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Title: The Sense of Small Number Discrimination: The Predictive Value in Infancy and Toddlerhood for Numerical Competencies in Kindergarten

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Abstract: Extending previous research on the predictive value of large number discrimination, this study explored the role of infants' and toddlers' small number discrimination for numerical competencies in kindergarten (NCK). Although no significant relationship could be found between number discrimination in infancy (8 months, T1) and NCK (48 months, T3), the predictive value of toddlers' number discrimination (24 months, T2) for NCK could be demonstrated at least for some NCK. The finding that only toddlers' small number discrimination related to NCK raised thoughts about the task, age, set size, stability and development of number discrimination or other influencing factors. Future research should study all small set sizes (not only 1vs3) and a broader range of NCK in a larger sample. Nevertheless, whereas infants' small number discrimination might be too early to predict NCK, performance in toddlerhood might be addressed in the future to establish a measure to detect at-risk mathematical development.

Cover Letter (confirming paper not published elsewhere)

FACULTY OF PSYCHOLOGY AND EDUCATIONAL SCIENCES

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Department of Experimental Clinical and Health Psychology

February 19, 2015

E.L. Grigorenko
Editor, *Learning and Individual Differences*
Yale University,
New Haven,
CT, USA

Dear,

I am enclosing a (2nd) revised submission to the journal *Learning and Individual Differences* entitled, "The sense of small number discrimination: The predictive value in infancy and toddlerhood for numerical competencies in kindergarten." The manuscript is 22 pages long (word count: 4,989), figures and tables are embedded and the reference pages are excluded from this word count.
We thank the reviewers for their constructive comments and think this has lead to an improved paper. My coauthors and I do not have any interests that might be interpreted as influencing the research, and APA ethical standards were followed in the conduct of the study. The work described has not been published previously and is not under consideration for publication elsewhere. I will be serving as the corresponding author for this manuscript. All of the authors listed in the byline have agreed to the byline order and to submission of the manuscript in this form. I have assumed responsibility for keeping my coauthors informed of our progress through the editorial review process, the content of the reviews and any revisions made. I understand that, if accepted for publication, a certification of authorship form will be required that all authors will sign.

Yours sincerely,

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Detailed response to reviewers' comments & suggestions (2nd round)

Ms. Ref. No.: LEAIND-D-14-00126R2

Title: The Sense of Number Sense: The Predictive Value of Number Discrimination in Infancy and Toddlerhood for Numerical Competencies in Kindergarten

First of all, we would like to thank the editor and reviewers for their constructive feedback on the revision of the manuscript. We are grateful for the opportunity to once again revise the manuscript based on these reviews. In the following letter the authors outlined each change made (point by point) as raised in the reviewer comments. When a specific comment was not addressed (or changed as suggested) we aimed to provide a suitable rebuttal. We truly hope that the made revisions in the manuscript are sufficient. Please take into account that all changes were made within the maximum word count of 5,000 words for the manuscript to be published as a brief report.

NEW ISSUES

1. Some points that need attention in the **introduction-section**:

Reviewer #2: *I am wondering why the authors want to take the concept Number Sense into their study. Number sense as a concept is defined and conceptualized in so many ways, that no one knows anymore what it really means. The authors seem to be mixed up with the definitions as well. I would suggest the authors to take the term number sense out of their introduction (at least not to give it so much space and role). I suggest the authors to concentrate on defining the Number Discrimination skill/ability. This will save some room for more relevant issues. It would be good idea to take the number sense out of the title as well, as it is not needed there.*

In the previous version of the manuscript we used number sense as a conceptual framework for studying number discrimination as an innate form of number sense which in its turn has frequently been studied as a predictor for later mathematical achievement, mostly in older children than toddlers or infants (e.g., DiPema, Lei, & Reid, 2007; Dowker, 2008; Mazocco & Thompson, 2005; Jordan, Kaplan, Locuniak, & Ramineni, 2007; Stock, Desoete, & Roeyers, 2009).
However, we understand the concern of reviewer #2 and acknowledge that a review of the literature indeed learns that the concept of 'number sense' is defined and conceptualized in many different ways. In order to meet the suggestion of this reviewer we aimed at building the 'Introduction-section' upon a framework starting from (large) 'number discrimination' as a predictor to later mathematical achievement as recently studied by Starr, Libertus, and Brannon (2013b). Changes in the 'Introduction-section' are shown in the 'track-changes-version' of the manuscript which is attached to this response to the reviewers.

In line with the revisions made within this new framework to build up the introduction, the manuscript title was accordingly changed to meet the core of the content to "The sense of small number discrimination: the predictive value in infancy and toddlerhood for numerical competencies in kindergarten". The concept of 'Number sense' is taken out the title, as suggested by reviewer #2, since it is no longer necessary to refer to the papers' content.

Reviewer #2: *Authors also need to define better the* *<u>numerical competencies</u>* *they study (counting, arithmetic operations and cardinality) and how these have been found to relate with number discrimination skills. Authors need to explain why these were selected from all mathematical skills that the children in kindergarten know. In current version these are missing.*

The named numerical competencies were first of all selected because previous research on mathematics has supported the value of these specific aspects for later mathematical achievement (Geary, Hamson, & Hoard, 2000; Powell and Fuchs, 2012).
Whereas procedural counting knowledge is predictive for numerical facility, conceptual counting knowledge predicts untimed mathematical achievement (Desoete, Stock, Schepens, Baeyens, & Roeyers, 2009). Counting as a whole, in its turn, influences the development of adequate mathematical abilities and early mathematical strategies (Aunola, Leskinen, Lerkkanen, & Nurmi, 2004; Fuson, 1988; Le Corre, Van de Walle, Brannon, & Carey, 2006; Wynn, 1990). Third, several studies demonstrated a relationship between arithmetic operations and math achievement (N.C. Jordan, Kaplan, Ramineni, & Locuniak, 2009; Jordan, Glutting, & Ramineni, 2010). Furthermore, arithmetic operations, as part of a larger early numerical competencies battery, have been proven predictive for later mathematical abilities (e.g., applied problem solving; Jordan et al., 2010). Following Powell and Fuchs (2012), we used the term numerical competencies in kindergarten (NCK) to delineate the counting and arithmetic operations abilities. Second, these aspects were selected in line with Starr et al. (2013b) - being as far as known the pioneering study in linking infant's individual differences in (large) number discrimination with later numerical abilities or competencies at kindergarten age - To be more specific, a similar Dutch mathematical test battery as the one used by Starr et al. (2013b) was chosen highlighting counting abilities with special attention to both procedural and conceptual counting knowledge as well as knowledge on arithmetic operations. Additionally, cardinality (as a more specific aspect of counting) was also assessed with a (variant of the; Sarnecka & Carey, 2008) Give-a-Number task (Wynn, 1992).

In the 'Limitation-section' (page 20) a brief motivation of why some tasks [as opposed to the study of Starr et al. (2013b)] were not incorporated in the current test protocol. On the same page also a (more) multicomponential approach is suggested for future research:

"Taking into account the fact that the current study was part of a broader large-scale project together with the short attention span of young children, (non)symbolic number comparison tasks were for example not part of the current test protocol due to (practical) time constraints." … "Nonetheless, the broader the range of mathematical abilities, the more insight would be obtained in how predictors relate to different aspects of mathematics later on. As such, it would be worthwhile and recommended to adhere to a mutlicomponential approach."

In the outline of the current study a brief description of the studied numerical competencies was added (on page 6) along with a short motivation of why the competencies were chosen:

"Furthermore, in line with Starr et al. (2013b), the following numerical competencies in kindergarten (NCK) were tested with a standardized test battery in these children at the age of 48 months (kindergarteners, T3): (procedural and conceptual) counting, with a more-in-depth test on cardinality, and arithmetic operations. In addition, general intelligence was tested. Items on procedural counting concerned children's ability to perform a mathematical task (LeFevre et al., 2006), whereas items on conceptual counting constituted the understanding of why a procedure works or is legitimate (Bisanz & LeFevre, 1992; Hierbert & LeFevre, 1986; LeFevre et al., 2006) referring to underlying principles of counting (Gelman & Gallistel, 1978). Knowing the meaning of a numeral (cardinality) as one of those principles was highlighted more in particular administering a widely used test on cardinality knowledge.

Arithmetic operation exercises prompted the understanding of composition and decomposition of groups by differentiating sets and subsets (i.e., addition and subtraction; Purpura & Lonigan, 2013). As such, all administered items within the scope of the current study resembled the respective abilities of counting, numeral literacy, and basic calculation assessed by Starr et al. (2013). For all these numerical competencies the value as a predictor for later mathematics has been supported (Geary, Hamson, & Hoard, 2000; Powell & Fuchs, 2012).”

Describing the pioneering study of Starr et al. (2013b) linking infants' large number discrimination with later numerical abilities, the relationship between the studied numerical competencies and number discrimination was addressed on page 3:

“Only recently, these individual differences were studied (Libertus & Brannon, 2010) and furthermore related for the first time to later numerical competencies (Starr, Libertus & Brannon, 2013b). One of the main findings of this latter study was that the performance on a number discrimination task administered in infancy (i.e., 6 months of age) significantly predicted later math scores in kindergarten (i.e., 3.5 years). Administered items covered counting and numeral literacy, number-comparison facility and basic calculation (Starr et al., 2013b). Furthermore, number discrimination performance also predicted children's mastery of cardinality in particular as children who understood the exact meaning of the number words ‘one’ to ‘six’ in kindergarten performed significantly higher on number discrimination in infancy than children who only understood a subset of those number words (Starr et al., 2013b). As such data of this pioneering study pointed toward a developmentally primary role of the preverbal to discriminate numerosities already from infancy on.”

Reviewer #2: *I also find it a bit strange that the authors introduce three <u>paradigms</u> to explain the skill of small number discrimination skill, and they will only use two of them in their own study. I think the authors should make a statement why they selected two out of three.*

Three paradigms are found in small number discrimination literature, but only the habituation and manual search task are frequently used as opposed to the numerical change paradigm only used in studies of Libertus and Brannon (2010) and Starr, Libertus, and Brannon (2013a, 2013b). Therefore, the first two paradigms were chosen taking into account children's age. The paradigm choice is more highlighted on page 7:

“In previous studies small set sizes were mainly investigated with either a habituation or a manual search task (e.g., Cordes & Brannon, 2009b; Feigenson & Carey, 2003, 2005; Xu, 2003). Since the numerical change task has only recently been used in the study of Starr et al. (2013b) to investigate small number discrimination, tasks according to the other two mentioned paradigms took precedence in the current study.”

Some thoughts were added on page 21 about the choice for (only) one paradigm to measure number discrimination at T1 and T2 along with the suggestion of a a multimethod approach:

“Again, due to the short attention span of in particular the children at T1 and the broader research protocol of the large-scale study of which this study was a small part, only one paradigm was chosen to measure number discrimination at each specific time point. Obviously, in a more ideal design multiple paradigms could have been used to assess small number discrimination in the same children at both T1 and T2. Moreover, especially because of questions (concerning reliability or task demands as referred to earlier) raised on the used paradigms, such a multimethod approach could reveal valuable information. Other findings could indeed have resulted from using other tasks to measure small number discrimination, since differences might be caused by the varying number processing system elicited by each task (Feigenson & Carey, 2003).”

2. Some points that need attention in the **results-section**:

Reviewer #3: *The hypotheses do not say anything about the expectations regarding lenient versus restrictive (reliability) scoring, nor do they mention cardinality vs subset knowers or hypotheses about that. Especially in a brief report, it is important to streamline, and so these parts of the report may not be necessary.*

In line with the suggestion of reviewer #3 and in order to achieve a more streamlined 'Discussion-section' with a clear 'take home message' (see also "3. Some points that need attention in the discussion-section"), we decided to streamline this brief report and to expunge the restrictive scoring, but hold on to the dichotomous cardinality measure as an outcome of numerical competencies in kindergarten in this study. We briefly motivate this choice below.

- *For restrictive scoring, has this type of method (reliable change) been used before (on infant data as a means of expressing reliability)? It seems an unusual application of RCI, which is typically used to assess change in clinical outcomes at a much more global level. It seems unusual to include both the lenient and strict measures in the same analyses, rather than in separate analyses (even though the two are virtually uncorrelated).*

  The restrictive scoring was retrieved from the study field on pain research through inter-disciplinary supervision within the own research group. This type of method has therefore, indeed, as noticed by reviewer #3, never been used before on infant data as a means of expressing reliability. Consequently, the application of RCI in number discrimination studies is indeed unusual, though a very interesting approach which we approved worthwhile to take into consideration. However, since inclusion of both the lenient and strict measure and the confound with a clear 'take home message' in this brief report we full agree with reviewer #3 that the content of the manuscript might be restricted within the scope of a brief report to the usual approach (i.e., the so-called 'lenient' approach in the previous version of the paper).

- *It appears though that the authors may include cardinality as another outcome (a measure of NCK); if so, why dichotomize this variable as opposed to treating it continuously?*

  Cardinality as measured with the Give-a-Number task (Sarnecka & Carey, 2008) is mostly assessed using a dichotomous variable in studies using this paradigm. In line with these studies, as well as with the recent study of Starr et al. (2013b) being the pioneer in studying (large) number discrimination as a predictor of later mathematical aspects, we would like to stick with this dichotomous approach of cardinality (if possible).

Reviewer #3: *There are no expectations presented about differential prediction among the three NCK tasks, and so perhaps they could be combined? Particularly in such a small sample, and the fact that the tasks correlated fairly well (including the GNT with the other NCK measures), this might be possible, and would reduce the number of analyses on the small sample.*

We fully agree with reviewer #3 that using a composite score for the three NCK-tasks would simplify analysis and would possibly reveal other (perhaps more significant) results. However, the standardized test battery on mathematical competencies that was used (TEDI-MATH; Grégoire, Noël, & Van Nieuwenhoven, 2004) covers different subcomponents of mathematics. Recent studies in the field of mathematics emphasize the importance of incorporating a multicomponential approach instead of applying only one math composite score or examining only one subcomponent of mathematics (J. A. Jordan, Mulhern, & Wylie, 2009; Mazzocco, 2009; Simms, Cragg, Gilmore, Marlow, & Johnson, 2013). This suggestion fits with the statement of Dowker (2005) that there is no unitary mathematical construct. Research taking into account a multicomponential approach could shed light onto specific profiles of mathematical functioning in a much more finegrained way (J.A. Jordan et al.,2009).

