The plural counts:

Inconsistent grammatical number hinders numerical development in
preschoolers — a cross-linguistic study

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Abstract

The role of grammar in numerical development, and particularly the role of grammatical number inflection, has already been well-documented in toddlerhood. It is unclear, however, whether the influence of grammatical language structure further extends to more complex later stages of numerical development. Here, we addressed this question by exploiting differences between Polish, which has a complex grammatical number paradigm, leading to a partially inconsistent mapping between numerical quantities and grammatical number, and German, which has a comparatively easy verbal paradigm: 151 Polish-speaking and 123 German-speaking kindergarten children were tested using a symbolic numerical comparison task. Additionally, counting skills (Give-a-Number and count-list), and mapping between non-symbolic (dot sets) and symbolic representations of numbers, as well as working memory (Corsi blocks and Digit span) were assessed. Based on the Give-a-Number and mapping tasks, the children were divided into subset-knowers, CP-knowers-non-mappers, and CP-knowers-mappers.

Linguistic background was related to performance in several ways: Polish-speaking children expectedly progressed to the CP-knowers stage later than German children, despite comparable non-numerical capabilities, and even after this stage was achieved, they fared worse in the numerical comparison task. There were also meaningful differences in spatial-numerical mapping between the Polish and German groups.

Our findings are in line with the theory that grammatical number paradigms influence the development of representations and processing of numbers, not only at the stage of acquiring the meaning of the first number-words but at later stages as well, when dealing with symbolic numbers.

Keywords: Numerical development; Cross-linguistic differences; Symbolic number comparison; Numerosity-to-number mapping; Grammatical number; Preschoolers

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1. Introduction

Already in toddlerhood and at an early preschool age, a child begins to master the meanings of the first numerals in their mother tongue, referring to exact and symbolically represented numbers (Barner & Bachrach, 2010; Sarnecka, 2014; Spelke, 2017). This allows for going beyond earlier, intuitive systems of non-symbolic number representation, including the system of approximate perception of cardinalities of sets. Understanding this process may be crucial to understanding the origin of the representation of symbolic numbers, which in turn is required for the process of mathematical education — an achievement of the cultural evolution that appears to be one of the pillars of modern civilization. Language is essential at an early developmental stage, both regarding the first numerical meanings, namely number-words, and grammatical number (Barner & Bachrach, 2010; Condry & Spelke, 2008; Le Corre & Carey, 2007; Sarnecka, 2014; see also Baillargeon & Levine, 2016 for discussion, and Gelman & Butterworth, 2005 for a viewpoint on denying the essential role of language). The effects of inter-language differences on numerical processing were also demonstrated in early school age and adulthood (e.g. place-value mapping effect, Moeller et al., 2011). However, whether number-word and grammatical number constructions also affect the key stage of numerical development of mastering counting principles and the first systems of symbolic numerical representations in the period immediately preceding the start of formal mathematical education has rarely been investigated.

Thus, the aim of the current study is to fill this gap. We investigated the role of language during the critical stage of mastering the cardinality principle and the concept of exact, symbolic numbers in preschoolers, exploiting some intriguing differences between Polish and German grammatical number morpho-syntax. Briefly, enumerative sentences in Polish use the common plural syntax for numbers two to four, while those above four use the singular verb, which leads to an inconsistent mapping between quantity and grammatical number; contrastingly, there is no such inconsistency in

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German (this cross-linguistic difference will be outlined further in detail). In our research, we additionally took into account the possible influence of cross-linguistic differences in the grammatical number paradigm on spatial-numerical associations. Spatial mapping of numbers can be an important factor in the early development of the concept of an exact number (Sella et al., 2018; 2019). As the undermentioned research reveals, grammatical number can also influence the expression of spatial-numerical associations, which in turn are believed to be an important aspect of the representation of the numbers used in their processing.

1.1. The role of number-words and grammatical number in numerical development

Children learn the exact meanings of number-words generally between their second and sixth birthdays. While several two- or three-year-old children (especially those associated with the middle class in Western countries) can recite the count-list at least up to 10 and may be aware that the words refer to exact numbers, they often have no idea which specific numerosity is represented by a given word (e.g., Lipton & Spelke, 2005, 2006). The process of learning the exact meanings of the first three or four number-words usually takes more than a year and proceeds step-by-step, with a few months required to master mapping each subsequent number-word onto numerosity (Le Corre & Carey, 2007; Wynn, 1992; see also Cordes & Gelman, 2005). While some models assume that the mapping between number-words and more primitive systems of number representation do not require any additional scaffolding (e.g., Gelman & Gallistel, 1982; cf. Baillargeon & Levine, 2016), the prominent model proposed by Le Corre and Carey (2007; see also Carey, 2010) suggests that this process is much more complex and also involves other linguistic structures such as grammatical number.

According to Le Corre and Carey's model, children can use the grammatical singular/plural distinction to determine the exact meaning of "one" against any larger numeral. Following this initial success in determining the meaning of a number-word, repeated contextual cues allow them

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to master the “two” against “more” distinction a few months later, and subsequently “three” and “four” against “more” over the next few months. This is sufficient to induce two constituent counting principles: the cardinality principle (the last number in the order of counts means size/cardinality of the set) and the successor function (the numeral next to N represents a cardinality of $N+1$). Understanding these principles allows children to overcome the restrictions posed by small number processing, and to induce the exact meaning of any numeral within the child's count-list (although it cannot be ruled out that this process also takes place gradually; Rousselle & Vossius, 2021; Sella et al., 2021)

It has been suggested that human beings, particularly young children (along with several other non-human species) have a separate system for the perception and exact representation of small numerical quantities, which allows parallel individuation of up to three or four visual objects. Numerosities above three or four activate a number-specific, modality-independent approximate number system (ANS) that only provides a rough representation of the number, with the precision of estimation decreasing with set size (scalar variability) and discriminability thresholds conforming to the Weber-Fechner law (Feigenson et al., 2004). The concept of exact numerical values above three or four arises only with cultural, primarily linguistic, numerical symbols. Interestingly, members of societies whose language contains little to no lexical representation of exact numbers have highly restricted abilities when representing and processing *exact* numbers above three, while their abilities of *approximate* numerical estimation and comparison appear to match other cultures (Everett, 2014; Gordon, 2005; Pica et al., 2004; see also Overmann, 2015, for an overview of number-word systems of 903 languages).

The very nature of the linguistic influence during the acquisition of number-word meanings and the process of inducing the successor and cardinality principles are still being debated (Baillargeon & Levine, 2016; Davidson et al., 2012; Huang et al., 2013; Kersey & Cantlon, 2017; Sarnecka et al.,

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2015; Sella et al, 2019, 2021; Spelke, 2017; Syrett et al., 2012; van Marle et al., 2018). However, over the last two decades, impressive evidence has been collected that supports the hypothesis that a clear morphological marking of the plural in a given language bootstraps the learning of the exact meanings of the first number-words (for a review see Sarnecka, 2014). In Sarnecka et al. (2007), English- and Russian-speaking toddlers learned the exact meaning of “one” earlier than Japanese children (as English and Russian have consistent morphological plural markings unlike Japanese). Le Corre et al. (2016) found a similar six-months gap between matched samples of Mandarin-speaking and English-speaking toddlers. This is important since Mandarin is relatively more similar to English than Japanese in some lexical and pragmatic aspects of the number-word system, but like Japanese it lacks clear plural morphology. Li et al. (2009) showed that Japanese- and Mandarin-speaking two-year-olds, like their English-speaking counterparts, discriminate single- and multi-element sets when tested outside a linguistic context in a manual search task. Thus, it is the grammar itself, rather than conceptual knowledge that stands behind these cross-linguistic differences. Additionally, Almoammer et al. (2013) demonstrated that children who acquired languages with grammatical number systems containing not only a singular and plural, but also a dual category (Slovenian and Saudi Arabic) achieve the “two-knower” level a few months earlier than those whose mother tongue only has a singular/plural distinction (here, English). However, such linguistic variability does not seem to influence the developmental time of inducing the counting principles (Sarnecka, 2014; but see Ceylan & Aslan, 2018, who report delayed induction of the cardinality principle, and even subsequent stages of subset knowledge in Turkish-speaking children; Turkish has regular plural, but in enumerative sentences the noun is always singular). Indeed, the majority of cross-linguistic studies to date have compared grammatical variations relevant to very small numbers (singular vs. dual vs. plural). Thus, the question remains

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whether grammatical number may also influence the process of inducing counting principles or even, numerical development at a later stage.

