learned that pressing the more numerous array would result in a reward and they could consistently find the more numerous array when feedback was provided.

Table 2. *The proportion of correct responses (SD) in the test phase for each of the three ratios together with test statistics for a single sample t-tests with $H_0 = 0.5$ for the entire sample.*

	Ratio			
	1:4	1:2	2:3	All
Uppsala	.55 (.20)	.52 (.18)	.59 (.21)	.55 (.11)
Ulster	.68 (.21)	.60 (.20)	.58 (.21)	.62 (.13)
Entire sample	.61 (.21)	.55 (.19)	.59 (.21)	.59 (.12)
(df) t-value	(64) 3.99	(64) 2.18	(64) 3.30	(64) 5.61
p-value	< .001	.003	.002	< .001
d	.50	.27	.41	.70

Test phase. In the test phase, participants completed 18 trials with a 1:4 (six trials), a 1:2 (six trials), or a 2:3 (six trials) ratio. Participants' performance in the test phase is summarized in Table 2. As is evident from the table, participants performed above chance on all three ratios as well as on a measure of overall performance. We investigated the possibility of a ratio effect by running a one-way within-subjects ANOVA with proportion correct responses as the dependent variable and ratio as the independent variable. This analysis indicated no effect of ratio, $F(2, 126) = 1.29$, $p = .28$, $\eta_p^2 = .02$. Thus, in contrast to what is often documented in older children and adults, we found no effect of ratio on performance.

To further explore this finding we ran a second analysis including site and age as dependent variables. This analysis revealed no significant main effects or interactions (all F s < 1.1). Thus, the lack of ratio effect was evident at both sites and over the entire sample in terms of age.

Non-symbolic dot-comparison task and Knower level

Finally, we investigated if there was any relation between participants' performance on the non-symbolic comparison task and their knower level. To do this, we created an aggregate score for the non-symbolic comparison task as the overall (learning and test phase) mean proportion of correct trials. We treated children's knower level as an ordinal variable with six steps [0 - pre knower, ..., 5 - CP knower] and tested the relation by means of a Spearman rank-order correlation. The results, $r_s(61) = .22, p = .078$, indicated a positive relation that did not reach statistical significance.

Discussion

The last decade has seen a surge of research into children's non-symbolic number processing and its relation to mathematics. Although researchers have studied the development of such abilities from infancy (Izard et al., 2009) and have suggested that non-symbolic number processing is foundational for learning mathematics (Gilmore et al., 2007), very few studies have investigated these abilities during the time period in childhood where the earliest mathematical concepts emerge.

In the current study, we aimed to develop a novel test that could be used to measure non-symbolic number processing in toddlers. More specifically, we developed a test that, in contrast to previous attempts (e.g., Bonny & Lourenco, 2013; Starr et al., 2013; Wagner & Johnson,

2011), did not require children to understand the concept of “more”. Indeed, it is possible that using verbal instructions asking the child to find the “more” numerous array is one reason that children have exhibited low performance in previous studies. Importantly, in an effort to evaluate the test in different contexts we recruited participants from two different countries, Sweden and Northern Ireland.

In our task, we demonstrated to the children that pressing the one of two arrays that was more numerous resulted in a reward. Our results indicated that children could learn this contingency and that they continued to identify the more numerous array above chance levels on their own when they were given feedback. In a test phase, when feedback was withheld, participants continued to perform above chance level on all three levels of difficulties (ratios of 1:4, 1:2, and 2:3).

Even though the children performed above chance levels on all three ratios, we did not establish a ratio effect. That is, children’s level of performance did not change as a function of ratio. This finding is somewhat surprising since the ratio effect has been described as a distinguishing signature of non-symbolic number processing (e.g., Halberda et al., 2008). One possible explanation for the lack of a ratio effect is that our task does not capture non-symbolic number processing. According to this account, the children in our study must be engaged in some other type of process when solving the task, though what this may be per se is beyond the scope of this study. Another possibility is that a ratio signature is not yet present in the non-symbolic number processing of 2 - 3.5 year olds, but rather emerge later in toddlerhood. Even though previous research has indicated that non-symbolic number processing abilities improve during early development no study has, to our knowledge, investigated the presence of a within-subjects ratio effect before the age of three (but see, Bonny & Lourenco, 2013). Thus, it is

unclear if the group level differences found in very young children reflect a true ratio effect.

Bonny and Lourenco (2013) demonstrated a ratio effect when pooling the data from 3, 4, and 5 year olds. However, it is clear from the visualization of their data that the effect is driven by the older children (see Bonny & Lourenco, 2013 Figure 2). Taken together, these findings seem to indicate that even though non-symbolic number processing can be captured using 2AFC-tasks from the age of 2, we should not expect to see the ratio effect found with older children.

In addition to evaluating our novel test of non-symbolic number processing, we also wanted to investigate the possibility that such abilities are related to early children's number-knowledge. We found a weak, non-significant relationship between performance on our task and performance on the Give-N-task. In contrast to some theoretical accounts (Gelman & Gallistel, 2004; Leslie et al., 2008), but in line with recent empirical findings (Schröder, Gredebäck, Forssman, & Lindskog, 2021), this would suggest these two abilities are not linked in toddlerhood, but instead become related later on in development. It is of course possible that the underlying relation between these two constructs is small and that a larger sample size is needed to detect it. It is also possible that our slightly skewed distribution with relatively few four- and CP-knowers did not allow us to fully evaluate this relation. It will be an important task for future studies to further investigate these possibilities.

To summarize, here we show that young children's non-symbolic number processing can be measured without verbal instructions involving the concept of more. With this measure, we also show that for toddlers non-symbolic number processing and number-knowledge is weakly related, at best. Our findings pave the way for a deepened understanding of how symbolic and non-symbolic number skills may co-develop during toddlerhood.

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