Reviewer #3: *The text of the Results does not appear to match Table 5 very well (which shows that none of the small number discrimination predictors are significant for any of the outcomes, with the exception of MSLSS for CC).*

Table 5 shows indeed that MSLSS (i.e., MSSS in the current version of the manuscript) is significant related to CC, but also marginally significant to AO. Because of the small sample of the current study both significant as well marginally significant results were reported since small samples may lead to the false conclusion that there are no significant results, even though, in reality there are (risk of type 2-mistakes; Field, 2009; pp. 55-56). As we wrote down these results in the body (on page 15-17) of the manuscript we addressed the statistical information as given in Table 5 along with some additional information on the IQ-measure.

3. Some points that need attention in the **discussion-section**:

Reviewer #2: *I have read the discussion-section several times and still I do not find the focus. It might be good idea that authors will think once more: What is the most important result, and what is the second important? And how they relate to existing literature. For instance, now it seems to me that, the discussion why the effects of number discrimination shows in arithmetical operations and counting skills, but not in cardinality, is missing. I think that is worthwhile considering.*

The 'Discussion-section' was adjusted to changes made within the removal of the 'restricted' number discrimination approach and the main findings were more clearly stated on page 17:

"Although no significant relationship could be found between number discrimination in infancy (8 months, T1) and NCK (48 months, T3), the predictive value of toddlers' number discrimination (24 months, T2) for NCK could be demonstrated at least for some NCK: for Arithmetic Operations (AO) and even on top of IQ for Conceptual Counting (CC). Furthermore, number discrimination in infancy (T1) and toddlerhood (T2) did not significantly relate mutually."

Because we thought the covering finding of number discrimination relating to NCK across time was the most important finding of this study (compared to previous studies), this finding was elaborated more on in the 'Discussion-section' (page 18), but hardly any changes were made. However, lessened attention was given to the other findings by reducing/removing the theory behind the explanations given for the inconclusive result of the first finding on page 17:

"The absence of a significant relationship between infants' number discrimination and later numerical competencies in kindergarten was in contrast with number discrimination at 6 months as a predictor of later mathematical abilities in a previous study (Starr et al., 2013b). Starr et al. (2013b), however, not only tested a younger cohort, but also used another number discrimination paradigm, probing moreover large instead of small number discrimination. These three differences in study design could all be responsible for this inconclusive result."

The following theoretical background of the offered explanations for this one specific result, was deleted in the revised version of the paper in order to obtain a more streamlined section (and is offered in the section below in this response on your comments for your interest only):

Starr et al. (2013b) stated that at 6 months of age the relationship between numerical representation using analogue magnitudes (triggering large number discrimination) and burgeoning math may be at its strongest. Because such a strong relationship at 6 months of age might also hold for small number discrimination, it is possible that a relationship between number discrimination and burgeoning math could not be replicated in older 8-month-olds in the current study. In this respect, the question evidently arises on which underlying system the ability of small number discrimination operates when measured by a habituation task.

However, no conclusive answer could be given, based on the results retrieved from this study, since not all small set sizes were investigated simultaneously in the same infants using habituation. Moreover, divergent findings exist on small number discrimination measured by this paradigm in other studies (Ceulemans et al., 2012; Cordes & Brannon, 2009b; Xu, Spelke & Goddard, 2005). Apart from which numerical representation system is triggered by the habituation paradigm, number discrimination driven by either analogue magnitudes or object-files might simply relate in a different way to later NCK. Considering the suggestion that the numerical change detection paradigm would be more likely to invoke analogue magnitudes than the habituation paradigm (Starr et al., 2013a) task-dependency of the recruited system might explain the different outcome of the current study and the one by Starr et al. (2013b). Though, even regardless of any underlying system, small (i.e., 1vs3; current study) and large number discrimination (i.e., 6vs24, 5vs15, 6vs18, 8vs16 or 10vs20; Starr et al., 2013b), considered as two abilities on different number ranges in se, may just contribute differently to later NCK.

To continue and to meet the suggestion of reviewer #2, however, the paragraph on the second finding was enlarged by adding some thoughts on why number discrimination related with some NCK, but not with others, on page 17-18. Though, we tried to be rather concise.

"Irrespective of the studied age, the predictive value of number discrimination at T2 (toddler age) for NCK (T3) is in line with the study of Starr et al. (2013b). Not for all investigated NCK the relationship with number discrimination could be confirmed however. An explanation regarding CC might be found in the higher amount of items on this subtest (compared to the other NCK-subtests). This larger number of items might have resulted in more variability in the score on CC which could have facilitated the detection of a (significant) relationship with toddlers' number discrimination performance. With respect to AO, a possible explanation for its relation to number discrimination, might be found in the items' complexity (in line with Purpura & Lonigan, 2013) being more difficult than the other NCK-items since counting and cardinality are often involved in carrying out these operations (Powell & Fuchs, 2012). A clear theoretical underpinning to explain the results, however, is difficult to achieve. More in-depth research on why specific NCK would relate to number discrimination (and others not) is warranted. Furthermore, also the formats of number discrimination (small vs large) should additionally be compared within this scope."

A shortened version of the following theoretical background of the offered explanations for the results on NCK, was given in the revised version of the paper in order to obtain a more streamlined section. A more extended background is offered below for your interest only:

[Elaborating on the fact of AO-items being more difficult than items on PC or cardinality] …

This is not surprising because conducting arithmetic operations find themselves on the border between early numerical skills and more advanced math knowledge acquired through formal teaching (Purpura & Lonigan, 2013), whereas counting and cardinality are often used in or involved in carrying out these operations (Powell & Fuchs, 2012). According to some literature (Briars & Siegler, 1984; Frye, Braisby, Lowe, Maroudas, & Nicholls, 1989) also CC might be more complex than PC. With moreover cardinality as one aspect of CC and sometimes even referred to as PC (Aunio & Niemivierta, 2010; Kroesbergen, van Luit, Van Lieshout, Van Loosbroek, & Van de Rijt, 2009), this suggestive train of thought might support the idea of AO and CC being more complex than the other NCK-measures. This difference in complexity level might serve as a possible explanation for the different relationships with number discrimination in the current study.

[Elaborating on the fact that achieving a clear theoretical underpinning is difficult] …

For example, the development of CC and PC may more likely result from an iterative processes, in which both aspects build upon each other (RittleJohnson & Siegler, 1998; Rittle-Johnson, Siegler, & Alibali, 2001). Because the current findings did not fully align with those of the pioneering study by Starr et al. (2013b), more in-depth research on why specific NCK-measures are related to number discrimination (and others may not) is warranted.

Reviewer #3: *It is somewhat unclear what the "take home" message from this work should be, especially given that T1 and T2 and the two methods of scoring each were all virtually unrelated. An extreme would be that neither paradigm is very useful (the habituation paradigm because of its low reliability, the manual search because of its extraneous demands). For example, do the authors think that the habituation paradigm is useful or not? Do they think that the typically used "lenient" scoring methods should be abandoned? Admittedly, these are difficult questions for a single study to answer definitively, but some clearer conceptual direction for further research (beyond methodological improvements) might help improve impact.*

We understand and agree with the comment of reviewer #3 on the above mentioned issues. Since this study is one of the scarce studies using two different paradigms on number discrimination in one study as well as two analysis approaches and moreover only includes a small sample of children, it is difficult to utter thoughts on the abandonment of the typically used scoring or the usefulness of the habituation paradigm. Based on these limitations we preferred not to explicitly take a position on this matter before the conduction of more in-depth research in the future. Though, we tried to more accentuate (and refer to) the mentioned thoughts on the low reliability and specific task demands (we agree on) in the 'Discussion' (and more specifically the 'Limitation')-section on page 21 of the revised version of the paper:

"Again, due to the short attention span of in particular the children at T1 and the broader research protocol of the large-scale study of which this study was a small part, only one paradigm was chosen to measure number discrimination at each specific time point. Obviously, in a more ideal design multiple paradigms could have been used to assess small number discrimination in the same children at both T1 and T2. Moreover, especially because of questions (concerning reliability or task demands as referred to earlier) raised on the used paradigms, such a multimethod approach could reveal valuable information.Other findings could indeed have resulted from using other tasks to measure small number discrimination, since differences might be caused by the varying number processing system elicited by each task (Feigenson & Carey, 2003)."

Reviewer #3: *The first two objectives were that small number discrimination assessed at 8 mo (via habituation) and 24 mo (via manual search) would be predictive of K skills. The third was whether small number discrimination at the two early ages were related. A central issue is that time and task are confounded; if the early tasks are not related (as was the case), it is unclear if this is due to instability in the construct of small number discrimination, or due to measurement error (since habituation and manual search have rather different physical demands). There should be some discussion of this issue in text.*

We understand and agree with the comment of reviewer #3 on the above mentioned issues. Both the instability-issue (page 19 – in combination with the 2nd paragraph on page 18 - which has not changed compared to the previous version of the manuscript) as well as the issue on measurement error (page 19) are more prominently addressed now in the 'Discussion'-section as both issues are implicitly linked to each other (first sentence of paragraph below) to enhance the flow between the different related sections on pages 18 and 19 respectively:

“Besides the possibility of number discrimination being an instable measure (as outlined in the previous section), no significant (mutual) relationship between infants’ (T1) and toddlers’ (T2) small number discrimination could also be suggestive for the presumption that the number discrimination tasks used at the different time points trigger a different underlying numerical representation system or simply appeal to different abilities. Assuming that habituation triggers object-files in small number discrimination (although not exclusively or conclusively) and the informed knowledge (Feigenson & Carey, 2003, 2005) that the manual search paradigm does this for sure the first presumption seems less likely. It can alternatively be stated that both tasks appeal to different abilities (and likewise measure different concepts).”

Reviewer #3: *It would be good to see the author's comment regarding what appears to be a sample that is of relatively high socioeconomic standing. This is relevant given studies that note a strong relation between number sense and SES.*

In order to meet the suggestion of reviewer #3 about the comment on the relatively high SES of the current sample, the following was added to the ‘Discussion’-section (page 19-20):

“Partly due to this small sample, but especially due to the majority of middle- and high-income-families (see Table 1), the impact of socio-economic status (SES) was not further explored. Based on literature on mathematical abilities with an additional focus on SES, no differences are expected between these subcategories of families, but rather between these two subgroups on the one hand and low-income families on the other hand (e.g., Jordan, Kaplan, Locuniak, & Ramineni, 2007; Jordan, Kaplan, Olah, & Locuniak, 2006). It would therefore be meaningful to include more families with a low SES who - based on income – only constituted a minority of the current sample (see Table 1). This is not surprising as individuals with a higher SES are more likely to participate in scientific research (Burg, Allred, & Sapp, 1997; Galea & Tracy, 2007; Hille et al., 2005) probably because of a greater trust in science and a higher degree of volunteerism(Bak, 2001; Putnam, 1995).”

MINOR ISSUES

Reviewer #2:

- *Keywords: APA advices to follow alphabetic order)*

Keywords were alphabetically ordered according to APA as suggested by reviewer #2.

- *Mathematical related terms, mostly without definition: I think they should be checked, defined and extra words deleted (e.g., p.2 early numerical competencies, p. 3 mathematical knowledge, later mathematical achievement, later mathematical outcome, p12 numerical competencies)*

As already outlined on page 2 of this response to your comments, we preferred to use the term ‘numerical competencies (in kindergarten)’ to delineate the different aspects on counting and arithmetic operations in the current study. Throughout the manuscript we tried to stick as much as possible to this specific term whenever it suited the right context (i.e., all measures on counting knowledge – procedural, conceptual, and cardinality - and arithmetic operations). Within the more general context of specific literature on (predictors) of later mathematics, the terms mathematical ‘achievement’ and ‘outcome’ were simply replaced by “mathematics”. Using the same terms to write about either the specific aspects studied in the current study (numerical competencies) or the general umbrella of mathematics (mathematics) we hope to clarify the confusion of the use of different mathematical related terms in the previous version of the manuscript. The changes were made throughout the manuscript (see track changes).

- *Clarify the sentence: p.3 " As yet, studies on number discrimination were mainly restricted on concurrent group results (e.g., Xu, Spelke & Goddard 2005)".*

  A clarification was added to the sentence on page 3 of the revised version of the manuscript.

  "This means that attention was mainly given to the group performances on different number discrimination tasks of children overall without mapping any individual differences in the specific ability to discriminate numerosities between children in a studied sample."

- *Abbreviations;*

  - *It would help the reader if authors will insert the abbreviation of the measurement when they first time mention them (p. 12 procedural counting knowledge, conceptual counting knowledge, arithmetic operations, cardinality)*

    Abbreviations of measurements (as they were for now only presented in the Tables) were inserted in text the first time they are mentioned in the manuscript in support of the reading process throughout the manuscript as suggested by reviewer #2.

  - *What does CCS means in p 19?*

    We would like to thank reviewer #2 to notice the mistake in the abbreviation "CCS". The abbreviation 'CCS' is correctly adjusted to 'CC' conform with its full meaning, namely 'Conceptual Counting' in accordance with the other abbreviations (AO/PC). On the same page the (wrong) abbreviation 'AOS' was adjusted likewise to 'AO'.

Reviewer #3:

- *Awkward phrasing (p.3)*

  - *"…some glosses could be raised"*

    In the revised version of the manuscript, the whole sentence was deleted.

  - *"Overall, small number…": Do the authors mean that object files are associated with small number discrimination and analogue magnitudes are associated with large number discrimination? Perhaps, but then later (p5) analogue magnitudes are associated with small number discrimination.*

    Given that infants have access to both systems (i.e., the object-file system and the analog magnitude system) and since it might depend on the kind of task which system is triggered (Feigenson & Carey, 2003), the choice of paradigm might be of crucial importance.

    Logically, studies about number discrimination initially connected small number discrimination with object-files and large number discrimination with analog magnitudes (see Cantrell & Smith, 2013 for a review), regardless of the task used. However, the claim that small numbers are only processed by object-files is currently tentative because both the successful discrimination of small from large numerosities in infants (Cordes & Brannon, 2009a) as well as the finding that infants show ratio-dependent discrimination regardless of set size also with small numerosities (Starr et al., 2013a) are incompatible with this (straightforward) two-system account.