1.2. Early stages of numerical development: the distinction between subset-knowers, CP-knowers, and CP-mappers

Establishing an appropriate relationship between the exact meanings of number-words determined through the counting procedure and those roughly represented in the ANS requires some additional development beyond inducing the counting principles. Depending on the stage of development of the exact number representation and its relation to the primitive systems, children may be classified as “subset-knowers” or “CP-knowers” (where “CP” stands for “counting principles” or “cardinality principle”; Le Corre & Carey, 2007). Subset-knowers know some exact meanings of number-words up to four (“one-knowers”, “two-knowers”, etc.), while CP-knowers know the exact meanings of number-words beyond four, though not all of them are able to map between counting procedure output and approximated numerosity provided by the ANS (“CP-knowers-non-mappers”). Most studies with the Give-a-Number procedure (Wynn, 1992; Le Corre & Carey, 2007) show that after reaching the limit of three or four, children induce the cardinality principle and successor function within a few months, which allows them to generate exact values for large numbers at least in the range of up to 10, and often much larger (but see Rousselle & Vossius, 2021, and Sella et al., 2021, for suggestion of a more gradual process). However, only a few months after inducing counting principles, children establish a correspondence between number-words and the ANS, reaching the stage of “CP-knowers-mappers”. The difference between CP-knowers-non-mappers and CP-knowers-mappers is subtle but important; both are able to accurately provide a given number of units within the scope of their knowledge of the count-list. However, CP-knowers-non-mappers fail when asked to quickly estimate the number of objects in the range of 6–10 without counting (Le Corre, 2014). The Give-a-Number procedure allows for distinguishing between the “subset-

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knowers” and “CP-knowers” with some level of uncertainty in the case of “four-knowers” and “five-knowers” (cf. Lee & Sarnecka, 2011; Krajcsi, 2021; Krajcsi et al., 2018; see also Marchand et al., 2022; O'Rear et al., 2020; Rousselle & Vossius, 2021). This task is, however, itself not sufficient to discriminate between CP-knowers-non-mappers and CP-knowers-mappers, since it only reveals a child’s understanding of the counting principles. One may adopt the heuristic that children at the intermediate stage (“non-mappers”) are more likely to make a few errors in this task, and thus finish the procedure with a lower N score, which seems reasonable but unwarranted. Indeed, most CP-knowers-non-mappers can count a set’s elements without error. To better discriminate between mappers and non-mappers, Le Corre and Carey (2007; see also Le Corre, 2014) proposed another procedure: the “fast cards task”. Here, the experimenter shows a card with a visual set of items (circles, dots, etc.) and asks how many items there are, not allowing counting. Since some level of estimation error is inherent to the ANS, CP-knowers-mappers would not be expected to be able to accurately estimate the numerosity. It is expected, however, that the mappers, but not non-mappers, exhibit a positive regression slope between the mean estimate and actual N. Non-mappers, if not allowed to count, choose random number-words above four for numerosities in the range 6 - 9, which results in slopes close to zero, and mean estimates of around seven. It is worth mentioning that the dependence of the ability of mapping between approximated numerosities and number-words on the mastery of the cardinality principle is not obvious and perhaps this ability begins to form just at the subset-knower stage (Gunderson et al., 2015). Nevertheless, the connection between the knowledge of counting principles (assessed with Give-a-Number task) and the efficiency of the ANS seems to be an important issue associated with the preschool development period. Mussolin et al. (2014) showed that both of these factors, measured at 3–4 years of age, predict proficiency of manipulating verbal and Arabic numerals 7 months later. Furthermore, Libertus (2015) reviewed research documenting the importance of the interplay of

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early symbolic and non-symbolic (approximate) numerical representation systems in preschool for mathematical achievement in early school education. One of the most popular models of neural underpinnings of numerical representations - Dehaene's triple code model (Dehaene et al., 2003), assumes that the semantic representation of a number was built based on early, approximate representations of numerical quantities. Testing the role of language in this process can, therefore have significant theoretical and practical implications.

1.3. The interrelations between grammatical number, the spatial representation of numbers, and number and numerical order processing

Grammatical number not only influences the ease of number acquisition and processing per se, it can additionally influence the nature of the spatial representation of numbers. This may also be important in a developmental context. Over the past several years, an increasing body of work has shown that in learning the numeral meanings the ordinal aspect, which can be associated with mapping numbers to spatial dimensions, plays an important role (Reynvoet & Sasanguie, 2016; Lyons & Beilock, 2011, 2013; Sella et al, 2018, 2019, 2020; see also Brannon & Van De Walle, 2002; Libertus, et al., 2014; Spaepen et al., 2018). In adults, the robustness of the spatial representation of a number and its association with cultural-linguistic variables has been demonstrated in the form of the SNARC effect (Spatial-Numerical Association of Response Codes; Cipora et al., 2019b; Dehaene et al., 1993). In Western cultures, respondents react faster to small numbers with the left hand and to large ones with the right hand, even if the magnitude is irrelevant for the task (e.g., if participants are asked to respond to the parity of the numbers). A similar effect, the MARC effect (linguistic Markedness of Response Codes, i.e., left-/right-handed advantage when responding to odd/even numbers, respectively; Nuerk et al., 2004) was also found for parity judgments, which may generalize onto other marked linguistic distinctions. Indeed, Roettger and

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Domahs (2015) demonstrated the grammatical SNARC effect — faster left-handed responses for singular nouns and right-handed responses for plural nouns).

Another aspect of spatial-numerical associations is the mapping of numerical orders to spatial orders. The importance of numerical orders and their mapping onto space was demonstrated in children at the stage of mastering the meanings of numerals (McCrink et al., 2017; Opfer et al., 2010; Opfer & Furlong, 2011; Van Rinsveld et al., 2020). For instance, it has been shown that number line estimation in preschoolers is correlated with numerical order knowledge (Berteletti et al., 2010). Additionally, Le Corre (2014) showed that only CP-knowers-mappers (but not non-mappers) can reliably answer the question about ordinal relations between numbers in the range of 5–10. This suggests that the relation between the order of linguistic count-list and the order of numerical magnitudes may not be obvious to children who have just mastered the counting principles. In the same vein, Sella et al. (2017) divided preschoolers into those who did not master the cardinality principle, those who mastered the cardinality principle but were unable to consistently map numerical quantities onto space, and those who mastered both skills. Only the latter succeeded in the task of comparing numerical magnitudes expressed in Arabic numerals. Essentially, spatial associations of numerical magnitude and order may play an important role in preschoolers and are related to their numerical skills, while they may be partly shaped by language — therefore, we have also included this aspect of numerical processes in our study.

1.4. The specificity of the Polish grammatical number paradigm and its possible role in numerical development

In many Slavic languages, different morpho-syntactic agreement patterns are used to generate typical enumerative sentences, such as “there are N [number] Xs [objects]”, depending on N.

Typically, Slavic syntactic constructions alternate between numerals up to four and numerals from 5–10 (Franks, 1994). Specifically in Polish for numbers from 2–4 (and then for multi-digit numbers

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above 20 with the units from 2–4), the noun is used in plural in the standard nominative case, while for numbers from 5–10 (and also for the teens), the enumerated noun comes in plural in the genitive case, which is characteristic of mass-noun syntax (in some cases, grammatical gender is altered as well). While enumerative sentences containing numbers 2–4 use a plural verb and nominative-plural noun inflection (“Tam są/leżą/dojrzewają cztery jabłka” — *there are four apples/four apples are lying/four apples ripen there*), sentences containing numbers 5–10 use a singular verb and the noun in plural-genitive (“Tam jest/leży/dojrzewa pięć jabłek” — *there is five of apples/five of apples is lying/ripen there*). The affinity of this construction to the psychological distinction between the small versus large number ranges in numerical cognition and to the development of numerical representations (as discussed above) appears to be persuasive. However, semantic and syntactic aspects of this construction are still being debated by linguists (Derwojedowa et al, 2003; Franks, 1994; Przepiórkowski, 2004; Świdziński, 2004; see also Overmann, 2015, for a general review).

There is some (although sparse) evidence that such a general class of syntactic distinctions may lead to significant differences in the processing of numerical information (so far, however, observed only in monolingual studies). Syrett and Musolino (2013) studied two possible interpretations of enumerative sentences in English (e.g., “Two boys push a car”): collective (two boys push the same car) and distributive (each of the two boys pushes his individual car). Three- and four-year-olds were able to acquire both types of meanings, but (in contrast to adults) clearly preferred the distributive meaning, which seems to better support the individuation and enumeration of set elements. Moreover, Odic et al. (2018) studied the distinction between count- and mass-nouns in adults. They found that the precision of count-noun quantification corresponds to the precision of the number processing system, while the precision of mass-noun quantification corresponds to the precision of the assessment of the surface area. This suggests the activation of different

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quantification systems depending on grammatical category (numerical quantification in the case of count nouns vs. non-numerical quantification in the case of mass-nouns).