Combining findings from different number discrimination studies or results on various number sets discloses features in paradigms which might be characteristic for the underlying systems (e.g., Cordes & Brannon, 2009a, 2009b; Feigenson & Carey, 2003, 2005; Libertus & Brannon, 2010; Starr et al., 2013a; Xu, 2003; Xu et al., 2005). These characteristics might give some notion of which system is probably used to discriminate numerosities using a particular task. Ratio-dependency, for example, as the key characteristic of number discrimination by means of the analog magnitude system, is mainly used to decide whether a task induces this specific kind of system (see Cantrell & Smith, 2013 for a review).

Since ratio-dependency does not affect small number discrimination measured with the manual search task, it is likely that this paradigm prompts the object-file system (e.g., Feigenson & Carey, 2003, 2005). This means that the connection between small number discrimination and the object-file system thus applies for this paradigm. To our knowledge, large number discrimination has not been investigated yet with the manual search task, so no conclusions can be drawn on this format of number discrimination with this paradigm. Whereas it is rather clear that the manual search task triggers the object-file system, it is also indisputable that the numerical change paradigm activates the analog magnitude system. This numerical change paradigm is rather new in its kind (Libertus & Brannon, 2010) and it is shown that number discrimination is ratio-dependent regardless of set size using this paradigm. For both formats of number discrimination (i.e., small and large), children are assumed to rely on analog magnitudes when performing numerical change tasks. Regarding habituation tasks, however, the story about the underlying system is more complicated. Initially, it was stated that tasks following this paradigm would (only) activate the analog magnitude system. Indeed, no success could be found for sets with small numerosities having the same ratio as sets with larger numerosities. An example is the failure of the discrimination between 1 vs 2 (small numerosities; Xu et al., 2005) compared to the success of 4 vs. 8 (large numerosities; Xu, 2003) in 6-month-old infants. These kinds of findings have led researchers to find support in a two-system account (e.g., Feigenson, Dehaene, & Spelke, 2004; Xu 2003): Because small numerosities could not be discriminated using habituation, they must have been processed differently by another system than the large ones (e.g., Xu et al., 2005). This system (i.e., the object-file system) was not thought to be triggered by these habituation tasks. Recently, however, habituation studies also indicated successful small number discrimination (e.g., Cordes & Brannon, 2009b) besides the abundance of positive findings regarding large number discrimination using these kinds of tasks (e.g., Cordes & Brannon, 2008; Xu, 2003; Xu et al., 2005; Xu & Spelke, 2000). As such, these divergent findings on small number discrimination using habituation, with failure for set 1 vs 2 (Xu et al., 2005) and success for the sets 2 vs 3 (Cordes & Brannon, 2009b) and 1 vs 3 (Ceulemans et al., 2012), still raise questions on the triggered system.

To elucidate this, however, falls beyond the scope of this manuscript. Though, it illustrates the impact of using different paradigms to measure a concept. Until all questions on the “paradigm-system” issue are answered one should bear this in mind.

Because this theoretical background could complicate the flow of the ‘Introduction’-section of the manuscript, the abovementioned section was not added in the body, but presented in this response to your comments, for your interest only.

- *Statistical values:*

    - *There aren't really any effect sizes presented. Betas are presented, which appear large, but perhaps an eta- or partial-eta based effect size for the unique contribution of particular variables might be helpful.*

    In the manuscript r-values are reported as a measure for effect size (in line with for example Field, 2009, p. 57) which is made clearer by adding 'effect size' each time a r-value is reported as an effect size in the 'Results'-section of the revised manuscript. An additional overview is given below for each of the (marginally) significant results.

Linear regression		*p*	Effect size	Interpretation
Lenient manual search success	Conceptual counting	.033	$r = 0.38$	medium
	On top of IQ	.009	$\beta = 0.30$	medium
Lenient manual search success	Arithmetic operations	.094	$r = 0.31$	medium
	[On top of IQ]	[.107]	[$\beta = 0.29$]	[small]

    - *p > .05 should just be referred to as not significant, particularly in the absence of effect size indicators.*

    In order to reply on this specific comment, we would like to refer to an earlier rebuttal (see page 5 of this letter) in which we motivate reporting both significant as well as marginally significant results: Because of the small sample of the current study both significant as well marginally significant results were reported since small samples may lead to the false conclusion that there are no significant results, even though, in reality there are (risk of type 2-mistakes; Field, 2009; pp. 55-56). In addition we would like to refer to the above mentioned reply on the question to report effect size values.

    - *The R2 for the full models should be presented as well.*

    The value for R^2 of the full (linear regression) model with MSSS as a marginally significant predictor of CC on top of IQ is $R^2 = .375$ [with $R^2_{adjusted} = .328$; r = .612]. The R^2 value was added on page 16 of the revised version of the manuscript.

- *Varia.*

    - *Is 48 mo typical for kindergarten in Belgium? In US 5 years is more typical*

    In the Flemish part of Belgium, children typically attend preschool (usually referred to as 'kindergarten'), when they are 2.5 years old, and enter elementary school (i.e., first grade) at 6 years of age.

    Although preschool education is not compulsory, the vast majority of children do attend school usually for three years. Compulsory education, according to a defined curriculum, starts in first grade. At T2, all children had received one year of preschool education and were assumed to have received similar preschool experiences concerning preparatory math.

- *The formula for the RCI should be presented (e.g., in an appendix or note) since there are many versions of RCI, mainly differing in their standard error term.*

  The formula of the RCI was retrieved from the manual written by Morley (2013). Because this manual is freely available online and it would take a lot of space (especially for a brief report) to fully describe the formula of the RCI-calculation we made the decision not to include this information in the body of the (previous version of the) manuscript. The reference list gave the necessary information to track the RCI-formula. However, taking into account the adjustments on rather skipping the RCI-approach based on the current review as suggested by reviewer #3, no pivotal role was given anymore to this approach of analyzing the number discrimination data in the revised version of the manuscript as it will now be submitted. Therefore, the need to include the RCI-formula might probably no longer remain.

- *In general, the amount of italics does not seem necessary.*

  The amount of italics was reduced to a necessary minimum throughout the paper.

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The Sense of Small Number DiscriminationNumber Sense: The Predictive Value of Number Discrimination in Infancy and Toddlerhood for Numerical Competencies in Kindergarten

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Abstract

~~*Number sense* as a predictor to later math outcome is mostly studied in kindergarteners, but is already known in infancy as *number discrimination*.~~ Extending previous research on the predictive value of large *number discrimination*, this study explored the role of infants' and toddlers' small number discrimination for numerical competencies in kindergarten (NCK). Although no significant relationship could be found between number discrimination in infancy (8 months, T1) and NCK (48 months, T3), the predictive value of toddlers' number discrimination (24 months, T2) for NCK could be demonstrated at least for some NCK. The finding that ~~O~~only toddlers' small number discrimination related to NCK ~~raising~~ raised ~~some~~ thoughts about the task, age, set size, stability and development of number discrimination or other influencing factors. ~~When approaching successful *number discrimination* more strictly, the relationship could not be confirmed anymore, highlighting the importance of defining success.~~ Future research should study all small set sizes (not only 1vs3) and a broader range of NCK in a larger sample. Nevertheless, ~~while~~ whereas infants' small number discrimination might be too early to predict NCK, performance in toddlerhood might be addressed in the future to establish a measure to detect at-risk mathematical development.

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Keywords: early numerical competencies; habituation task; manual search task; small number discrimination~~; early numerical competencies; habituation task; manual search task; reliable change index~~

1. Introduction

Infants are found to non-verbally discriminate between sets with a different number of items. This so--called *number discrimination* (e.g., Xu & Arriaga, 2007) can be subsumed in the concept of *number sense* (e.g., Jordan, 2007; Kaminski, 2002; Wagner & Davis, 2010)has frequently been studied as an innate sense of quantity that develops without or with little verbal input early in life (Butterworth, 1999; Dehaene, 1997; Jordan & Levine, 2009). Most children thus enter kindergarten demonstrating some sense of number (Powell & Fuchs, 2012). Individual differences, however, exist as shown by a diversity in mathematical knowledge (Klibanoff, Levine, Huttenlocher, Vasilyeva, & Hedges, 2006; Zulauf, Schweiter, & von Aster, 2003) and motivated researchers to study *number sense* as a predictor of later mathematical achievement (e.g., DiPema, Lei, & Reid, 2007; Dowker, 2008; Mazocco & Thompson, 2005; Jordan, Kaplan, Locuniak, & Ramineni, 2007; Stock, Desoete, & Roeyers, 2009).

Although *number discrimination* is considered as a basic form of *number sense* present from infancy on (Xu & Arriaga, 2007) some glosses could be raised. Research on number discrimination is remarkable, as it shows that even infants are already able to (non-verbally) discriminate between numerosities (e.g., Cordes & Brannon, 2009a, 2009b; Starr, Libertus, & Brannon, 2013a; Xu, 2003). The precise nature and underlying processes of this ability, however, remain topic of an abundance of studies. As yet, studies on number discrimination were mainly restricted to concurrent group results (e.g., Xu, Spelke, & Goddard, 2005). This means that attention was mainly given to group performances on different number discrimination tasks of children overall without mapping any individual differences between children in a studied sample. Only recently, these individual differences were studied (Libertus & Brannon, 2010) and furthermore related for the first time to later numerical competencies (Starr, Libertus, & Brannon, 2013b).

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One of the main findings of this latter study was that the performance on a number discrimination task administered in infancy (i.e., 6 months of age) significantly predicted later math scores in kindergarten (i.e., 3.5 years). Administered items covered counting and numeral literacy, number-comparison facility and basic calculation (Starr et al., 2013b). Furthermore, number discrimination performance also predicted children's mastery of cardinality in particular as children who understood the exact meaning of the number words 'one' to 'six' in kindergarten performed significantly higher on number discrimination in infancy than children who only understood a subset of those number words (Starr et al., 2013b). As such data of this pioneering study pointed toward a developmentally primary role of the preverbal ability to discriminate numerosities already from infancy on.

~~As yet, studies on *number discrimination* were mainly restricted to concurrent group results (e.g., Xu, Spelke, & Goddard, 2005). Besides, studies that investigated *number sense* as a predictor mainly focused on kindergarteners (e.g., Jordan, Kaplan, Ramineni, & Locuniak, 2009). Recently, it is however shown that individual differences in *number sense* do already occur from infancy (Libertus & Brannon, 2010) and related to later mathematical outcome (Starr, Libertus, & Brannon, 2013b).~~ Nevertheless, ~~I~~it should be noted that this finding concern~~s~~eds *large* as opposed to *small* number discrimination, with the latter being another format of this ability and the focus of the current study. Overall, small number discrimination has been connected with object files and large number discrimination with analogue magnitudes as underlying systems of number discrimination (Feigenson, Dehaene, & Spelke, 2004; Xu, 2003;~~,~~ and see Cantrell & Smith, 2013 for a review).

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The object-file system allows an exact representation of a limited number (up to three) items (Kahneman & Treisman, 1984; Kahneman, Treisman, & Gibbs, 1992; Leslie, Xu, Tremoulet, & Scholl, 1998; Trick & Pylyshyn, 1994) and the analogue magnitude system allows an approximate representation of a larger (from four on) set of items (Feigenson et al.,

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2004). In the latter case discrimination is ratio-dependent: with a larger ratio numerosities are easier to discriminate. For example, Xu and Spelke (2000) demonstrated that 6-month-olds discriminate differences at a 1:2 ratio (8vs16) but not at a 2:3 ratio (8vs12).

Nonetheless, the claim that small numbers are only processed by object-files is tentative since the successful discrimination of small from large numerosities (Cordes & Brannon, 2009a) and the finding that number discrimination is ratio-dependent regardless of set size (Starr, Libertus, & Brannon, 2013a) are incompatible with this assumption. Moreover, one should acknowledge that young children probably have access to both systems but that the system they rely on ~~may~~ might depend on the paradigm that is used (Feigenson & Carey, 2003).

Reviewing literature on small number discrimination- three paradigms step into the limelight: the habituation (Clearfield & Mix, 1999; Cordes & Brannon, 2009b; Xu et al., 2005), the manual search (Feigenson & Carey, 2003; 2005) and (only) recently the numerical change detection paradigm (Libertus & Brannon, 2010). Habituation can be described as learning which reflects a changing responsiveness toward reiterated information leading children to less heed stimuli which are repeatedly shown (Bornstein, Pêcheux, & Lécuyer, 1988). The paradigm relies on a preference for novelty (e.g., Colombo & Mitchell, 2009) which is in this case a new number of items. Like the name suggests, the manual search task relies on how children search for a certain amount of objects which are being hidden after presentation (Feigenson & Carey, 2003). Reaching/Searching for objects is an action aimed at retrieving individual objects. Therefore, children are less prone to draw attention on the perceptual features (i.e., size, color, and shape) and give attention to the number of objects (Feigenson & Carey, 2005). Recently, the numerical change detection paradigm was developed by Libertus and Brannon (2010) based on a paradigm initially ~~developed~~ created by Ross-Sheehy, Oakes, and Luck (2003) to test infants' visual short-term memory. By means

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of two peripheral offered streams of rapidly changing images (relying on infants' preference for numerical change above constant numerosity) it was modified to test infant's ability to detect numerical changes.

Regarding small number discrimination, the numerical change paradigm is assumed to activate the analogue magnitude system (Starr et al., 2013a), whereas the manual search task would prompt the use of the object-file system (e.g., Barner, Thalwitz, Wood, Yang, & Carey, 2007; Feigenson & Carey, 2003, 2005). Divergent findings on small number discrimination emerge with failure for set size 1vs2 (Xu et al., 2005) and success for 2vs3 (Cordes & Brannon, 2009b) ~~and~~ as well as for 1vs3 (Ceulemans et al., 2012), however, leaves the question on which system is triggered by this habituation paradigm unresolved.

The current study tried to further disentangle the role of ~~*number sense* as operationalized by~~ number discrimination in addition to earlier topic-related studies (Libertus & Brannon, 2010; Starr et al., 2013b). For this purpose, number discrimination was assessed in children at the age of 8 (infants, T1) and 24 months (toddlers, T2) using an age-appropriate task (a habituation and manual search paradigm~~,~~ respectively) at both time points. Up till now, number discrimination studies mostly used habituation tasks in younger infants (mostly aged 6 months up till 10 months; e.g., Cordes & Brannon, 2009b; Xu, 2003~~,~~; Xu & Arriaga, 2007; Xu et al., 2005) whereas the manual search task was more often used in (older) toddlers (aged 1 to 2 years; e.g., Barner et al., 2007; Feigenson & Carey, 2003, 2005).

Furthermore, in line with Starr et al. (2013b), the following numerical competencies in kindergarten (NCK) were tested with a standardized test battery in these children at the age of 48 months (kindergarteners, T3)~~in addition to general intelligence~~: (procedural and conceptual) counting, with a more-in-depth test on cardinality,~~,~~ and arithmetic operations~~, and cardinality~~. In addition, general intelligence was tested. Items on procedural counting concerned children's ability to perform a mathematical task (LeFevre et al., 2006), whereas

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items on conceptual counting constituted the understanding of why a procedure works or is legitimate (Bisanz & LeFevre, 1992; Hierbert & LeFevre, 1986; LeFevre et al., 2006) referring to underlying principles of counting (Gelman & Gallistel, 1978). Knowing the meaning of a numeral (cardinality) as one of those principles was highlighted more in particular with a widely used test on cardinality knowledge. Arithmetic operation exercises prompted the understanding of composition and decomposition of groups by differentiating sets and subsets (i.e., addition and subtraction; Purpura & Lonigan, 2013). As such, administered items within the scope of the current study resembled the respective abilities of counting, numeral literacy, and basic calculation assessed by Starr et al. (2013). For all these numerical competencies the value as a predictor for later mathematics has been supported (Geary, Hamson, & Hoard, 2000; Powell & Fuchs, 2012).

Three research objectives were formulated. First, it was investigated whether performance on the habituation task (T1) related to NCK (T3). Second, this was examined for performance on the manual search task (T2) and NCK (T3). In other words, were infants' and toddlers' number discrimination performances predictive to later NCK? When a specific relationship between a number discrimination measure and a NCK-measure was significant, it was further explored whether number discrimination still had an additional value when taking into account intelligence. Finally, in the third research objective, it was studied whether number discrimination performance at 8 and 24 months of age was significantly related and could be considered as a stable measure throughout development.

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Number discrimination in this study focused on small numerosities. From the age of 2 years onwards, children learn to count by acquiring consecutively the meaning of the first number words (Mix, 2009) in a first stage, which leads them to learn larger number words in a later stage. As such, investigating the predictive value of *small number discrimination* to for later mathematicsal outcome - even from infancy on but certainly at the critical age of 24

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months - seemed to be a meaningful addition to previous research on the predictive value of *large number discrimination* (Starr et al., 2013b). Based on the findings of Starr et al. (2013b), it was expected that infant's number discrimination (T1) would relate significantly to NCK (T3). Consequently, number discrimination in toddlerhood (T2) was also expected to relate significantly to NCK (T3), since the assessed number discrimination tasks at both ages - although different in design - are assumed to tap the same ~~*number sense*~~ ability.

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In previous studies ~~S~~small set sizes were ~~previously~~ mainly investigated with either ~~the~~a habituation ~~and~~or a manual search task (e.g., Cordes & Brannon, 2009b; Feigenson & Carey, 2003,~~;~~ 2005; Xu, 2003). Since the numerical change task has only recently been used in the study of Starr et al. (2013b) to investigate small number discrimination, tasks according to the other two mentioned paradigms took precedence in the current study. Furthermore, ~~I~~in order to make a prediction possible between number discrimination and later outcome, at least some children needed to be able to successfully discriminate the specified numerosities. Accordingly, the small set size with the largest ratio (1vs3) was chosen, since this warranted success with both tasks (Ceulemans et al., 2012; Feigenson & Carey, 2003, 2005).

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In addition to previous studies, only providing binary information in terms of success or failure based on one overall task performance (Starr et al., 2013b), this study took into account successes and failures on different test trials of the tasks instead. As such, the study aimed at taking the binary information to a higher level and making it sensitive to individual differences. ~~Moreover, the particular cut-off (i.e. a positive difference score larger than zero) mainly used to define success in *number discrimination* studies (e.g., Feigenson & Carey, 2003, 2005; Starr et al., 2013b; Xu, 2003, Xu & Arriaga, 2007) was questioned by taking into account the reliability of measures.~~

2. Method

2.1. Participants (see Table 1)

Participants were part of a large-scale birth cohort living in different Flemish districts in Belgium. This ~~large~~ cohort was recruited within the scope of a longitudinal (governmental) study (http://www.steunpuntwvg.be) of which the reported study is only one small part. Children were randomly selected to participate in several cross-sectional studies on number discrimination on which will not elaborated here. Due to practical limitations such as expiration of the project and availability of complete data on small number discrimination it was only possible to follow-up a handful of children until the age of 48 months. As such, parents of 31 (out of 39) children consented to participate with their child at the ages of 8 (T1), 24 (T2), and 48 months (T3).

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Table 1

Descriptive Sample Characteristics

		M	*(SD)*	
Age (*in months*)				
	8 months (T1)	8.10	(1.16)	
	24 months (T2)	23.55	(1.18)	
	48 months (T3)	48.42	(0.92)	
IQ[a]				
T3		101.33	(12.53)	
		Boys (*n*)	Girls (*n*)	
Sex				
T1,T2,T3		15	16	
		Mothers (*n*)	Fathers (*n*)	
Educational level (T1)[b]				
	Primary education	1	0	
	Higher secondary education	7	15	
	Higher education	23	13	
		Low (*n*)[d]	Medium (*n*)[e]	High (*n*)[f]
Family income (T1)[c]		2	13	13

Note. T1 = time point (1) at 8 months of age; T2 = time point (2) at 24 months of age; T3 = time point (2) at 48 months of age; IQ = Intelligence Quotient
[a]Intelligence Quotient retrieved from the Wechsler Preschool and Primary Scale of Intelligence – Third edition (WPPSI-III-NL; Wechsler, 2002; Dutch translation Hendriksen & Hurks, 2009). [b]Information unknown for 3 of 31 fathers [c]Three families did not disclose information on income. [d]income < €1500. [e]€1501 < income < €3000. [f]income > €3000

2.2. Procedure and measures.

At T1 and T2 number discrimination was assessed. At T3 children's counting, arithmetic operations, and cardinality knowledge were tested. All tasks were part of a broader research protocol. Research was always conducted in a distraction-free room either at '*Child & Family'* services (which have governmental responsibility for guidance and support of young children and families in Flanders, http://www.kindengezin.be) at T1 and T2 or at home (T3). The number discrimination tasks were assessed while children sat on a parent's' lap. Parents were instructed to remain neutral and not to elicit attention or communication. NCK-tests were assessed individually, in absence of any parents, in the same order for all children.

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Parents signed an informed consent and the study was approved by the ethical commissions of the involved faculties. All test leaders (graduate students) received training in the assessment and interpretation of the tests.

2.2.1. Number discrimination performance (see Table 2).

2.2.1.1. Habituation task.

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Children received a number discrimination task (T1) following habituation (e.g., Xu, 2003; Xu & Spelke, 2000,; Xu et al., 2005) using one- and three- element arrays of red dots on a white background. Stimuli were controlled for continuous variables (i.e., item size, inter item distance, total item size, and occupied set area) according to the procedure of Dehaene, Izard, and Piazza (2005). The task consisted of a phase aimed at habituating children randomly to one of these arrays using six different displays shown in repeating random order. In a test phase in which six displays contained the habituated and new dot arrays in alternation (counterbalanced for order across participants), longer looking at the novel arrays was considered as an indication of successful discrimination (Xu, 2003; Xu & Arriaga, 2007).

Expanding previous studies using this paradigm (Cordes & Brannon, 2009a; Xu et al., 2005), habituation software (i.e., Habit X version 1.0; Cohen, Atkinson, & Chaput, 2004) was combined with Eye Tracking (ET, Tobii T60; Tobii Technology, 2007). Looking times were coded afterwards from ET data in *Tobii Studio* software (Tobii Technology, 2007) by identifying total eye fixation duration per dot-array. Experimenters and coders were blind to the assigned conditions. Inter-rater reliability between the two coders (r = .97) was good.

Analysis focused on the difference between looking time at the habituated and new number of dots per test trial pair, which is a common practice (e.g., Xu, 2003; Xu & Arriaga, 2007; Xu & Spelke, 2000). This resulted in three difference scores.

According to a *lenient* approach of success oneOne credit was given for each difference score larger than zero in line with the mainly used definition of successful discrimination (e.g., Feigenson & Carey, 2003, 2005; Starr et al., 2013b; Xu, 2003, Xu & Arriaga, 2007) resulting in a so-called *Habituation Success Score* (HSS). According to a *restricted* approach, one credit was only given for each difference score larger than a reliable change index (RCI). These indexes - calculated for the difference scores from all trial pairs - were computed following Morley (2013) and helped to find out whether differences between looking times were reliable, a method generally used for defining a meaningful change (e.g., Jacobson & Truax, 1999) and/or evaluating clinical data for which no control group is available to compare the sample group with (e.g., Fenton & Morley, 2013).

2.2.1.2. Manual search task.

A manual search task presenting a 1vs3 comparison as described by Feigenson and Carey (2005) was administered at T2. A wooden box (25 cm x 12.5 cm x 31.5 cm) had a slit at the front oriented to the toddlers and an opening at the backside oriented to the experimenter who faced the child at an - besides the box - empty table. Parents were told that some balls would be hidden by the experimenter (through the slit in front of the box) to explore how children reacted and that no wrong reaction existed. The task consisted of three kinds of trials as illustrated more in detail in Figure 1: a first *box empty* trial, a *more remaining* trial, and a second variant of the box empty trial, which always followed after a more remaining trial.

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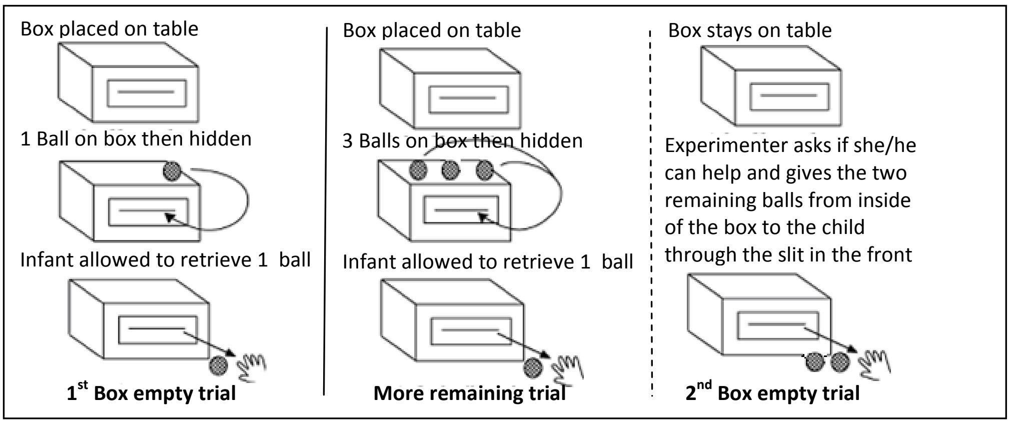

Figure 1. Different trial types of the manual search task. Adopted from "On the limits of infants' quantification of small object arrays," by L. Feigenson and S. Carey, 2005, *Cognition, 97*, p. 301. Copyright 2004 by Elsevier B.V.

Each of the trial types was presented twice and the order of the trials was counterbalanced. Children could search through the slit for ten seconds after each type of trial. It was expected that children would search longer after the more remaining trials than after the box empty trials. This would indicate successful discrimination. Cumulative searching time, was coded manually afterwards using *The Observer XT* software (http://www.noldus.com). Searching was defined as the period during which knuckles of one or both child's hands passed through the slit. Grasping of the slit did not count (Feigenson & Carey, 2003, 2005). Since administration of the search task revealed that children also looked into the box to search for the (supposedly) hidden balls, looking through the split was additionally considered as searching.

Equivalent outcome measures were constructed for the manual search task (T2) as for the habituation task (T1). Subtracting searching time after box empty trials from searching time after more remaining trials resulted in four difference scores. A positive difference score was considered as indicative for success and credited with one point if it was larger than zero, resulting in a so-called *Manual Search Success Score* (MSSS)~~ for the *lenient* measure~~. ~~For the *restricted* measure, one credit was only given if the difference score was larger than the specified RCI (Morley, 2013). Respectively, four indexes were calculated for the difference~~

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~~scores resulting from the four possible subtractions between searching times on the different trial pairs.~~

Table 2

Description of Number Discrimination Tasks and Related Measures

Tasks	Description	Maximum	Reliability[a]
Habituation Success Score (HSS; T1):			
~~Lenient Success Score (HLSS)~~	Credit difference score > 0	3	.21
~~Restrictive Success Score (HRSS)~~	~~Credit difference score > RCI~~	~~3~~	
Manual Search Success Score (MSSS; T2):		4	.79
~~Lenient Success Score (MSLSS)~~	Credit difference score > 0	4	
~~Restrictive Success Score (MSRSS)~~	Credit difference score > RCI		

Note. T1 = time point (1) at 8 months of age; T2 = time point (2) at 24 months of age
[a] Reliability of difference scores as measured with Cronbach's α

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2.2.2. Numerical competencies in kindergarten (see Table 3).

NCK (T3) were assessed using the counting and arithmetic operations subtests -of the *Test for the Diagnosis of Mathematical Competencies* (TEDI-MATH; Grégoire, Noël, & Van Nieuwenhoven, 2004). The psychometric value of this assessment battery was tested on 550 Dutch-speaking Belgian children (Grégoire, 2005) and has proven to be conceptually accurate and clinically relevant. Its predictive value has been demonstrated in several studies (Desoete & Grégoire, 2006; Desoete, Stock, Schepens, Baeyens, & Roeyers, 2009; Stock, Desoete, & Roeyers, 2007). A variant of the *Give-a-Number* task (GNT), designed by Wynn (1990, 1992) and adjusted by Sarnecka and Carey (2008), was used to additionally tap cardinality.

To assess counting (T3), two subtests of the TEDI-MATH (Grégoire et al., 2004) were used. Procedural Counting (PC) knowledge included accuracy in reproducing a counting sequence starting from one (up till 31), counting up to an upper bound (e.g., 'count to 9') and/or from a lower bound (e.g., 'count from 3'). Conceptual Counting (CC) knowledge implied the validity of counting procedures, based on the counting principles of Gelman and

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Gallistel (1978). Children had to judge the counting of linear and non-linear patterns of objects, and were asked the counted amount of objects (e.g., ‘How many objects are there?’). Furthermore, they had to construct two numerical equivalent amounts of objects and use counting as a problem-solving strategy in a riddle. At last, A~~a~~rithmetic O~~o~~perations (AO) were assessed by presenting a series of visually supported additions and subtractions to the children.