Another issue is that in Polish declension, morphological markers of plural nouns may be ambiguous due to syncretism: The same endings can appear both in the singular and plural in different cases. This, perhaps, draws more attention to the verb as an indicator of a grammatical number, which may also lead to inconsistent interpretations, as we have shown above. As some studies have demonstrated, this syncretism leads to certain problems with the processing of the numerical information carried by these words even in adults (Gulgowski & Błaszczak, 2018).

Thus, the Polish grammatical number paradigm provides partly ambiguous hints about numerical quantities above four. In terms of number-to-space mapping, the singular of a verb in enumerative sentences containing (unit) numbers above four, aggravated by the syncretism of a noun's grammatical number and case affixation, can lead to opposite effects of numerical SNARC and grammatical SNARC. Additionally, some of the aforementioned studies allow us to speculate that the Polish syntax associated with numbers above four (genitive-plural noun combined with singular verb form) can lead to a preference for a collective interpretation, which does not encourage the individuation and exact enumeration of the set's elements. During development, this may lead to a delayed mapping between number-words and numerical quantities at the stage of inducing the counting principles and mapping number-word meanings onto approximate numerosities. Finally, first evidence of the influence of the specificity of the Polish plural on spatial-numerical associations in adults has been found (Cipora et al., 2019a).

1.5. Research questions and hypotheses

Assuming that the grammatical number paradigm of the child's language is a main scaffold for acquiring the meanings of numerals, one should expect significant differences between Polish and German children at the stage of mastering the counting principles and mapping between numerals

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associated with numbers above four and their approximate representations. It seems that the specificity of the Polish grammatical number system can have certain important consequences, which guided our research questions and hypotheses, stated below:

1.5.1. Difficulties in passing the boundary of four

The lack of a consistent mapping between the grammatical number of the verb (i.e., singular) and quantities larger than four in enumerative sentences may hinder passing the boundary of four in the development of number-word meanings, which was indicated in earlier works to be the moment of mastering the counting principles, and thus, constructing accurate meanings for numbers outside the scope of subitizing. This effect can be additionally augmented by the "mass-noun-like" or collective form (genitive case) of the noun, which does not encourage individuation and enumeration of the set's elements above four. Therefore, it can be hypothesized (H1a) that in the same age ranges, there will still be a significantly higher proportion of subset-knowers among Polish children than among German ones (or any other language groups in which mapping between grammatical number and numerical quantity is consistent). The mass-noun-like syntax may make it additionally difficult to map numerals to quantities (cf. Odic et al., 2018), which would also result in a delayed subsequent transition to the CP-knowers-mappers stage (H1b).

1.5.2. Worse performance for larger symbolic numbers

The non-numerical (mass-like) syntax for larger numbers can generally make access to quantities represented by numerals more difficult (H2), and thus can impede performance in tasks that require a direct reference to the quantities above four, such as comparing two numbers (H2a) or mapping set numerosities onto number-words, revealed in a lower slope of the regression between estimated and actual numerosity (H2b). Although these effects can be expected at any stage of development, they will probably weaken as the understanding of number and counting principles (and general numerical skills) improve. As shown by neuroimaging and behavioral studies, symbolic

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representations of numbers begin to function independently of the ANS along with development, from an early school age or even earlier (cf. De Smedt et al., 2013; Lyons et al., 2015; see also Lussier & Cantlon, 2018 for overlapping neural correlates). However, at the CP-knowers-non-mapper stage, a child only establishes the relationship between the counting outcome (cardinal number) and the non-symbolic numerosity representation (Le Corre, 2014), and therefore, this effect may be the strongest at this stage. It is not clear to what extent the mapping test can be applied to subset-knowers, as it can require an understanding of ordinal relations for number-words and numerals above 5 (for discussion see: Gunderson et al., 2015; Le Corre, 2014; Lipton & Spelke, 2005; Odic et al., 2015; Sella & Lucangeli, 2020; Sella et al. 2020). Therefore, H2b will be tested both in the whole sample and in the CP-knowers subgroups.

1.5.3. Benefits for cross-range comparisons

In the Polish paradigm of grammatical number not only the transition between one and more, but also the transition between four and more corresponds to a salient change in grammatical marking. Consequently, comparing numbers from the 2–4 range with numbers from the 5–10 range may be facilitated in Polish children (compared to German ones), at least partially eliminating the effect of the previous factors. Nevertheless, here, the opposite is also possible: the singular verb used in the enumeration of "large" numbers, and the plural for "small" numbers could cause difficulties in comparing numerical quantities between these ranges. Thus, two opposite hypotheses are possible: (H3a) Different grammatical number categories may facilitate symbolic comparisons between numbers in small and large number ranges in Polish children, and alternatively (H3b), since grammatical number is inconsistent with number magnitude (plural for 2–4, singular for 5–9), it might create additional interference, leading to a worsening performance.

1.5.4. Other possible indirect influences of grammatical number — Ordinality and spatial mapping

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The impact of morpho-syntax on the acquisition of numerical symbols may also be more indirect. As we previously argued, not only does quantity play an important role, but so does the ordinal aspect, which can be related to mapping numbers and spatial dimensions. A few recent studies have shown some subtle differences in this regard, comparing Polish-, German-, and English-speaking adults (Cipora et al., 2019a; Heubner et al., 2018). Above we had also discussed studies that showed a developmental relationship between mastering the cardinality principle, understanding numerical orders, and mapping between number and spatial orders. Considering these sources of evidence, one may speculate that if grammatical number inflection is a cue to numerical ordinality, then (H4) an interaction of the spatial arrangement of numbers, language, and numerical range is to be expected. The specificity of the Polish grammatical number paradigm may disturb the mapping between numerals and spatial order, as there is trade-off between the numerical SNARC effect (common for Polish and German: small numbers mapped to the left, large numbers mapped to the right) and the grammatical SNARC effect (reversed in Polish: singular, linked to large numbers, to the left, plural, linked to small numbers, to the right). This trade-off can lead to cancellation of spatial-numerical mapping, but also impaired numerical comparison in a situation where these effects are in conflict. This is expected mostly at the CP-knower-non-mapper stage, that is, in the period when the relations between symbolic representations of numbers and space are just emerging (McCrink & De Hevia, 2018; Sella et al 2019), and when linguistic information may be the only source of spatial-numerical associations in symbolic tasks because the child is not yet able to map symbolic quantities to non-symbolic ones. Cross-linguistic effects related to spatial mapping should apply to those numerical ranges in which contain numbers above four, and should not be visible in the range up to 4.

2. Methods

2.1. Participants

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Two hundred seventy-four monolingual, three-to-six-year-old children were recruited, including 123 German speakers from 19 kindergartens in Tübingen (Germany) and 151 Polish speakers from three kindergartens in Warsaw (Poland). Participants were recruited for a larger project on the role of language differences in mathematical cognition. Of this sample, 120 German children (53 female; age range 3.02–6.76, $M=5.04$, $SD=1.00$ years) and 150 Polish children (77 female; age range 3.41–6.93, $M=5.09$, $SD=1.02$ years) completed the first session, including the Give-a-Number task, allowing for their classification as subset-knowers or CP-knowers; only these children were included in subsequent analyses. There was no significant age difference between the German and Polish groups ($t(268)=-0.43$, $p=.67$).

Written informed consent was collected from the parents of all children participating in the study. Additionally, each child was verbally asked if they agreed to participate and was allowed to resign at any time during the experiment. Moreover, if the experimenter observed that a child felt uncomfortable, they were obliged to terminate the experiment or propose some rest. The procedures were accepted by each researcher's respective ethics committees of the Faculty of Psychology, at the University of Warsaw, and the University of Tübingen, and conformed to the requirements of the Declaration of Helsinki.

2.2. Materials and procedures

Testing consisted of two sessions, both lasting about 20-30 minutes, each with four or five tasks. In the first session, a child's knowledge of the count-list was initially tested. The child was then examined with the Give-a-Number procedure and two tests of working memory (Digit span and Corsi blocks). In the second session, the child was tested with the quick numerical estimation task (modelled after Le Corre & Carey, 2007, "Fast cards"), followed by the test of their knowledge of Arabic numerals, after which they performed two tasks: non-symbolic and symbolic comparison of numerical quantities. Finally, a simple handedness test was conducted. Below we describe the

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procedures of those tasks, the results of which are included in the current report. Results of the non-symbolic numerical comparison task, however, will be reported in a separate paper. The children were examined individually in their respective kindergartens in a separate, quiet room. The computerized tasks (the magnitude comparison tasks and quick numerical estimation task) were designed in E-Prime 2.0 software (Psychological Software Tools, Pittsburgh, PA, USA) and presented on a 14" Lenovo Yoga 700 laptop equipped with a touch screen, running on Windows 10 OS at 1920×1080 pixels resolution. The children were rewarded with stickers after completing each task.