In addition, all children were tested with the GNT-variant (Sarnecka & Carey, 2008) to determine whether they knew the exact meaning of numbers (cardinality) from one to six. Children were asked to give N objects to a puppet, followed by the question whether they gave N items. This question was restated, until children answered positively. First, one object, then three objects were asked. After a correct answer, the next request was ‘N + 1’, otherwise ‘N – 1’. Requests continued until at least two successes at N and at least two failures at N + 1. A credit was given if the child had at least twice as many successes as failures for that numeral. Failure included giving the wrong number of items. Each child’s knower level corresponded to the highest number he/she reliably generated. In line with Sarnecka and Carey (2008), children who had at least twice as many successes as failures for trials of ‘five’ and ‘six’ were called *cardinality-knowers*, while all others were called *subset-knowers* (Le Corre & Carey, 2007; Le Corre, Van de Walle, Brannon, & Carey, 2006).

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Table 3

Description of Tasks on Numerical Competencies and Related Measures

Tasks (T3)	Description	Maximum	Reliability[a]
TEDI-MATH:			
Procedural Counting (PC)	Items on counting sequence	8	.62
Conceptual Counting (CC)	Items on counting principles	13	.76
Arithmetic Operations (AO)	Simple additions & subtractions	6	.73
GNT:			
Cardinality-knowers (*n* = 13)	Cardinality from number 5 on	6	.82
Subset-knowers (*n* = 18)	Cardinality below number 5		

Note. T3 = time point (3) at 48 months of age; TEDI-MATH = *Test for the Diagnosis of Mathematical Competencies*; GNT = Give-a-Number task
[a]Reliability of subscale as measured with Cronbach's α

2.3. Analysis

Since graphical inspection revealed no strong evidence against non-normality, parametric tests were conducted. More specifically, because of graphically supported linear trends between outcome and predictors linear regressions were performed in SPSS Version 21.0 (IBM Corp., 2012) to explore the relationship between number discrimination and TEDI-MATH-measures. In case of a significant result a hierarchical multiple linear regression was conducted to determine the additional effect of number discrimination on top of intelligence. Furthermore, independent sample *t*-tests were conducted to reveal whether cardinality- and subset-knowers (GNT, Sarnecky & Carey, 2008) differed on number discrimination.

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3. Results

See Table 4 for an overview of descriptives and intercorrelations of the variables.

Table 4

Summary of Intercorrelations, Means and Standard Deviations for Number Discrimination, Numerical Competencies, and Intelligence Measures

Measure	1	2	3	4	5	6	7	8	9	*n*	*M (SD)*
1. HLSS	--									31	1.45 *(0.93)*
~~2. HRSS~~	~~-.10~~	~~--~~								~~31~~	~~0.23 *(0.43)*~~
3. MSLSS	.05	-.21	--							31	2.42 *(1.48)*
~~4. MSRSS~~	~~-.01~~	~~-.10~~	~~-.17~~	~~--~~						~~31~~	~~1.45 *(1.43)*~~
5. PC	-.23	.14	.20	-.03	--					31	1.45 *(1.61)*
6. CC	-.13	-.14	.38*	-.03	.38*	--				31	4.39 *(2.70)*
7. AO	-.19	.05	.31^t	-.07	.41*	.57***	--			31	1.97 *(1.80)*
8. Cardinality[a]	-.21	.01	.16	.19	.58***	.49**	.35^t	--			
Cardinality knowers										13	5.69 *(0.48)*
Subset knowers										18	2.50 *(1.04)*
9. IQ[b]	-.24	.14	.11	.36^t	.55**	.53**	.34^t	.59***	--	30	101.33 *(12.53)*

Note. HLSS = ~~Lenient approach of~~ Habituation (task) Success Score~~; HRSS = Restrictive approach of Habituation (task) Success Score~~; MSLSS = ~~Lenient approach of~~ Manual Search (task) Success Score; ~~MSRSS = Restrictive approach of Manual Search (task) Success Score;~~ PC = Procedural Counting; CC = Conceptual Counting; AO = Arithmetic Operations; IQ = Intelligence Quotient
[a]Cardinality- or subset-knower based on score on Give-a-Number task; [b]Intelligence Quotient (IQ) retrieved from the Wechsler Preschool and Primary Scale of Intelligence - Third edition (WPPSI-III-NL; Wechsler, 2002; Dutch translation Hendriksen & Hurks, 2009)
$* p \leq .05$. $** p \leq .01$. $*** p \leq .001$ $^t .05 < p > .10$

In what follows the results of the analyses, conducted to give an answer on the research questions, are given. A summary of the results can be additionally found in Table 5.

~~Using the *lenient* measure of *number discrimination*, l~~Linear regression revealed no significant relationship between infants' *number discrimination* (HLSS, T1) and NCK-scores (T3). Furthermore, cardinality- and subset-knowers did not differ significantly (GNT, T3) on their number discrimination in infancy (HLSS, T1) as indicated by an independent sample *t*-test. ~~Analyses using the *restricted* measure of infants' *number discrimination* (HRSS, T1) provided the same results with respect to the NCK-scores and the difference on this *number discrimination* performance (HRSS, T1) between cardinality- and subset-knowers (GNT, T3).~~

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Table 5

Summary of Linear Regression for Numerical Competencies measured with TEDI-MATH.

	Procedural Counting (PC)				
Variable	*B*	*SE(B)*	*β*	*t*	*p*
H~~L~~SS	-.40	.31	-.23	-1.28	.211
~~HRSS~~	~~0.52~~	~~.70~~	~~.14~~	~~-.75~~	~~.458~~
MS~~L~~SS	.22	.20	.20	1.09	.286
~~MSRSS~~	~~-.04~~	~~.21~~	~~-.03~~	~~-.18~~	~~.858~~
	Conceptual Counting (CC)				
Variable	*B*	*SE(B)*	*β*	*t*	*p*
H~~L~~SS	-.37	.54	-.13	-.68	.501
~~HRSS~~	~~-.87~~	~~1.17~~	~~-.14~~	~~-.74~~	~~.464~~
MS~~L~~SS	.70	.31	.38	2.24	.033
~~MSRSS~~	~~-.06~~	~~-.35~~	~~-.03~~	~~-.16~~	~~.875~~
	Arithmetic Operations (AO)				
Variable	*B*	*SE(B)*	*β*	*t*	*p*
H~~L~~SS	-.37	.35	-.19	-1.05	.302
~~HRSS~~	~~-.23~~	~~.78~~	~~.05~~	~~-.29~~	~~.775~~
MS~~L~~SS	.37	.22	.31	1.73	.094
~~MSRSS~~	~~-.09~~	~~.23~~	~~-.07~~	~~-.39~~	~~.701~~

	Cardinality			
Variable	Cardinality-knowers (*n* = 13)	Subset-knowers (*n* = 18)	*t*	*p*
	M (SD)	*M (SD)*		
H~~L~~SS	1.23 *(0.60)*	1.61 *(1.09)*	1.24	.225
~~HRSS~~	~~0.23 *(0.44)*~~	~~0.22 *(0.43)*~~	~~-.06~~	~~.957~~
MS~~L~~SS	2.69 *(1.60)*	2.22 *(1.40)*	-.87	.391
~~MSRSS~~	~~1.77 *(1.59)*~~	~~1.22 *(1.31)*~~	~~-1.05~~	~~.302~~

Note. H~~L~~SS = ~~Lenient approach of~~ Habituation (task) Success Score; ~~HRSS = restrictive approach of Habituation (task) Success Score;~~ MS~~L~~SS = ~~Lenient approach of~~ Manual Search (task) Success Score~~; MRSS = Restrictive approach of Manual Search (task) Success Score~~

Linear regression analysis with the ~~*lenient*~~ *number discrimination* measure in toddlerhood (MS~~L~~SS, T2) as a predictor, revealed no significant relationship with PC (T3).

~~However, f~~For CC and AO, a significant (effect size r = .38) and marginally significant (effect size r = .31) relationship was found, respectively. Even on top of IQ, a marginally significant effect was found on CC, F_{change} (1, 27) = 3.87, p = .060, β = .301 with R^2 = .38 for the full linear regression model. Furthermore, no significant difference was found between cardinality-and subset-knowers (GNT, T3) on this number discrimination performance (MS~~L~~SS, T2) as demonstrated by an independent sample *t*-test. ~~Conducting the same analysis with the *restricted number discrimination* measure (MSRSS, T2), revealed the same findings regarding the relationship with PC. For CC and AO, however, no relationship was found anymore. Furthermore, no significant difference was found between cardinality- and subset-knowers (GNT, T3) on this *number discrimination* performance (MSRSS, T2) as demonstrated by an independent sample *t*-test.~~

Finally, the infants' (T1) and toddlers' (T2) number discrimination measures were not significantly related, ~~neither using the *lenient* measures,~~ B = .083, SE (B) = .296, β = .052, t (29) = .280, p = .782~~, nor using the *restricted* measures, B = .339, SE (B) = .623, β = .101, t (29) = .544, p = .590~~.

4. Discussion

4.1. General Findings

This study aimed to shed light on infants' (T1) and toddlers' (T2) number discrimination in relation to numerical competencies in kindergarten (NCK, T3) and revealed the following main findings. Although no significant relationship could be found between number discrimination in infancy (8 months, T1) and NCK (48 months, T3), the predictive value of toddlers' number discrimination (24 months, T2) for NCK could be demonstrated at least for some NCK: for Arithmetic Operations (AO) and even on top of IQ for Conceptual

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Counting (CC). Furthermore, number discrimination in infancy (T1) and toddlerhood (T2) did not significantly relate mutually.

Results showed that noThe absence of a significant relationship could be found between infants' number discrimination (8 months, T1) and later numerical competenciesoutcome in kindergarten (48 months, T3). Thiswas in contrasts with the found relationship between number discrimination at 6 months as a predictor of and later mathematical abilities in a previous study (Starr et al., 2013b). Important to note, however, is that Starr et al. (2013b), however, not only tested a younger cohort, but also used another number discrimination paradigm, a younger cohort and probing moreovered large instead of small number discrimination. These three differences in study design could all be responsible for the this other inconclusive findingsresult.

First, Starr et al. (2013a) highlighted that a numerical change detection paradigm would be more likely to invoke analogue magnitudes than the habituation paradigm. Task-dependency of the recruited numerical system may therefore be a plausible explanation for different findings between the current study and the study of Starr et al. (2013b). Ratio-dependency is a well-known characteristic of numerical representation using analogue magnitudes (e.g., Xu & Spelke, 2000, Cantrell & Smith, 2013 for a review). Since infants successfully discriminated the set sizes 1vs3 and 1vs2 but not 2vs3 - having the most difficult ratio - hereby revealing ratio-dependency, it was concluded that the numerical change paradigm elicits the analogue magnitude system to represent small numerosities. On the contrary, as yet, not all small set sizes were investigated simultaneously in the same group of infants using habituation. Moreover, divergent findings (Ceulemans et al., 2012; Cordes & Brannon, 2009b; Xu et al., 2005) with success for the set sizes 1vs3 (Ceulemans et al., 2012) and 2vs3 (Cordes & Brannon, 2009b) - suggesting the recruitment of object files - and failure of the set size 1vs2 (Xu et al., 2005) - even undermining the use of both object-files and

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~~analogue magnitudes - makes it difficult to draw any conclusion on which system is triggered to discriminate small numbers with the habituation paradigm. Another explanation might be the age of the infants. Starr et al. (2013b) stated that at 6 months of age the relationship between numerical representation using analogue magnitudes and burgeoning math may be at its strongest. Therefore, it is possible that this relationship could not be replicated in older infants (8 months) as this also might hold for small number discrimination. Though, because of investigating *small* (1vs3) instead of large number discrimination (6vs24, 5vs15, 6vs18, 8vs16 or 10vs20; Starr et al., 2013b), it may well be that the representation of small and large numbers just contributes differently to later NCK. This could be, finally, a third possible explanation for the different findings of the current study and the one by Starr et al. (2013b).~~

~~Although no significant relationship could be found between number discrimination in infancy (T1) and NCK (T3), the predictive value of toddlers' number discrimination (T2) for NCK could be demonstrated at least for some NCK aspects (AOS and even on top of IQ, CCS) when using the *lenient* approach of successful *number discrimination*.~~ Irrespective of ~~Aside from~~ the studied age, the predictive value of number discrimination at T2 (toddler age) for NCK (T3) ~~this finding~~ is in line with the study of Starr et al. (2013b). Not for all investigated NCK the relationship with number discrimination could be confirmed however. An explanation regarding CC might be found in the higher amount of items on this subtest (compared to the other NCK-subtests). This larger number of items might have resulted in more variability in the score on CC which could have facilitated the detection of a (significant) relationship with toddlers' number discrimination performance. With respect to AO, a possible explanation for its relation to number discrimination, might be found in the items' complexity (in line with Purpura & Lonigan, 2013) being more difficult than the other NCK-items since counting and cardinality are often involved in carrying out these operations (Powell & Fuchs, 2012). A clear theoretical underpinning to explain the results, however, is

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difficult to achieve. More in-depth research on why specific NCK would relate to number discrimination (and others not) is warranted. Furthermore, also the formats of number discrimination (small vs large) should additionally be compared within this scope.

To recapitulate the findings on number discrimination in infancy and toddlerhood relating to NCK, some explanations can be provided for the pattern of results across T1 and T2. From different points of view some explanations can be provided for the current pattern of results across all time points. First, small number discrimination at the age of 8 months is possibly not yet stable enough to reliably predict numerical functioning over a period longer than three months (i.e., from 8 to 24 or 48 months of age) in contrast to stable (although large) number discrimination abilities between 6 and 9 months of age (Libertus & Brannon, 2010). Second, the development of number discrimination may bloom in the first half year of life, stabilize and again take a leap at 24 months of age because children start to count and manipulate small numbers to further elaborate their counting skills with large numbers (Mix, 2009). Therefore, it might be more likely to find a significant relationship between number discrimination at 24 months of age and later numerical competencies than with the 8-month-measure. Third, also other factors such as numerical mother-child interactions or educational systems which vary across countries may influence lower or higher number discrimination ability in infancy and/or toddlerhood resulting in different findings throughout childhood or between studies. Important to keep in mind, however, is that for the above mentioned results a merely positive difference score was interpreted as success (in line with Starr et al., 2013b). These results vanished when using a more *restricted* approach of success taking into account a particular *cut-off* (Reliable Change Index, RCI, Morley, 2013) for this difference score. RCI-analysis takes into account the reliability of tasks to determine the index. Next, this index is available to decide whether a difference in participants' behavior across trials is real and not just due to for example measurement error (Morley, 2013). Defining success using RCI-

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~~analysis, therefore, seems to lead to more reliable conclusions and demands further exploration, without detracting from successful *number discrimination* merely defined by a positive difference score (e.g., Feigenson & Carey, 2003, 2005; Starr et al., 2013b; Xu, 2003, Xu & Arriaga, 2007). Perhaps with a larger sample positive significant results could be found with this advanced approach as well.~~

Besides the possibility of number discrimination being an instable measure (as outlined in the previous section), ~~That~~ no significant (mutual) relationship ~~was found~~ between infants' (T1) and toddlers' (T2) small number discrimination could also be ~~is~~ suggestive for the presumption that ~~both~~ the number discrimination tasks used at the different time points trigger a different underlying numerical representation system or simply appeal to different abilities. ~~Given~~ Assuming that habituation triggers object~~-~~-files in small number discrimination (although not exclusively or conclusively) and the informed knowledge (Feigenson & Carey, 2003, 2005) that the manual search paradigm does this for sure ~~–based on success for of all small set sizes (Feigenson & Carey, 2003, 2005) –~~the first presumption seems less likely. It can alternatively be ~~alternatively~~ stated that both tasks appeal to different abilities (and likewise measure different concepts). Cantrell and Smith (2013) questioned the suitability of the manual search tasks for studying small number discrimination because infants' performances may require more than mere discrimination of quantities in these tasks. Infants need to remember amounts and their locations and are required to base behavior on this knowledge. Manual search tasks are therefore more demanding than other discrimination tasks since they also dependent upon visual working memory, object representation, and knowledge of 'more'. This in turn aligns with the notion of the use of the manual search task in infants relatively older than those participating in previously conducted habituation studies (Cantrell & Smith, 2013).

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4.2. Limitations and implications

The current study tried to disentangle the role of small number discrimination for later ~~mathematical outcome~~numerical competencies, but some limitations remain to inspire future ~~research~~studies on this topic.

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First, the small sample size might explain the marginally significant results. Although, trends can indicate relevant findings, future research needs to incorporate a larger sample. Partly due to this small sample, but especially due to the majority of middle- and high-income-families (see Table 1), the impact of socio-economic status (SES) was not ~~further~~ explored. Based on literature on mathematical abilities with an additional focus on SES, no differences are expected between these subcategories of families, but rather between these two subgroups on the one hand and low-income families on the other hand (e.g., Jordan, Kaplan, Locuniak, & Ramineni, ~~et al.,~~ 2007; Jordan, Kaplan, Olah, & Locuniak, 2006). It would ~~Second, regarding the sample it would also~~therefore be meaningful to include more families with a low ~~socio-economic status (~~SES~~)~~ who ~~-~~– based on income ~~-~~– only constituted a minority of the current sample (see ~~also~~ Table 1). This is not surprising as ~~a bulk of evidence suggests that~~ individuals with a higher SES are more likely to participate in scientific research (Burg, Allred, & Sapp, 1997; Galea & Tracy, 2007; Hille et al., 2005)~~. This~~ probably ~~reflects~~because of a greater trust in science and a higher degree of volunteerism ~~in this group~~ (Bak, 2001; Putnam, 1995). ~~Partly due to the small sample size in this study and moreover this majority of middle- and high-incomes (see also Table 1), the impact of SES was not further explored. Based on literature on mathematical abilities with an additional focus on SES, one should not expect differences between these subcategories of families, but rather between these two subgroups on the one hand and low-income families on the other hand (e.g., Jordan et al., 2007; Jordan, Kaplan, Olah, & Locuniak, 2006).~~

SecondThird, only some competencies were studied, despite the wide range of math related abilities. Taking into account the fact that the current study was part of a broader large-scale project together with the short attention span of young children, (non)symbolic number comparison tasks were for example not part of the test protocol at T3 due to time constraints. This is A non-symbolic task, for example, was not integrated at T3, in contrast with Starr et al. (2013b) and could have been informative. To illustrate, Oone may, indeed, expect to find positive correlations between a non-symbolic performance and number discrimination as the latter situates itself on a non-symbolic level too by relying on internal mental number representations (Feigenson et al., 2004). Nonetheless, the broader the range of studied mathematical abilities, the more insight would be obtained in how predictors relate to different aspects of mathematics later on. As such, it would be worthwhile and recommended to adhere to a multicomponential approach.ThirdFourth, only the set 1vs3 was investigated, implying a clear interpretation based on one ratio. whereas iIncluding all small set sizes, though, could have provided more insight in (the nature and the role of) small number discrimination. Moreover, although the standards for administration of the habituation task (e.g., Xu, 2003; Xu & Spelke, 2000, Xu et al., 2005)of previous studies were followed for administration of the habituation task (e.g., Xu, 2003; Xu & Spelke, 2000, Xu et al., 2005), its reliability was low. Including more trials, would therefore be indicated as long as infants' (short) attention-span is taken into account. FourthFifth, from the few frequently used paradigms to investigate small number discrimination, the tasks in this study were (chosen to be) age-appropriate resulting in different paradigms at T1 and T2 making comparison of number discrimination abilities more difficult (yet, not impossible). It seems however crucial for future studies to provide children with both paradigms at the same time point but alsoone and across the various time points. Again, due to the short attention span of in particular the children at T1 and the broader research protocol of the large-scale study of which this study

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was a small part, only one paradigm was chosen to measure number discrimination at each specific time point. Obviously, in a more ideal design multiple paradigms could have been used to assess small number discrimination in the same children at both T1 and T2.

Moreover, especially because of questions (concerning reliability or specific task demands as ~~both~~ referred to earlier) raised on the used paradigms ~~used in the current study~~, su a multimethod approach could reveal valuable information. Other findings could indeed have resulted from using other tasks to measure small number discrimination, since differences might be caused by the varying number processing system elicited by each task (Feigenson & Carey, 2003).

Despite these limitations, the main implication ~~of the findings~~ regarding later NCK is the suggestion that whereas small number discrimination could not be valued yet as a ~~possible~~ predictor at 8 months of age, this ~~could~~might be ~~however~~ be the case from 24 months of age onwards.~~re are some implications. First, small number discrimination at the age of 8 months (T1) might be too early to predict later outcome (T2, T3). From 24 months (T2) on, it seems possible to predict some numerical competencies (T3) taking into account how children repeatedly succeed on a series of trials within a task and not just an overall performance.~~ Following ~~the~~ this line of thought ~~about the value of toddler's number discrimination~~, it might be valuable to follow up (clinically) low number discrimination performers ~~on number discrimination~~ in toddlerhood to establish sensitive measures to detect at-risk development of later mathematical problems. Especially for those at higher risk ~~for these problems~~ (i.e., siblings of children with a mathematical learning disorder; Shalev et al., 2001) this could be worthwhile. If, moreover, problems might be reduced by providing at-risk children opportunities to improve their skills (Clements & Sarama, 2011; DiPema, Lei, & Reid, ~~et al.,~~ 2007; Fuchs, 2011), additional numerical stimulation in toddlerhood might be beneficial. ~~Within this context, a~~Agencies ~~or initiatives~~ in support of parenting (such as~~,~~ local parent

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support consultations, parenting shops, or ~~parenting~~ support centers); might play a sensibilizing role ~~toward parents. Nevertheless, implications are tentative, as different approaches of success unfold other patterns of results.~~

4.3. Conclusion

The current study focused on ~~questioned~~ the predictive value of infants' and toddlers' number discrimination for later numerical competencies in kindergarten (NCK). ~~Only when using a *lenient* approach of toddlers' *number discrimination*, a~~A relationship between toddlers' number discrimination with ~~later conceptual counting and arithmetic operations in kindergarten~~ some NCK could be observed. ~~When taking into account intelligence, this relationship only held for conceptual counting.~~

Several hypotheses may underpin the importance of toddlerhood above infancy~~:~~ such as the stability, development, the format ~~(small instead of large number discrimination)~~ and influencing factors of number discrimination. Nevertheless, the found relationship may inspire future research to follow up ~~children~~ toddlers with low number discrimination in order to find out whether at-risk detection in ~~toddlers~~ toddlerhood for mathematical problems is already possible. ~~A *restricted* approach of *number discrimination* (which could not confirm the relationship with NCK) additionally suggested the importance of defining success to reveal significant results.~~

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The Sense of Small Number Discrimination: The Predictive Value in Infancy and Toddlerhood for Numerical Competencies in Kindergarten

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The Sense of Small Number Discrimination: The Predictive Value in Infancy and Toddlerhood for Numerical Competencies in Kindergarten

Abstract

Extending previous research on the predictive value of large *number discrimination*, this study explored the role of infants' and toddlers' small number discrimination for numerical competencies in kindergarten (NCK). Although no significant relationship could be found between number discrimination in infancy (8 months, T1) and NCK (48 months, T3), the predictive value of toddlers' number discrimination (24 months, T2) for NCK could be demonstrated at least for some NCK. The finding that only toddlers' small number discrimination related to NCK raised thoughts about the task, age, set size, stability and development of number discrimination or other influencing factors. Future research should study all small set sizes (not only 1vs3) and a broader range of NCK in a larger sample. Nevertheless, whereas infants' small number discrimination might be too early to predict NCK, performance in toddlerhood might be addressed in the future to establish a measure to detect at-risk mathematical development.

Keywords: early numerical competencies; habituation task; manual search task; small number discrimination

1. Introduction

Infants are found to non-verbally discriminate between sets with a different number of items. This so-called *number discrimination* (e.g., Xu & Arriaga, 2007) has frequently been studied as an innate sense of quantity that develops without or with little verbal input early in life (Butterworth, 1999; Dehaene, 1997; Jordan & Levine, 2009).

Research on number discrimination is remarkable, as it shows that even infants are already able to (non-verbally) discriminate between numerosities (e.g., Cordes & Brannon, 2009a, 2009b; Starr, Libertus, & Brannon, 2013a; Xu, 2003). The precise nature and underlying processes of this ability, however, remain topic of an abundance of studies. As yet, studies on number discrimination were mainly restricted to concurrent group results (e.g., Xu, Spelke, & Goddard, 2005). This means that attention was mainly given to the group performances on different number discrimination tasks of children overall without mapping any individual differences in the specific ability to discriminate numerosities between children in a studied sample. Only recently, these individual differences were studied (Libertus & Brannon, 2010) and furthermore related for the first time to later numerical competencies (Starr, Libertus, & Brannon, 2013b). One of the main findings of this latter study was that the performance on a number discrimination task administered in infancy (i.e., 6 months of age) significantly predicted later math scores in kindergarten (i.e., 3.5 years). Administered items covered counting and numeral literacy, number-comparison facility and basic calculation (Starr et al., 2013b). Furthermore, number discrimination performance also predicted children's mastery of cardinality in particular as children who understood the exact meaning of the number words 'one' to 'six' in kindergarten performed significantly higher on number discrimination in infancy than children who only understood a subset of those number words (Starr et al., 2013b). As such data of this pioneering study pointed toward a developmentally primary role of the preverbal ability to discriminate numerosities already from infancy on.

Nevertheless, it should be noted that this finding concerned *large* as opposed to *small* number discrimination, with the latter being another format of this ability and the focus of the current study. Overall, small number discrimination has been connected with object files and large number discrimination with analogue magnitudes as underlying systems of number discrimination (Feigenson, Dehaene, & Spelke, 2004; Xu, 2003; and see Cantrell & Smith, 2013 for a review).

The object-file system allows an exact representation of a limited number (up to three) items (Kahneman & Treisman, 1984; Kahneman, Treisman, & Gibbs, 1992; Leslie, Xu, Tremoulet, & Scholl, 1998; Trick & Pylyshyn, 1994) and the analogue magnitude system allows an approximate representation of a larger (from four on) set of items (Feigenson et al., 2004). In the latter case discrimination is ratio-dependent: with a larger ratio numerosities are easier to discriminate. For example, Xu and Spelke (2000) demonstrated that 6-month-olds discriminate differences at a 1:2 ratio (8vs16) but not at a 2:3 ratio (8vs12).

Nonetheless, the claim that small numbers are only processed by object-files is tentative since the successful discrimination of small from large numerosities (Cordes & Brannon, 2009a) and the finding that number discrimination is ratio-dependent regardless of set size (Starr et al., 2013a) are incompatible with this assumption. Moreover, one should acknowledge that young children probably have access to both systems but that the system they rely on might depend on the paradigm that is used (Feigenson & Carey, 2003).

Reviewing literature on small number discrimination three paradigms step into the limelight: the habituation (Clearfield & Mix, 1999; Cordes & Brannon, 2009b; Xu et al., 2005), the manual search (Feigenson & Carey, 2003, 2005) and (only) recently the numerical change detection paradigm (Libertus & Brannon, 2010). Habituation can be described as learning which reflects a changing responsiveness toward reiterated information leading children to less heed stimuli which are repeatedly shown (Bornstein, Pêcheux, & Lécuyer, 1988). The paradigm relies on a preference for novelty (e.g., Colombo & Mitchell, 2009) which is in this case a new number of items. Like the name suggests, the manual search task relies on how children search for a certain amount of objects which are being hidden after presentation (Feigenson & Carey, 2003). Reaching/Searching for objects is an action aimed at retrieving individual objects. Therefore, children are less prone to draw attention on the perceptual features (i.e., size, color, and shape) and give attention to the number of objects (Feigenson & Carey, 2005). Recently, the numerical change detection paradigm was developed by Libertus and Brannon (2010) based on a paradigm initially created by Ross-Sheehy, Oakes, and Luck (2003) to test infants' visual short-term memory. By means of two peripheral offered streams of rapidly changing images (relying on infants' preference for numerical change above constant numerosity) it was modified to test infant's ability to detect numerical changes.

Regarding small number discrimination, the numerical change paradigm is assumed to activate the analogue magnitude system (Starr et al., 2013a), whereas the manual search task would prompt the use of the object-file system (e.g., Barner, Thalwitz, Wood, Yang, & Carey, 2007; Feigenson & Carey, 2003, 2005). Divergent findings on small number discrimination emerge with failure for set size 1vs2 (Xu et al., 2005) and success for 2vs3 (Cordes & Brannon, 2009b) as well as for 1vs3 (Ceulemans et al., 2012), however, leaves the question on which system is triggered by this habituation paradigm unresolved.