2.2.1. Session 1

2.2.1.1. Count list

Each child was first asked to recite the count-list. Children were allowed to count up to 20 before being asked to stop. The child's score was considered the highest number they reached with one mistake at most (like swapping neighboring number-words). In our analyses, however, we use the index reduced to 10 because no numbers above 10 were used in any of our tasks, which seems to be a more important factor than the size of the individual count-list above this limit (Barth et al., 2009; Davidson, 2012). On the other side Polish and German pre-school math curricula differ in the scope of teaching counting in the last kindergarten section (Polish kindergartens 1-10, German 1-20). We refer to this difference further in discussion. If the child did not start counting, they were prompted by the experimenter with "one, two..., what goes then?".

2.2.1.2. Give-a-Number

In the Give-a-Number task, a child was asked to "feed" a puppet with N plastic strawberries. After "feeding" the puppet, the experimenter asked the child to confirm if there were indeed N strawberries. When $N > 4$, the child was encouraged to count the strawberries in a produced set. If the child succeeded in stating N , they were asked to give the puppet $N+2$ strawberries (following

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the procedure of Patro & Haman, 2012); otherwise, the child was tested for $N-1$. The procedure started at $N=2$ and ended at either $N=10$ or when the child failed at $N+1$ twice, having twice succeeded at N . The highest N with which the child succeeded twice was the final score.

2.2.1.3. Corsi blocks

After the Give-a-Number, a child performed the Corsi block-tapping task (Farrell Pagulayan et al., 2006) to evaluate spatial working memory capacity. An experimenter touched blocks at approximately one block/second in a predefined order. If the child succeeded in repeating a sequence of length N twice, they proceeded with a sequence of length $N+1$ (up to nine). If a mistake was made, one more trial was conducted with N . The task was stopped after two out of three failed trials with a given N . The last sequence length (N), in which the child succeeded at least twice, was the final score. Note that only forward Corsi block-tapping was administered, which minimizes the executive aspect of the task and focuses on memory.

2.2.1.4. Digit span

To assess a child's ability to memorize a number sequence (verbal working memory), a digit span task was used (Gathercole, 1995). The task was performed analogous to the Corsi blocks task.

Numerals in the range of 1–9 organized in predefined sequences of different lengths were used. An experimenter spoke at approximately one number-word/second. If the child succeeded in repeating a sequence of length N twice, they proceeded with a sequence of length $N+1$. If a mistake was made, one more trial was conducted with N . The task was stopped after two out of three failed trials with a given N . The last sequence length (N) in which the child succeeded constituted the final result. Only the forward version was used.

2.2.2. Session 2

2.2.2.1. Quick numerical estimation

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To differentiate between mappers and non-mappers, a computerized procedure was used, modelled on the “Fast cards” task (Le Corre & Carey, 2007; Le Corre, 2014). Sets of red dots of varying sizes within a circle of diameter 300 pixels were displayed. An experimenter first explained that they were cherries on a plate, and that the child’s task was to quickly guess how many there were without counting. The stimuli were generated using the script designed by Gebuis and Reynvoet (2011), in order to control for non-numeric (spatial) parameters. There were 27 test trials, arranged in three blocks of nine trials each. Each block consisted of sets ranging from 1–9 elements in a random order. The blocks differed in the initial parameters of the spatial characteristics of the sets in Gebuis and Reynvoet’s (2011) algorithm. Test trials were preceded with practice trials. In the first practice trial, a ten-element set was shown to convince the child that the number cannot be read directly without counting, and thus, must be guessed (estimated). In the second practice trial, the child was tested with the easiest single-element set (however, with spatial properties different from the test trials). The 27 test trials were subsequently administered; each set was displayed for 5s and then replaced with a blank screen allowing an additional 5s for a response. This was a relatively long time, but if the child began to count the dots, they were reprimanded by the experimenter to answer immediately. All such cases were recorded in the study protocol. The child’s answer was entered into the computer by the experimenter, using a remote keyboard, before the next trial was started.

For the purposes of the current study, we computed the unstandardized slope of the regression between the estimated and actual numerosity for numbers in the range of 6–9. A positive slope (above 0,3) in this range indicated that even if the children perceived only the approximate sizes of sets, they were able to map these magnitudes onto the order of numerals (cf. Le Corre, 2014).

2.2.2.2. Arabic digit knowledge

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To test their knowledge of Arabic digits, the children were presented with printed cards of the numbers 2–9 in a random order. The number ‘1’ was used to explain the task. An experimenter asked a child if they knew what this symbol meant, and if the child could not give a generally correct answer (e.g., "Number", "This is a digit", "How many are here", "One", etc.), the experimenter explained that it was a digit representing “one”. This was followed by the statement “Do you know other digits? I’ll show you some digits, and you’ll tell me, if you know what number it is. OK?”, after which the child was shown subsequent cards and asked what number it was. The number of correctly named digits yielded the child’s score.

2.2.2.3. Symbolic number comparison task (combined spoken number-words and Arabic digits)

In the symbolic number comparison task, a child was asked to observe a screen which displayed two circles with Arabic digits within each (range 2–9). The numbers were inscribed in a circle (“plate”) with a diameter of 300 pixels, the center of which was located at halfway of the screen’s length and either a quarter or three-quarters of its width, respectively. The presentation of digits was accompanied by a prerecorded audio file being played, presenting an appropriate number-word, while the “plate” was surrounded by a frame (see Figure 1). Each digit was highlighted twice in the order ABBA or BAAB, with the first element of the sequence randomly determined. This dual format of presentation was used to allow those children who were not yet familiar with Arabic numerals to complete the task as well. The presentation lasted 5s, after which the child had to touch either a larger or smaller number, depending on the experimental condition.

There were two conditions in a between-subject design. Half of the children were asked to touch the larger number and the other half the smaller number. There were 18 trials: six with small number pairs (2-3, 2-4, 3-4), six with large number pairs (5-8, 5-9, 6-8), and six cross-range trials (3-5, 3-6, 5-8); each pair was shown twice with an altered spatial order. Instead of using all possible pairing combinations, we matched the sets based on their numerical ratio. Each pair within each range

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represented a numerical ratio of varying degrees of difficulty, with numerical ratios as close as possible between the ranges ($M=0.64$ for both small and large numbers, and $M=0.59$ for cross-range comparison). Once the child touched the screen, the next trial was immediately displayed. Screen coordinates X and Y of the child's touch were recorded and ascribed to one of the response options or classified as “missed” (out of any option area extended by 10% in each direction to compensate for imprecise touch). The number of correct choices (broken down into a numerical range and the side on which the correct option appeared) constituted the child's score. Test trials were preceded with three practice trials during which the experimenter introduced the task with two numbers not used in the test: ‘1’ and ‘10’.

Figure 1. Screen layout presented to children in the symbolic number comparison task. After 1s of a still image, each number was twice surrounded for 1s by a frame and its auditory form was played from a computer loudspeaker in ABBA or BAAB order (A representing the left digit and B the right). The presentation was displayed for total of 5s and was then frozen.

2.2.2.4. Handedness

To test a child's handedness, we asked them to perform three actions: draw a circle (on a horizontally oriented piece of paper with a pen placed vertically above it along the midline), throw a paper ball to an experimenter, and pretend to eat with a plastic spoon. The hand that was used most often was considered dominant. This simple test was previously used in a study by Patro, Nuerk,

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and Cress (2015) and had shown an impact on spatial processing of numbers. Sixteen children (5 German, 2 non-mappers, 3 mappers; 11 Polish, 3 subset-knowers, 4 non-mappers, 4 mappers) were classified as left-handed. Thirteen of them (5 German, 8 Polish) were consistently left-handed. Since their results in the main tasks (numerical comparison and quick numerical estimation) did not differ significantly from the rest of the sample (all t values < 1 , independent sample t -tests with separate estimates of variances for non-equal group sizes), this variable was not further analyzed.

3. Results

3.1. Assessing the counting principles (CP) knowledge level

In our study, 120 German and 150 Polish children completed the first experimental session, including the Give-a-number task, which allowed for their classification into subset-knowers and CP-knowers. The procedure proposed by Le Corre and Carey (2007) was modified marginally and adapted for this study's purpose. Those children who obtained a score of 5 or lower in the Give-a-number task were classified as "subset-knowers", those who scored above 5 but estimated the numbers in the 6–9 element sets poorly in the quick numerical estimation task (unstandardized slope in the best-fitted regression equation below 0.3) were classified as "CP-knowers-non-mappers", while those with a score above 5 in the Give-a-Number who also showed a regression slope of at least 0.3 were classified as "CP-knowers-mappers". It should be noted that the vast majority of children in the latter category achieved the maximum score in the Give-a-Number; only one Polish child scored 8, and one Polish and one German child each scored 6.