The current study tried to further disentangle the role of number discrimination in addition to earlier topic-related studies (Libertus & Brannon, 2010; Starr et al., 2013b). For this purpose, number discrimination was assessed in children at the age of 8 (infants, T1) and 24 months (toddlers, T2) using an age-appropriate task (a habituation and manual search paradigm respectively) at both time points. Up till now, number discrimination studies mostly used habituation tasks in younger infants (mostly aged 6 months up till 10 months; e.g., Cordes & Brannon, 2009b; Xu, 2003; Xu & Arriaga, 2007; Xu et al., 2005) whereas the manual search task was more often used in (older) toddlers (aged 1 to 2 years; e.g., Barner et al., 2007; Feigenson & Carey, 2003, 2005).

Furthermore, in line with Starr et al. (2013b), the following numerical competencies in kindergarten (NCK) were tested with a standardized test battery in these children at the age of 48 months (kindergarteners, T3): (procedural and conceptual) counting, with a more-in-depth test on cardinality, and arithmetic operations. In addition, general intelligence was tested. Items on procedural counting concerned children's ability to perform a mathematical task (LeFevre et al., 2006), whereas items on conceptual counting constituted the understanding of why a procedure works or is legitimate (Bisanz & LeFevre, 1992; Hierbert & LeFevre, 1986; LeFevre et al., 2006) referring to underlying principles of counting (Gelman & Gallistel, 1978). Knowing the meaning of a numeral (cardinality) as one of those principles was highlighted more in particular administering a widely used test on cardinality knowledge. Arithmetic operation exercises prompted the understanding of composition and decomposition of groups by differentiating sets and subsets (i.e., addition and subtraction; Purpura & Lonigan, 2013). As such, administered items within the scope of the current study resembled the respective abilities of counting, numeral literacy, and basic calculation assessed by Starr et al. (2013b). For all these numerical competencies the value as a predictor for later mathematics has been supported (Geary, Hamson, & Hoard, 2000; Powell & Fuchs, 2012).

Three research objectives were formulated. First, it was investigated whether performance on the habituation task (T1) related to NCK (T3). Second, this was examined for performance on the manual search task (T2) and NCK (T3). In other words, were infants' and toddlers' number discrimination performances predictive to later NCK? When a specific relationship between a number discrimination measure and a NCK-measure was significant, it was further explored whether number discrimination still had an additional value when taking into account intelligence. Finally, in the third research objective, it was studied whether number discrimination performance at 8 and 24 months of age was significantly related and could be considered as a stable measure throughout development.

Number discrimination in this study focused on small numerosities. From the age of 2 years onwards, children learn to count by acquiring consecutively the meaning of the first number words (Mix, 2009) in a first stage, which leads them to learn larger number words in a later stage. As such, investigating the predictive value of *small number discrimination* for later mathematics - even from infancy on but certainly at the critical age of 24 months - seemed to be a meaningful addition to previous research on the predictive value of *large number discrimination* (Starr et al., 2013b). Based on the findings of Starr et al. (2013b), it was expected that infant's number discrimination (T1) would relate significantly to NCK (T3). Consequently, number discrimination in toddlerhood (T2) was also expected to relate significantly to NCK (T3), since the assessed number discrimination tasks at both ages - although different in design - are assumed to tap the same ability.

In previous studies small set sizes were mainly investigated with either a habituation or a manual search task (e.g., Cordes & Brannon, 2009b; Feigenson & Carey, 2003, 2005; Xu, 2003). Since the numerical change task has only recently been used in the study of Starr et al. (2013b) to investigate small number discrimination, tasks according to the other two mentioned paradigms took precedence in the current study. Furthermore, in order to make a prediction possible between number discrimination and later outcome, at least some children needed to be able to successfully discriminate the specified numerosities. Accordingly, the small set size with the largest ratio (1vs3) was chosen, since this warranted success with both tasks (Ceulemans et al., 2012; Feigenson & Carey, 2003, 2005).

In addition to previous studies, only providing binary information in terms of success or failure based on one overall task performance (Starr et al., 2013b), this study took into account successes and failures on different test trials of the tasks instead. As such, the study aimed at taking the binary information to a higher level and making it sensitive to individual differences.

2. Method

2.1. Participants (see Table 1)

Participants were part of a large-scale birth cohort living in different Flemish districts in Belgium. This cohort was recruited within the scope of a longitudinal (governmental) study (http://www.steunpuntwvg.be) of which the reported study is only one small part. Children were randomly selected to participate in several cross-sectional studies on number discrimination on which will not elaborated here. Due to practical limitations such as expiration of the project and availability of complete data on small number discrimination it was only possible to follow-up a handful of children until the age of 48 months. As such, parents of 31 (out of 39) children consented to participate with their child at the ages of 8 (T1), 24 (T2), and 48 months (T3).

Table 1

Descriptive Sample Characteristics

		M		*(SD)*
Age (*in months*)				
	8 months (T1)	8.10		(1.16)
	24 months (T2)	23.55		(1.18)
	48 months (T3)	48.42		(0.92)
IQ[a]				
T3		101.33		(12.53)
		Boys (*n*)		Girls (*n*)
Sex				
T1,T2,T3		15		16
		Mothers (*n*)		Fathers (*n*)
Educational level (T1)[b]				
	Primary education	1		0
	Higher secondary education	7		15
	Higher education	23		13
		Low (*n*)[d]	Medium (*n*)[e]	High (*n*)[f]
Family income (T1)[c]		2	13	13

Note. T1 = time point (1) at 8 months of age; T2 = time point (2) at 24 months of age; T3 = time point (2) at 48 months of age; IQ = Intelligence Quotient
[a]Intelligence Quotient retrieved from the Wechsler Preschool and Primary Scale of Intelligence – Third edition (WPPSI-III-NL; Wechsler, 2002; Dutch translation Hendriksen & Hurks, 2009). [b]Information unknown for 3 of 31 fathers
[c]Three families did not disclose information on income. [d]income < €1500. [e]€1501 < income < €3000. [f]income > €3000

2.2. Procedure and measures.

At T1 and T2 number discrimination was assessed. At T3 children's counting, arithmetic operations, and cardinality knowledge were tested. All tasks were part of a broader research protocol. Research was always conducted in a distraction-free room either at '*Child & Family'* services (which have governmental responsibility for guidance and support of young children and families in Flanders, http://www.kindengezin.be) at T1 and T2 or at home (T3). The number discrimination tasks were assessed while children sat on a parent's lap. Parents were instructed to remain neutral and not to elicit attention or communication. NCK-tests were assessed individually, in absence of any parents, in the same order for all children.

Parents signed an informed consent and the study was approved by the ethical commissions of the involved faculties. All test leaders (graduate students) received training in the assessment and interpretation of the tests.

2.2.1. Number discrimination performance (see Table 2).

2.2.1.1. Habituation task.

Children received a number discrimination task (T1) following habituation (e.g., Xu, 2003; Xu & Spelke, 2000; Xu et al., 2005) using one- and three- element arrays of red dots on a white background. Stimuli were controlled for continuous variables (i.e., item size, inter item distance, total item size, and occupied set area) according to the procedure of Dehaene, Izard, and Piazza (2005). The task consisted of a phase aimed at habituating children randomly to one of these arrays using six different displays shown in repeating random order. In a test phase in which six displays contained the habituated and new dot arrays in alternation (counterbalanced for order across participants), longer looking at the novel arrays was considered as an indication of successful discrimination (Xu, 2003; Xu & Arriaga, 2007).

Expanding previous studies using this paradigm (Cordes & Brannon, 2009a; Xu et al., 2005), habituation software (i.e., Habit X version 1.0; Cohen, Atkinson, & Chaput, 2004) was combined with Eye Tracking (ET, Tobii T60; Tobii Technology, 2007). Looking times were coded afterwards from ET data in *Tobii Studio* software (Tobii Technology, 2007) by identifying total eye fixation duration per dot-array. Experimenters and coders were blind to the assigned conditions. Inter-rater reliability between the two coders (r = .97) was good.

Analysis focused on the difference between looking time at the habituated and new number of dots per test trial pair, which is a common practice (e.g., Xu, 2003; Xu & Arriaga, 2007; Xu & Spelke, 2000). This resulted in three difference scores.

One credit was given for each difference score larger than zero in line with the mainly used definition of successful discrimination (e.g., Feigenson & Carey, 2003, 2005; Starr et al., 2013b; Xu, 2003, Xu & Arriaga, 2007) resulting in a so-called *Habituation Success Score* (HSS).

2.2.1.2. Manual search task.

A manual search task presenting a 1vs3 comparison as described by Feigenson and Carey (2005) was administered at T2. A wooden box (25 cm x 12.5 cm x 31.5 cm) had a slit at the front oriented to the toddlers and an opening at the backside oriented to the experimenter who faced the child at an - besides the box - empty table. Parents were told that some balls would be hidden by the experimenter (through the slit in front of the box) to explore how children reacted and that no wrong reaction existed. The task consisted of three kinds of trials as illustrated more in detail in Figure 1: a first *box empty* trial, a *more remaining* trial, and a second variant of the box empty trial which always followed after a more remaining trial.

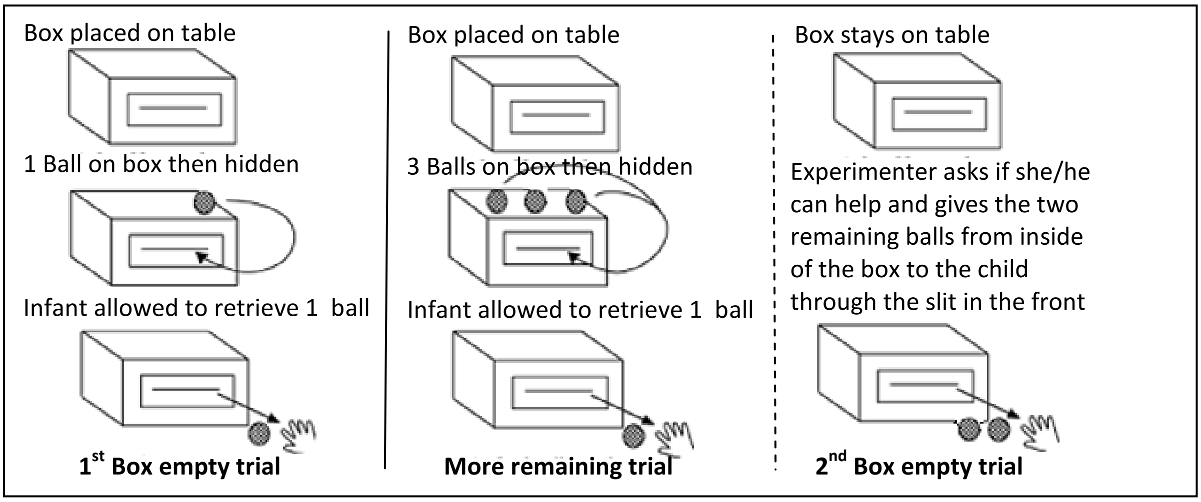

Figure 1. Different trial types of the manual search task. Adopted from "On the limits of infants' quantification of small object arrays," by L. Feigenson and S. Carey, 2005, *Cognition, 97*, p. 301. Copyright 2004 by Elsevier B.V.

Each of the trial types was presented twice and the order of the trials was counterbalanced. Children could search through the slit for ten seconds after each type of trial. It was expected that children would search longer after the more remaining trials than after the box empty trials. This would indicate successful discrimination. Cumulative searching time, was coded manually afterwards using *The Observer XT* software (http://www.noldus.com). Searching was defined as the period during which knuckles of one or both child's hands passed through the slit. Grasping of the slit did not count (Feigenson & Carey, 2003, 2005). Since administration of the search task revealed that children also looked into the box to search for the (supposedly) hidden balls, looking through the split was additionally considered as searching.

Equivalent outcome measures were constructed for the manual search task (T2) as for the habituation task (T1). Subtracting searching time after box empty trials from searching time after more remaining trials resulted in four difference scores. A positive difference score was considered as indicative for success and credited with one point if it was larger than zero, resulting in a so-called *Manual Search Success Score* (MSSS).

Table 2

Description of Number Discrimination Tasks and Related Measures

Tasks	Description	Maximum	Reliability[a]
Habituation Success Score (HSS; T1):	Credit difference score > 0	3	.21
Manual Search Success Score (MSSS; T2):	Credit difference score > 0 Credit difference score > RCI	4	.79

Note. T1 = time point (1) at 8 months of age; T2 = time point (2) at 24 months of age
[a] Reliability of difference scores as measured with Cronbach's α

2.2.2. Numerical competencies in kindergarten (see Table 3).

NCK (T3) were assessed using the counting and arithmetic operations subtests of the *Test for the Diagnosis of Mathematical Competencies* (TEDI-MATH; Grégoire, Noël, & Van Nieuwenhoven, 2004). The psychometric value of this assessment battery was tested on 550 Dutch-speaking Belgian children (Grégoire, 2005) and has proven to be conceptually accurate and clinically relevant. Its predictive value has been demonstrated in several studies (Desoete & Grégoire, 2006; Desoete, Stock, Schepens, Baeyens, & Roeyers, 2009; Stock, Desoete, & Roeyers, 2007). A variant of the *Give-a-Number* task (GNT), designed by Wynn (1990, 1992) and adjusted by Sarnecka and Carey (2008), was used to additionally tap cardinality.

To assess counting (T3), two subtests of the TEDI-MATH (Grégoire et al., 2004) were used. Procedural Counting (PC) knowledge included accuracy in reproducing a counting sequence starting from one (up till 31), counting up to an upper bound (e.g., ‘count to 9’) and/or from a lower bound (e.g., ‘count from 3’). Conceptual Counting (CC) knowledge implied the validity of counting procedures, based on the counting principles of Gelman and Gallistel (1978). Children had to judge the counting of linear and non-linear patterns of objects, and were asked the counted amount of objects (e.g., ‘How many objects are there?’). Furthermore, they had to construct two numerical equivalent amounts of objects and use counting as a problem-solving strategy in a riddle. At last, Arithmetic Operations (AO) were assessed by presenting a series of visually supported additions and subtractions to the children.

In addition, all children were tested with the GNT-variant (Sarnecka & Carey, 2008) to determine whether they knew the exact meaning of numbers (cardinality) from one to six. Children were asked to give N objects to a puppet, followed by the question whether they gave N items. This question was restated, until children answered positively. First, one object, then three objects were asked. After a correct answer, the next request was ‘N + 1’, otherwise ‘N – 1’. Requests continued until at least two successes at N and at least two failures at N + 1.

A credit was given if the child had at least twice as many successes as failures for that numeral. Failure included giving the wrong number of items. Each child's knower level corresponded to the highest number he/she reliably generated. In line with Sarnecka and Carey (2008), children who had at least twice as many successes as failures for trials of 'five' and 'six' were called *cardinality-knowers*, while all others were called *subset-knowers* (Le Corre & Carey, 2007; Le Corre, Van de Walle, Brannon, & Carey, 2006).

Table 3

Description of Tasks on Numerical Competencies and Related Measures

Tasks (T3)	Description	Maximum	Reliability[a]
TEDI-MATH:			
Procedural Counting (PC)	Items on counting sequence	8	.62
Conceptual Counting (CC)	Items on counting principles	13	.76
Arithmetic Operations (AO)	Simple additions & subtractions	6	.73
GNT:			
Cardinality-knowers (n = 13)	Cardinality from number 5 on	6	.82
Subset-knowers (n = 18)	Cardinality below number 5		

Note. T3 = time point (3) at 48 months of age; TEDI-MATH = *Test for the Diagnosis of Mathematical Competencies*; GNT = Give-a-Number task
[a]Reliability of subscale as measured with Cronbach's α

2.3. Analysis

Since graphical inspection revealed no strong evidence against non-normality, parametric tests were conducted. More specifically, because of graphically supported linear trends between outcome and predictors linear regressions were performed in SPSS Version 21.0 (IBM Corp., 2012) to explore the relationship between number discrimination and TEDI-MATH-measures. In case of a significant result a hierarchical multiple linear regression was conducted to determine the additional effect of number discrimination on top of intelligence.

Furthermore, independent sample *t*-tests were conducted to reveal whether cardinality- and subset-knowers (GNT, Sarnecky & Carey, 2008) differed on number discrimination.

3. Results

See Table 4 for an overview of descriptives and intercorrelations of the variables.

Table 4

Summary of Intercorrelations, Means and Standard Deviations for Number Discrimination, Numerical Competencies, and Intelligence Measures

Measure	1	2	3	4	5	6	7	8	9	*n*	*M (SD)*
1. HSS	--									31	1.45 *(0.93)*
3. MSSS	.05	-.21	--							31	2.42 *(1.48)*
5. PC	-.23	.14	.20	-.03	--					31	1.45 *(1.61)*
6. CC	-.13	-.14	.38*	-.03	.38*	--				31	4.39 *(2.70)*
7. AO	-.19	.05	.31^t	-.07	.41*	.57***	--			31	1.97 *(1.80)*
8. Cardinality[a]	-.21	.01	.16	.19	.58***	.49**	.35^t	--			
Cardinality knowers										13	5.69 *(0.48)*
Subset knowers										18	2.50 *(1.04)*
9. IQ[b]	-.24	.14	.11	.36^t	.55**	.53**	.34^t	.59***	--	30	101.33 *(12.53)*

Note. HSS = Habituation (task) Success Score; MSSS = Manual Search (task) Success Score; PC = Procedural Counting; CC = Conceptual Counting; AO = Arithmetic Operations; IQ = Intelligence Quotient
[a]Cardinality- or subset-knower based on score on Give-a-Number task; [b]Intelligence Quotient (IQ) retrieved from the Wechsler Preschool and Primary Scale of Intelligence - Third edition (WPPSI-III-NL; Wechsler, 2002; Dutch translation Hendriksen & Hurks, 2009)
* $p \leq .05$. ** $p \leq .01$. *** $p \leq .001$ ^{t} $.05 < p > .10$

In what follows the results of the analyses, conducted to give an answer on the research questions, are given. A summary of the results can be additionally found in Table 5. Linear regression revealed no significant relationship between infants' *number discrimination* (HSS, T1) and NCK-scores (T3). Furthermore, cardinality- and subset-knowers did not differ significantly (GNT, T3) on their number discrimination in infancy (HSS, T1) as indicated by an independent sample *t*-test.

Table 5

Summary of Linear Regression for Numerical Competencies measured with TEDI-MATH.

	Procedural Counting (PC)				
Variable	*B*	*SE(B)*	*β*	*t*	*p*
HSS	-.40	.31	-.23	-1.28	.211
MSSS	.22	.20	.20	1.09	.286

	Conceptual Counting (CC)				
Variable	*B*	*SE(B)*	*β*	*t*	*p*
HSS	-.37	.54	-.13	-.68	.501
MSSS	.70	.31	.38	2.24	.033

	Arithmetic Operations (AO)				
Variable	*B*	*SE(B)*	*β*	*t*	*p*
HSS	-.37	.35	-.19	-1.05	.302
MSSS	.37	.22	.31	1.73	.094

	Cardinality			
Variable	Cardinality-knowers (*n* = 13)	Subset-knowers (*n* = 18)	*t*	*p*
	M (SD)	*M (SD)*		
HSS	1.23 *(0.60)*	1.61 *(1.09)*	1.24	.225
MSSS	2.69 *(1.60)*	2.22 *(1.40)*	-.87	.391

Note. HSS = Habituation (task) Success Score; MSSS = Manual Search (task) Success Score

Linear regression analysis with the *number discrimination* measure in toddlerhood (MSSS, T2) as a predictor, revealed no significant relationship with PC (T3). For CC and AO, a significant (effect size $r = .38$) and marginally significant (effect size $r = .31$) relationship was found, respectively. Even on top of IQ, a marginally significant effect was found on CC, F_{change} (1, 27) = 3.87, $p = .060$, $\beta = .301$ with $R^2 = .38$ for the full linear regression model.

Furthermore, no significant difference was found between cardinality-and subset-knowers (GNT, T3) on this number discrimination performance (MSSS, T2) as demonstrated by an independent sample *t*-test. Finally, the infants' (T1) and toddlers' (T2) number discrimination measures were not significantly related, $B = .083$, $SE (B) = .296$, $\beta = .052$, $t (29) = .280$, $p = .782$.

4. Discussion

4.1. General Findings

This study aimed to shed light on infants' (T1) and toddlers' (T2) number discrimination in relation to numerical competencies in kindergarten (NCK, T3) and revealed the following main findings. Although no significant relationship could be found between number discrimination in infancy (8 months, T1) and NCK (48 months, T3), the predictive value of toddlers' number discrimination (24 months, T2) for NCK could be demonstrated at least for some NCK: for Arithmetic Operations (AO) and even on top of IQ for Conceptual Counting (CC). Furthermore, number discrimination in infancy (T1) and toddlerhood (T2) did not significantly relate mutually.

The absence of a significant relationship between infants' number discrimination and later numerical competencies in kindergarten was in contrast with number discrimination at 6 months as a predictor of later mathematical abilities in a previous study (Starr et al., 2013b). Starr et al. (2013b), however, not only tested a younger cohort, but also used another number discrimination paradigm, probing moreover large instead of small number discrimination. These three differences in study design could all be responsible for this inconclusive result.

Irrespective of the studied age, the predictive value of number discrimination at T2 (toddler age) for NCK (T3) is in line with the study of Starr et al. (2013b). Not for all investigated NCK the relationship with number discrimination could be confirmed however.

An explanation regarding CC might be found in the higher amount of items on this subtest (compared to the other NCK-subtests). This larger number of items might have resulted in more variability in the score on CC which could have facilitated the detection of a (significant) relationship with toddlers' number discrimination performance. With respect to AO, a possible explanation for its relation to number discrimination, might be found in the items' complexity (in line with Purpura & Lonigan, 2013) being more difficult than the other NCK-items since counting and cardinality are often involved in carrying out these operations (Powell & Fuchs, 2012). A clear theoretical underpinning to explain the results, however, is difficult to achieve. More in-depth research on why specific NCK would relate to number discrimination (and others not) is warranted. Furthermore, also the formats of number discrimination (small vs large) should additionally be compared within this scope.

To recapitulate the findings on number discrimination in infancy and toddlerhood relating to NCK, some explanations can be provided for the pattern of results across T1 and T2. First, small number discrimination at the age of 8 months is possibly not yet stable enough to reliably predict numerical functioning over a period longer than three months (i.e., from 8 to 24 or 48 months of age) in contrast to stable (although large) number discrimination abilities between 6 and 9 months of age (Libertus & Brannon, 2010). Second, the development of number discrimination may bloom in the first half year of life, stabilize and again take a leap at 24 months of age because children start to count and manipulate small numbers to further elaborate their counting skills with large numbers (Mix, 2009). Therefore, it might be more likely to find a significant relationship between number discrimination at 24 months of age and later numerical competencies than with the 8-month-measure. Third, also other factors such as numerical mother-child interactions or educational systems which vary across countries may influence lower or higher number discrimination ability in infancy and/or toddlerhood resulting in different findings throughout childhood or between studies.

Besides the possibility of number discrimination being an instable measure (as outlined in the previous section), no significant (mutual) relationship between infants' (T1) and toddlers' (T2) small number discrimination could also be suggestive for the presumption that the number discrimination tasks used at the different time points trigger a different underlying numerical representation system or simply appeal to different abilities. Assuming that habituation triggers object-files in small number discrimination (although not exclusively or conclusively) and the informed knowledge (Feigenson & Carey, 2003, 2005) that the manual search paradigm does this for sure the first presumption seems less likely. It can alternatively be stated that both tasks appeal to different abilities (and likewise measure different concepts). Cantrell and Smith (2013) questioned the suitability of the manual search tasks for studying small number discrimination because infants' performances may require more than mere discrimination of quantities in these tasks. Infants need to remember amounts and their locations and are required to base behavior on this knowledge. Manual search tasks are therefore more demanding than other discrimination tasks since they also dependent upon visual working memory, object representation, and knowledge of 'more'. This in turn aligns with the notion of the use of the manual search task in infants relatively older than those participating in previously conducted habituation studies (Cantrell & Smith, 2013).

4.2. Limitations and implications

The current study tried to disentangle the role of small number discrimination for later numerical competencies, but some limitations remain to inspire future studies on this topic.

First, the small sample size might explain the marginally significant results. Although, trends can indicate relevant findings, future research needs to incorporate a larger sample. Partly due to this small sample, but especially due to the majority of middle- and high-income-families (see Table 1), the impact of socio-economic status (SES) was not explored.

Based on literature on mathematical abilities with an additional focus on SES, no differences are expected between these subcategories of families, but rather between these two subgroups on the one hand and low-income families on the other hand (e.g., Jordan, Kaplan, Locuniak, & Ramineni, 2007; Jordan, Kaplan, Olah, & Locuniak, 2006). It would therefore be meaningful to include more families with a low SES who - based on income - only constituted a minority of the current sample (see Table 1). This is not surprising as individuals with a higher SES are more likely to participate in scientific research (Burg, Allred, & Sapp, 1997; Galea & Tracy, 2007; Hille et al., 2005) probably because of a greater trust in science and a higher degree of volunteerism (Bak, 2001; Putnam, 1995).

Third, only some competencies were studied, despite the wide range of math related abilities. Taking into account the fact that the current study was part of a broader large-scale project together with the short attention span of young children, (non)symbolic number comparison tasks were for example not part of the test protocol at T3 due to (practical) time constraints. This is in contrast with Starr et al. (2013b) and could have been informative. To illustrate, one may indeed expect to find positive correlations between a non-symbolic performance and number discrimination as the latter situates itself on a non-symbolic level too by relying on internal mental number representations (Feigenson et al., 2004). Nonetheless, the broader the range of studied mathematical abilities, the more insight would be obtained in how predictors relate to different aspects of mathematics later on. As such, it would be worthwhile and recommended to adhere to a multicomponential approach.

Fourth, only the set 1vs3 was investigated, whereas all small set sizes could have provided more insight in (the nature and the role of) small number discrimination. Moreover, although standards for administration of the habituation task (e.g., Xu, 2003; Xu & Spelke, 2000, Xu et al., 2005) were followed, its reliability was low. Including more trials, would therefore be indicated as long as infants' (short) attention-span is taken into account.

Fifth, from the few frequently used paradigms to investigate small number discrimination, the tasks in this study were (chosen to be) age-appropriate resulting in two different paradigms at T1 and T2 making comparison of number discrimination abilities more difficult (yet, not impossible). It seems however crucial for future studies to provide children with both paradigms at the same time point but also across the various time points. Again, due to the short attention span of in particular the children at T1 and the broader research protocol of the large-scale study of which this study was a small part, only one paradigm was chosen to measure number discrimination at each specific time point. Obviously, in a more ideal design multiple paradigms could have been used to assess small number discrimination in the same children at both T1 and T2. Moreover, especially because of questions (concerning reliability or task demands as referred to earlier) raised on the used paradigms, such a multimethod approach could reveal valuable information. Other findings could indeed have resulted from using other tasks to measure small number discrimination, since differences might be caused by the varying number processing system elicited by each task (Feigenson & Carey, 2003).

Despite these limitations, the main implication regarding later NCK is that whereas small number discrimination could not be valued yet as a predictor at 8 months of age, this might be the case from 24 months of age onwards. Following this line of thought, it might be valuable to follow up (clinically) low number discrimination performers in toddlerhood to establish sensitive measures to detect at-risk development of later mathematical problems. Especially for those at higher risk (i.e., siblings of children with a mathematical learning disorder; Shalev et al., 2001) this could be worthwhile. If, moreover, problems might be reduced by providing at-risk children opportunities to improve their skills (Clements & Sarama, 2011; DiPema, Lei, & Reid, 2007; Fuchs, 2011), additional numerical stimulation in toddlerhood might be beneficial. Agencies in support of parenting (such as local parent support consultations, parenting shops, or support centers) might play a sensibilizing role.

4.3. Conclusion

The current study focused on the predictive value of infants' and toddlers' number discrimination for later numerical competencies in kindergarten (NCK). A relationship between toddlers' number discrimination with some NCK could be observed. Several hypotheses may underpin the importance of toddlerhood above infancy such as the stability, development, the format and influencing factors of number discrimination. Nevertheless, the found relationship may inspire future research to follow up toddlers with low number discrimination in order to find out whether at-risk detection in toddlerhood for mathematical problems is already possible.

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Highlights

- No relation infants' small number discrimination and later numerical competencies
- Toddlers' small number discrimination relates to later conceptual counting
- Toddlers' small number discrimination relates to later arithmetic operations
- Infants' and toddlers' small number discrimination do not relate mutually
- Results may inspire follow-up studies in toddlers with low number discrimination