A Give-a-Number score above 5 is a conservative criterion for recognizing a child as a CP-knower. However, this criterion has been frequently used in previous studies (e.g., Le Corre & Carey, 2007; Le Corre, 2014; Odic et al., 2015; Cheung et al, 2016) and is based on the observation that the responses of subset-knowers for numbers above four are not completely random. In particular, providing the next element of the count-list as the first numerosity above the mastered range of

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counting is quite likely (Sarnecka & Carey, 2008; but see Geary, 2018; Geary et al., 2018).

Moreover, the counting principles induction process itself, which takes several months, does not have to be "all-or-none", but may gradually extend the meaning of counters above four before it is fully generalized (O'Rear et al., 2020; Rousselle & Vossius, 2021). It should be noted, however, that only two German and four Polish children obtained a score of 5 in the Give-a-Number; an additional analysis showed that reclassifying them as CP-knowers did not substantially change the pattern of results.

The results of the classification in terms of the level of CP-knowledge mastery are presented in Table 1.

	German children total N=120	Polish children total N=150
Subset-knowers	17 (7 female)	36 (20 female)
Mean age (years)	3.69	4.22
Range	3.02–5.78	3.41–6.30
SD	0.66	0.68
CP-knowers	103 (46 female)	114 (57 female)
Mean age (years)	5.28	5.37
Range	3.45–6.76	3.44–6.93
SD	0.85	0.94
CP-knowers-non-mappers	43 (17 female)	38 (17 female)
Mean age (years)	5.10	4.97
Range	3.51–6.61	3.44–6.86
SD	0.85	1.01
Magnitude comparison task passers	41	36
CP-knowers-mappers	57 (27 female)	63 (32 female)
Mean age (years)	5.44	5.59
Range	3.45–6.76	3.54–6.93
SD	0.84	0.82
Magnitude comparison task passers	56	62
Quick numerical estimation task passers	112	133

Table 1. Demographic data of the German and Polish groups after classification in terms of CP-knowledge mastery level

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It should be noted that among 217 children classified as CP-knowers on the basis of Give-a-number, only 100 German and 101 Polish children passed the quick numerical estimation task and could be qualified to the CP-knower-mapper and CP-knowers-non-mapper categories. Only these children were included in the calculations where this classification was relevant. Also, not all children successfully passed the magnitude comparison task, which we refer to later in the text.

3.2. Comparison of the proportions of subset-knowers CP-knowers-non-mappers and CP-knowers-mappers ratio between the German and Polish samples (H1 test)

To verify the hypothesis about the delayed induction of the counting principles in the Polish compared to German children (H1a), we compared the proportions of subset-knowers and CP-knowers in the Polish and German samples, demonstrating that the difference was significant (17/120, i.e., 14.2% in the German sample, 36/152, i.e., 23.7% in the Polish sample; $p=.024$, one-tailed Fisher's exact test). We further compared the average age of the German and Polish subset-knowers; here too, the difference was significant ($M_{PL}=4.22$, $N=36$, $M_{DE}=3.69$; $N=17$, $Z=-3.06$, $p<.002$, one-tailed Mann-Whitney test; non-parametric test was used due to the large disproportion in N and variance between Polish and German subset-knower samples). This difference was observed despite the distribution of age of the German and Polish children in the entire sample generally being equal. Importantly, the difference in CP-knowledge level cannot be accounted for by factors such as working memory or knowledge of numerical symbols. Polish and German children in the age range from which all German subset-knowers come from (up to 4.10 years), do not differ significantly in the level of any of the control variables (Corsi blocks, $M_{PL}=2.14$, $M_{DE}=1.84$, $t[58]=1.03$, $p>.3$; Digit span $M_{PL}=2.91$, $M_{DE}=2.76$, $t[58]=0.6$, $p>.5$); count-list knowledge, $M_{PL}=6.94$, $M_{DE}=7.38$, $Z=-0.20$, $N_{PL}=35$, $N_{DE}=29$, $p>.8$; Arabic digit knowledge, $M_{PL}=3.94$, $M_{DE}=2.97$, $t[62]=1.11$, $p>.25$), and variances of these variables also were equal in both linguistic groups (except for count-list knowledge, therefore nonparametric Mann-Whitney test was

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used in this case). Nevertheless, a substantial proportion of Polish children at this age did not yet reach the CP-knower level. Significant differences in terms of these variables were also not found in the entire sample (distributions of control variables for both groups of CP-knowers are visualized in Figure 2).

More importantly, we constructed a forward stepwise logistic regression model with CP-knowledge level (subset-knowers vs. CP-knowers) as the dependent variable, and age, both working memory measures (Corsi blocks and Digit span), count-list span (reduced to 10), Arabic digit knowledge, and country (language) as predictors. The final model included age (Wald's stat. = 14.15, $p < .001$), count-list span (Wald's stat. = 14.07, $p < .001$), Arabic digit knowledge (Wald's stat. = 25.39, $p < .001$) and country (Wald's stat. = 6.39, $p < .02$; see Appendix A for the model parameters). While the presence of age and the knowledge of digits and count-list (which are strongly correlated with age) in the model is obvious, the significant contribution of the country (language) factor after controlling for other variables is an argument in favor of the hypothesis about the delayed induction of counting principles by Polish kids. This model also obtained the lowest value of the Akaike information criterion (AIC), that is, it loses the least information among all combinations of factors (it should be noted, however, that the differences in the AIC values between the best-fitting alternative models are so small that it does not provide a basis to reject them).

Contrastingly, the hypothesis that Polish children also find it more difficult moving from the CP-knower-non-mapper to CP-knower-mapper stage (H1b) was not confirmed. The proportion of CP-knower-mappers was only slightly lower in the Polish than in the German sample among fully classified children (46% vs. 49%). There was no significant difference between the German and Polish children in the proportion of non-mappers and mappers (two-tailed Fisher's exact test, $p = .47$). Furthermore, the average age between Polish and German children in the mappers and non-mappers groups did not differ significantly (Non-mappers: $M_{DE} = 5.10$, $M_{PL} = 4.97$, $t[79] = 0.63$, $p > .5$;

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Mappers: $M_{DE}=5.44$, $M_{PL}=5.59$, $t[119]=-0.97$, $p>.3$). These results are consistent with the theoretical claim that the grammatical differences between the Polish and German children hamper the induction of counting principles, but not a further transition from the CP-knower-non-mapper to CP-knower-mapper stage.

Figure 2. Distribution of control variables in the German (DE) and Polish (PL) samples with their classification into CP-knowers-mappers and CP-knowers-non-mappers.

3.3. Numerical comparison task

In the next step, a 2 (Country: Germany or DE vs. Poland or PL) $\times$ 2 (CP-knowledge level: non-mappers vs. mappers) $\times$ 2 (Comparison condition: “Where is More/Less”) $\times$ 2 (correct Response

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side: Left/Right) $\times$ 3 (Range: small, large, cross-range) repeated-measures ANOVA was run on percentage of correct choices. The Country, CP-knowledge level, and Comparison condition were between-subject factors, while Response side and Range were within-subject factors. Only significant effects are reported here, the complete table of effects may be found in Appendix B. Consistent with H2a, Polish children generally performed worse than German ($M_{DE}=88.13$, $SE=2.14$; $M_{PL}=79.44$, $SE=2.20$, $F[1,188]=8.00$, $p<.006$, $\eta^2_p=.041$). Moreover, CP-knowers-non-mappers performed worse than mappers ($M_{non-Mappers}=77.66$, $SE=2.40$, $M_{Mappers}=89.91$, $SE=1.92$; $F[1,188]=15.91$, $p<.001$, $\eta^2_p=.078$). Both these effects, however, were modified by a significant three-way interaction with the Comparison condition ($F[1,188]=5.92$, $p<.02$, $\eta^2_p=.031$). This interaction indicates that there are greater cross-country differences in non-mappers than in mappers (which is in line with expectations), and especially in the "more" condition, which was not expected in advance, but is clarified in further analyses (see Figure 3).

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Figure 3. Symbolic numerical comparison task. Three-way interaction: Country $\times$ CP-knowledge level $\times$ Comparison condition (more/less). Bars represent ± 1 SE.

The test for H3a and H3b on cross-linguistic differences for performance in comparisons between numbers from the 2–4 vs. 5–9 ranges (cross-range trials) did not reveal a clear answer. The Range effect was significant ($F[2,376]=9.98$, $p<.001$, $\eta^2_p=.050$), but did not interact significantly with the Country ($F[2,376]=0.41$, $p>.6$) nor Country and CP-knowledge level ($F[2,376]=1.65$, $p>.19$).

Furthermore, although cross-range trials had more accurate responses in all groups than within-range ones, one possible explanation of this may be the distance effect, as the average numerical ratio was inevitably slightly larger (and therefore, easier) in the cross-range trials (see: Materials and Procedure). Finally, there was a significant interaction of Range and Response side

($F[2,376]=4.87$, $p<.01$, $\eta^2_p=.025$). In the small numbers range, the reactions were more accurate

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when the correct option was placed on the left, while for both the other ranges, this was true on the right (Figure 4), which is ultimately congruent with a hypothesis about improved processing of the large numbers on the right side. This effect does not depend on the Country factor ($F[2,376]=0.42$, $p>.6$ for 2-way interaction), however it differs depending on the CP-level ($F[2,376]=3.33$, $p<.04$, $\eta^2_p=.017$), being much stronger in CP-knowers-non-mappers (see Figure 4).

The results so far may suggest some contribution of spatial factors to the performance in the symbolic magnitude comparison task, but these effects are rather indirect and, so far, independent of the country. It should be noted, however, that H4 concerns primarily CP-knowers-non-mappers and only those ranges where the numbers greater than four are involved. Thus, we used a planned comparison approach to test the interaction between Country (DE/PL) $\times$ Magnitude comparison condition ("Where is More/Less") $\times$ correct Response side (left/right) factors, including only CP-knowers-non-mappers and collapsed Large- and Cross-range. This test revealed a significant effect ($F[1,188]=4.40$, $p<.04$, $\eta^2_p=.051$), shown on Figure 5. As revealed by Bonferroni-corrected post-hoc tests, the Polish non-mappers performance was particularly hampered in the "more" condition when the correct response was placed on the left, and this was responsible for most of the cross-linguistic differences (Bonferroni corrected $p<.04$, PL vs DE). Such a pattern of results, although still consistent with H2, supports also H4 as a more specific explanation of these cross-linguistic differences. According to H4, the mapping between symbols and quantities can be mediated by space, and this may be disrupted by the Polish grammatical number paradigm. Polish non-mappers seemed particularly confused when the "more" option containing numbers above four appeared on the left, as it was inconsistent with the typical spatial-numerical association (large numbers on the right, small numbers on the left) but consistent with grammatical number (plural on the right, singular on the left; c.f. grammatical SNARC effect).

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Figure 4. Symbolic numerical comparison task. Range $\times$ correct Response side $\times$ CP-knowledge Level interaction in the numerical comparison task. Bars represent ± 1 SE.

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Figure 5. Symbolic numerical comparison task. Planned comparison test for Country $\times$ Response side $\times$ Comparison condition interaction in CP-knowers-non-mappers in Cross-range and Large number ranges. Bars represent ± 1 SE.

3.4. Quick numerical estimation task

According to H2b, due to the inconsistency in grammatical agreement for numbers greater than four, Polish children may have had more difficulties in establishing a mapping between the approximate number system and the exact meanings of numerals compared to German ones, determined on the basis of counting principles. This may manifest as worse performance in the quick numerical estimation task, specifically as a lower slope of the regression between the estimates and the actual set size. We tested this for sets in the range 6–9. Estimation of the five-element set can be based on specific, not ANS-based strategies, so six was used as the lower bound

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in most previous research (Le Corre, 2014; Odic et al., 2015; Cheung et al., 2016). The estimates ranged from 2 to 19, so there were no extreme outliers. We compared the regression slope for all children who completed the quick numerical estimation task, showing no significant differences between language groups in general ($M_{DE}=0.36$, $SD=0.37$, $M_{PL}=0.39$, $SD=0.44$, $t[243]=-0.62$, $p=.54$). In the next steps, we made comparisons for individual levels of CP-knowledge. At neither CP-knowledge level was the difference significant (Subset-knowers: Mann-Whitney $U = 175$, $N_{DE} = 12$, $M_{DE}=0.18$, $SD=0.38$, range: $-0.29 - 1.15$, $N_{PL} = 32$, $M_{PL}=0.28$, $SD=0.44$, Range: $-0.26 - 2.04$, $p = .67$, all CP-knowers: $M_{DE}=0.38$, $SD=0.36$, range: $-0.37 - 1.64$, $M_{PL}=0.43$, $SD=0.44$, range: $-1.64 - 2.00$, $t[199]=-0.84$, $p=.4$, Non-mappers: $M_{DE}=0.07$, $SD=0.16$, range: $-0.37 - 0.27$, $M_{PL}=0.00$, $SD=0.31$, range: $-1.64 - 0.26$, Mann-Whitney $U = 696$, $N_{DE} = 43$, $N_{PL} = 38$, $p = .25$; Mappers: $M_{DE}=0.62$, $SD=0.29$, range: $0.30 - 1.64$, $M_{PL}=0.69$, $SD=0.27$, range: $0.30 - 2.00$, $t[118]=-1.41$, $p=.16$; all tests two-tailed). Therefore, the H2b was not confirmed

4. Discussion

Language is an important driver for numerical development. However, in the case of the grammatical attributes of language, and particularly the morpho-syntactic paradigms of grammatical number, the effects have so far only been shown very early in development in the acquisition of the first few number-word meanings. When it comes to induction of the counting principles and more complex processing of magnitudes, however, grammatical influences were so far only rarely investigated. Therefore, one can question whether linguistic, or more specifically, grammatical influences really are important for numerical knowledge acquisition, or whether they rather are a transient phenomenon when it comes to acquisition of first number-words, but have little importance for further development. Using a cross-linguistic design the current study examined, whether grammatical number attributes also influence developmental processes at the

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stage of forming counting principles and creating a link between the number-word meanings and approximate representations of numerical quantities (including possible role of spatial-numerical associations as the mediator in this process). As outlined in the introduction, the Polish grammatical number system is much more complex and less consistently mapped onto numerical magnitudes compared to either the German or English systems. Therefore, we expected specific delays in numerical development in Polish children.

Our results indeed confirmed most of our key expectations based on the differences between Polish and German grammatical number structures. Firstly, Polish children showed a delayed understanding of the counting principles compared to German children (as stated in H1). This was demonstrated in both the larger proportion of Polish subset-knowers in the otherwise comparable samples and their higher average age, despite the even age and other control variables distribution in the Polish and German samples.

Secondly, as expected in H2a, even after mastering the counting principles, Polish children fared worse in the symbolic numerical magnitude comparison task, with this difference being particularly evident in the CP-knowers-non-mappers group. Interestingly, this difference additionally depended on the comparison condition (less/more) and, as further analysis showed, also on the side on which the correct option was displayed. Thus, in addition to the possibility of an impaired process of creating representations of exact numbers after crossing the subitizing limit in Polish children, there is also a factor related to the current processing of numbers, as the comparison condition (less/more) is a feature of the task (not of permanent representation of numbers). This factor seems to be further related to the spatial arrangement of the task and thus indicates the importance of H4 for the interpretation of the results. However, analogous cross-linguistic differences were not found in the quick numerical estimation task (H2b), which tests the mapping of non-symbolic numerical quantities to number-words.

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No direct evidence was provided for the expectations concerning the cross-linguistic differences in the cross-range comparison (H3a and H3b). Although children scored significantly higher in the cross-range condition than in both the other ranges, this applied equally to both Polish and German samples. Thus, different grammatical number agreement patterns in Polish for different numerical ranges neither helped nor hindered cross-range comparisons between numbers of different grammatical categories.

Finally, some of the abovementioned effects were modified by spatial factors in a language-specific manner, which provided support to H4. One particular effect indicated that Polish CP-knowers-non-mappers found it particularly difficult to process large numbers displayed on the left, which is superficially consistent with typical spatial-numerical associations (small numbers on the left, large on the right) but, given the strong negative effect, it may also document a conflict between typical SNA and grammar-space associations (grammatical SNARC) in Western countries (singular on the left, plural on the right, cf. Roettger & Domahs, 2015). This effect accounts for a large part of the difference in overall numerical comparison task performance between Polish and German children, and thus seems to be of special interest here. It may suggest that the mapping of numerical quantities onto space may play an important role in the processing of numbers at the stage of inducing the counting principles, and that the formation of such spatial-numerical associations may in turn be affected by the grammatical number paradigm specific to the language.

4.1. Linguistic differences in preschoolers due to grammatical number structure

In summary, the specific pattern of our results suggest some linguistic basis for differences in processing numbers in Polish and German preschoolers during and after inducing counting principles. Thus, they augment previous discoveries on the role of grammatical number inflection in the earliest period of shaping the concept of an exact number and show that it continues in a further developmental period. However, in our study, we observed grammatical number effects in

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preschoolers in a few but not all of the numerical tasks, and thus, received support for some but not all of our hypotheses. This mixed results pattern requires a more thorough consideration; thus, we discuss various possible explanations for our results.

As stated in the introduction, the typical Polish morpho-syntax of enumerative sentences is somewhat inconsistent. Like many languages, it distinguishes singular and plural at the morphological level, both for the noun and verb, and uses them consistently in the numerical range of 1–4. However, for numbers above four, the verb takes the singular, while the noun remains in the plural. Moreover, the noun changes its case from nominative to genitive, which makes its syntax similar to that used in the quantification of mass-nouns. Therefore, we hypothesized that this pattern may hinder the induction of counting principles after reaching the limit of direct accurate perception of number (up to four).

As can be observed from the aforementioned results summary, this hypothesis has been confirmed. Note that the Polish children were not younger than the German ones; they had a similar level of working memory performance (Corsi blocks and Digit span), and although they showed a poorer knowledge of the count-list, this was only limited to the range above 10, which should not affect the numbers tested in the current tasks (only single-digit numbers were used in the magnitude comparison and quick numerical estimation tasks), and which is likely linked to preschool curricula differences, and is specific to the older part of the sample. Furthermore, according to other studies (Barth et al., 2009), for children who just count, the knowledge of an extended count-list is not crucial for number-word — numerical magnitude mapping. Another argument that the pattern of results observed in the present study is the effect of grammatical differences may be a certain similarity of the results of Polish children obtained in our study to Turkish preschoolers. Turkish has the usual plural syntax, but always uses the singular in enumerative sentences. As Ceylan and Aslan (2018) showed, Turkish children are delayed in acquiring counting principles and some of

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them, at the age of 4, are at the "one-knower" stage. Altogether, this provides considerable arguments that the difference in count-list knowledge, or other side variables may not be a plausible explanation for the cross-linguistic differences evidenced in our study. It also does not seem that Polish children mastered numerals up to 4 with any more difficulty than German ones. As the Polish subset-knowers were on average older than the German ones, also their average performance in the Give-a-number task was noticeably, though statistically insignificantly higher $M_{DE}=1.64$, $M_{PL}=2.17$. So the problem only appeared at the border of four and more. Additionally, Polish children did not consistently perform worse across all numerical tasks (see below for details); this suggests that there is no general unknown cognitive variable nor an unknown sampling bias, which causes the numerical development of the Polish sample to be generally delayed compared to the German children.

Since the abovementioned possible alternative explanations seem less probable in light of our data, the differences in grammatical number paradigms between the languages therefore remain one of the most likely factors that can explain the delayed transition of the Polish children to the CP-knower stage as well as the worse performance of Polish CP-knowers-non-mappers in the symbolic number comparison task. However, the question of the mechanisms mediating between grammar and numerical development remains open. Multiple but not mutually exclusive mechanisms may underlie this influence. In our view, there are three viable accounts, which we discuss in detail below.

4.2. The possible mechanisms mediating between grammatical number paradigm and numerical processes

4.2.1. Disinformation by grammatical number

The simplest of these possibilities is that the inconsistent agreement between the (singular) verb and the (plural) noun for numbers above four disinforms a "subset-knower" child who has reached the

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limit of four (the largest numerical quantity that may be precisely perceptually differentiated) since the grammatical number morpho-syntax was a reliable and useful cue in previous developmental stages. This may well explain why the proportion of subset-knowers was significantly higher in the Polish sample than in the German one, and why the average age of the subset-knowers in the former was almost 6 months higher, but it does not explain why, after crossing the limit of four and reaching the CP-knower stage, the level of performance in the symbolic magnitude comparison task in Polish children is still lower than in their German peers.

4.2.2. Mass-noun-like morpho-syntax slows down numerical development in the “large” number range

Polish morpho-syntax, using the singular verb and the noun's genitive plural form which resembles the mass-noun syntax, does not encourage the creation of exact representations of numbers above four as meanings for number-words. But what would this representation be? Early models, based on the Dehaene's triple code model (Dehaene et al., 2003), assumed that the semantic representation of a number was built based on early, approximate representations of numerical quantities. There are studies that show that the approximate understanding of number-words precedes understanding of their exact meanings (Wagner et al., 2019; Gunderson et al., 2015). However, as other studies show, the approximate and exact systems for representing meanings of number-words develop independently (at least to some extent) or even symbolic representations precede links to non-symbolic ones (cf. Le Corre & Carey, 2007; Lyons et al., 2015, 2016; Reynvoet, & Sasanguie, 2016). Yet, unlike a counting task (e.g., Give-a-Number), for which acquiring cardinality and successor principles is sufficient, comparing numerical quantities may require activation of the representation of numerical magnitudes. Recent research further shows that mastering the counting principles and, generally, symbolic codes of number representation, leads to or at least coincides with an improvement in the accuracy of non-symbolic representations of numbers (Lyons et al.,

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2018). The process of linking exact meanings of numerals to amodal representations of numerical magnitude could be weakened by the inconsistent Polish grammatical number marking for numbers above four. Indeed, the comparatively worse performance in the symbolic number comparison task in Polish children was observed in our study even after acquiring the counting principles, mostly at the non-mapper stage.

This explanation, however, only applies to a limited extent. Firstly, under this hypothesis, not only the proportion of subset-knowers, but also of CP-knowers-non-mappers should be higher among Polish children than among their age-matched German peers. Polish children should actually reach the CP-knower-mapper level later. Contrastingly, it seems that after a delayed crossing of the barrier of four, the Polish pass through the CP-knowers-non-mapper to the CP-knower-mapper stage as quickly as German children.

Secondly, the effects of the Polish grammatical number paradigm should also be visible in the task of mapping non-symbolic to symbolic representations (our quick numerical comparison task).

Polish CP-knowers-non-mappers indeed obtained descriptively slightly lower results than their German counterparts. The difference, however, was not significant and the average regression slope in Polish non-mappers still oscillated around zero, as expected from Le Corre's (2014) model. In the entire sample, Polish children produced mappings with even a slightly higher mean slope, than the German ones, but the difference also was not significant. So we have no clear evidence for the conclusion that Polish children at any stage fared worse than the Germans in the mapping task.

4.2.3. Grammatical number inconsistency impairs the acquisition of ordinality and establishing spatial-numerical associations

The process of mastering symbolic, exact representations of numbers, the understanding of numerical order, and their mapping onto spatial relations play a special role in numerical development. The most well-known examples of such mappings are the SNARC effect and the task

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of estimating the position of a number on a number line. Although most studies in this area have been conducted in schoolchildren or even in adults, there is sufficient data showing that numerical magnitude and order mapping onto space already occur at earlier stages, even in infancy and toddlerhood (see for review, McCrink & de Hevia, 2018; see also Nuerk et al., 2015, for discussion). Previous studies with adults (e.g., Roettger & Domahs, 2015) have shown that a similar mapping effect also applies to grammatical number ("grammatical SNARC"). Furthermore, one study involving adults showed that the Polish grammatical number paradigm can lead to a reversal of this effect when compared with German- and English-speaking groups (Cipora et al., 2019a). Recently, Sella et al. (2019) reported a study involving preschool children at various stages of mastering the counting principles. They showed that the results of the symbolic numerical comparison task in children mastering the cardinality principle and predecessor-successor functions depend on the child's skill to organize numbers on a visual line. Additionally, this skill also mediates the relationship between working memory capacity and the ability to compare numbers. It should be noted that spatial-numerical mapping effects also appeared in our study in the numerical comparison task. When considering CP-knowers only, there were two significant interactions observed involving CP-knowledge level and either Response side (left/right) and Range, or Comparison Condition and Country. In addition, the planned comparison showed the Response side $\times$ Comparison condition $\times$ Country interaction when limiting the analysis to CP-knowers-non-mappers and those ranges that contain numbers above four (cross-range and within large-number comparisons). In trials with both numbers belonging to the small numbers range (2–4), children performed better when the correct option appeared on the left side of the screen, but the opposite effect was found for both ranges containing numbers above four, which conforms to a spatial-numerical association pattern typical for Western cultures. The difference was stronger in CP-knowers-non-mappers than mappers. This implies that, generally, spatial factors also play an

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important role at this stage in the development of number processing and, particularly, directing attention to the right facilitates the processing of large numbers. As far, these effects did not differentiate between the Polish and German groups. However, both remaining interactions included the Country factor. First, the Polish CP-knowers-non-mappers' performance was particularly poor for the "Where is more?", while Polish CP-knowers-mappers generally fared better in the "More" condition. A more detailed analysis showed that this effect is due to the particularly low accuracy of the decisions of the Polish non-mappers in the "more" condition, when a number greater than four appears on the left. This condition is inconsistent with the typical spatial-numerical association (large numbers on the right, small numbers on the left) but consistent with the Polish grammatical number (plural on the right, singular on the left; c.f. grammatical SNARC effect). Although such an interpretation would be somewhat *ad hoc*, we think that the diminished accuracy of the Polish children's responses in this condition may be the effect of conflicting spatial cues carried by the Polish grammatical number morpho-syntax and numerical magnitude. The singular/mass-like syntax of the "large numbers" may activate the left side of the numerical space, while the numerical magnitude itself activates the right side. As a result, spatial-numerical mapping in Polish children (especially non-mappers) may be less clear-cut, which disorganizes the ordering process and thus, hampers the process of comparing symbolic numbers. Further note that according to other recent reports (e.g., Cheung et al., 2017; Le Corre, 2014; longitudinal study by Geary & Van Marle, 2018, c.f. Sella et al. 2017, 2019, 2020), an understanding of numerical relations and numerical ordering develops rapidly just after inducing the cardinality principle. In light of this, the current account (unlike the two previously discussed explanations) well explains why the differences in performing the numerical comparison task appear primarily in symbolic numbers and are strongest at the CP-knower-non-mapper stage (although they can also be observed at a later stage in the development of number representation).

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However, this explanation is more difficult to apply to the delayed transition between the subset-knower and CP-knower stages in Polish children, which, in turn, was well explained by both previous hypotheses.

4.3. Final remarks

To summarize, each of the three factors, (i) disinformation, (ii) negative impact of mass-noun syntax, and (iii) problems with acquisition of ordinality and spatial alignment, may contribute to the worse performance of Polish children compared to German ones, in some but not all numerical tasks. We wish to reiterate that these hypotheses are not mutually exclusive; these mechanisms cannot be distinguished from one another only from a comparison between the Polish and German grammatical number paradigms; other grammatical number paradigms need to be investigated (if they exist) that would also allow for finer predictions (e.g., inconsistent grammatical number paradigms for smaller numbers). Perhaps a comparison of the different Slavic languages would be helpful here, since most of them involve a singular verb and mass-like syntax but are mapped differently onto numerical ranges (cf. Franks, 1994).

Finally, we must make a reservation that, although the evidence seems appealing, we cannot completely exclude some effects of the non-linguistic differences between Polish and German participants. This may concern the preschool curriculum (e.g. older Polish preschoolers learn to count verbally to 10 and German to 20), but also some environmental differences. Tübingen, where research was carried out in Germany, is a typical small university-centered city. Warsaw, where the Polish part of the research was conducted, has one of the highest education rates in the entire European Union among young mothers, but a much more diverse population (which was not controlled in our study). We did not rule out the possible influence of these (or other, currently unknown) factors that might be worth controlling in future studies.

5. Conclusion

The study presented here is the first to show that cross-linguistic differences in the morpho-syntax of grammatical number possibly influence the development of representation and processing of numbers, not only at the stage of acquiring the meanings of the first number-words, but at the stage of induction and mastering of the counting principles (cardinality and successor principles) as well. Until now, it has been known that language may be necessary to produce accurate, symbolic representations of numbers, but this concerned “coarse-grained” linguistic properties, such as the lack of numerals in a language to specify exact numerical quantities (e.g., Mundurucu, cf. Pica, 2004, Piraha and Nicaraguan homesigners; Gordon, 2004; Everett, 2013) or the absence of grammatical number morphological markers (Sarnecka, 2014, for review). Showing that even the nuances of the grammatical number agreement system, such as differences in Polish for small and larger numbers, can significantly affect the comparison of numerical quantities at the crucial stage of creating representations of exact numbers, significantly broadens our knowledge on the role of language in the development of numerical cognition. Specifically, it sheds new light on the role of natural language morpho-syntax in the process of creating and processing symbolic numerical representations.

We further discussed three possible mechanisms for the influence of grammatical number structure on children’s numerical processing: disinformation, negative impact of mass-noun morpho-syntax, and problems with the acquisition of ordinality and spatial alignment. Further research will be needed to determine the relative importance of each of these mechanisms. Altogether, the current results support the notion of a complex nature of the interaction between language and numerical cognition rather than either simple relativistic/deterministic conceptions in the Worfian tradition or those arguing for the priority of cognition over language.

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Supplementary materials

Dataset: Haman, M., Lipowska, K., Soltanlou, M., Cipora K., Domahs, F. & Neurk, H.C., (2023, January 16). <https://osf.io/392qx/>

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Appendix A: Logistic regression (forward stepwise) model for CP-knowledge level and control variables

	Effect	DF	Wald's Stat.	Wald's p
Step 1	Age	1		
	Corsi_span	1		
	Digit.Span	1		
	Count list span	1		
	Arabic digit knowledge	1		
	Country	1		
Step 2	Arabic digit knowledge	1	58.26	0.001
	Corsi_span	1		
	Digit.Span	1		
	Count list span	1		
	Age	1		
	Country	1		
Step 3	Arabic digit knowledge	1	37.66	0.001
	Count list span	1	25.95	0.001
	Digit.Span	1		
	Corsi_span	1		
	Age	1		
	Country	1		
Step 4	Arabic digit knowledge	1	25.3	0.001
	Count list span	1	12.95	0.001
	Age	1	11.15	0.001
	Corsi_span	1		
	Digit.Span	1		
	Country	1		
Step 5	Arabic digit knowledge	1	25.39	0.001
	Count list span	1	12.07	0.001
	Age	1	14.15	0.001
	Country	1	6.37	0,01
	Digit.Span	1	Not included	
	Corsi_span	1	Not included	

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Appendix B: Full table of ANOVA results in the symbolic numerical comparison task

Effect	SS	DF	MS	F	P	eta2
Intercept	7017.22	1	7017.22	3119.62	0.001	0.944
(1) Country	18.77	1	18.77	8	0.01	0.04
(2) Magnitude comparison condition	0.06	1	0.06	0.03	0.87	0
(3) CP-knowledge level	37.33	1	37.33	15.91	0.001	0.08
1 * 2	0.03	1	0.03	0.01	0.92	0
1 * 3	6.08	1	6.08	2.59	0.11	0.01
2 * 3	1.1	1	1.1	0.47	0.49	0
1 * 2 * 3	13.89	1	13.89	5.92	0.02	0.03
Error	441.18	188	2.35			
(4) Side of the correct option	0.91	1	0.91	1.21	0.27	0.01
1 * 4	0.55	1	0.55	0.73	0.39	0
2 * 4	0.67	1	0.67	0.89	0.35	0
3 * 4	0.65	1	0.65	0.87	0.35	0
1 * 2 * 4	1.45	1	1.45	1.93	0.17	0.01
1 * 3 * 4	0.04	1	0.04	0.05	0.82	0
2 * 3 * 4	0.97	1	0.97	1.29	0.26	0.01
1 * 2 * 3 * 4	1.35	1	1.35	1.79	0.18	0.01
Error	141.34	188	0.75			
(5) Range	6.7	2	3.35	9.98	0.001	0.05
1 * 5	0.28	2	0.14	0.41	0.66	0
2 * 5	0.36	2	0.18	0.54	0.58	0
3 * 5	0.87	2	0.44	1.3	0.27	0.01
1 * 2 * 5	0.95	2	0.47	1.41	0.25	0.01
1 * 3 * 5	1.29	2	0.65	1.92	0.15	0.01
2 * 3 * 5	1.11	2	0.56	1.65	0.19	0.01
1 * 2 * 3 * 5	0.01	2	0.01	0.02	0.99	0
Error	126.26	376	0.34			
4 * 5	1.85	2	0.93	4.87	0.01	0.03
1 * 4 * 5	0.16	2	0.08	0.42	0.66	0
2 * 4 * 5	1.03	2	0.51	2.7	0.07	0.01
3 * 4 * 5	1.26	2	0.63	3.33	0.04	0.02
1 * 2 * 4 * 5	0.16	2	0.08	0.41	0.66	0
1 * 3 * 4 * 5	0.36	2	0.18	0.96	0.39	0.01
2 * 3 * 4 * 5	0.24	2	0.12	0.63	0.53	0
1 * 2 * 3 * 4 * 5	0.57	2	0.28	1.49	0.23	0.01
Error	71.39	376	0.19			