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Number words, quantifiers, and arithmetic development with particular respect of zero

Mathematics and language. Apparently two independent fields. Why apparently? Looking at adults with mathematical knowledge, you can observe great differences in both directions in the sense of a double dissociation with regard to these two competences, that is, language and arithmetic competences. This means that there are people who have very good language competences but weak mathematical competences and vice versa. This dissociation would indicate a certain independence from language and arithmetic competences. In this chapter we would therefore like to shed light on both associations and certain independencies between language and arithmetic competences. Above all, we would like to show that both views are correct, since it always depends on the respective moment of observation in development and especially on the skills of interest. Arithmetic competences include the understanding of numbers and their relations as well as the mastery of basic arithmetic operations. Therefore, we will first look at some general associations between language and numerical competences, based on the Triple Code Model by Dehaene (1992). Then we will go into more detail about the development and the interdependence between language and numerical competences as they are in a permanent interaction. Finally, we want to give some specific insights into the associations between quantifiers and the development of cardinality before explaining the role of zero in this context. We believe that a specific knowledge of these associations is essential not only for research, but also for practical work with children with dyscalculia. This applies not only to the work with children with a migration background or a specific language development impairment and how these difficulties can be countered. It is also important to keep in mind that language can also be a resource for children with dyscalculia to better grasp numerical content.

Looking at the current leading number processing model, the Triple Code Model by Dehaene (1992), it quickly becomes clear that arithmetic competences do not represent a single homogeneous competence, but actually consist of several sub-competences that are predominantly independent of each other. This means that some sub-competences in numeracy may be more dependent on language, while others may be less dependent on language. The three representations of Dehaene's model are the verbal code, the visual Arabic code, and the

https://doi.org/10.1515/9783110661941-008

semantic code. The verbal code includes not only the spoken and written number words, but also the verbal counting and especially the verbal memorized arithmetic facts (e.g., $4 + 3 = 7$ or $3 \cdot 4 = 12$). Therefore the verbal code represents most language-dependent numerical skills. The link between language competences and the verbal code appears to be strongest at this point. Opposite to this the semantic code includes semantic knowledge about size and quantities for number comparison or estimation as well as the numerical quantities represented on the mental number line. The third representation is called the visual Arabic code and represents the numbers in Arabic format. This is mainly used for multi-digit calculation and also for parity judgments. Apart from that it must be considered that, depending on the mathematical task, the different codes are activated to different degrees or, in addition, can also be different in terms of their quality within a person. This means that someone can be very good at verbal fact retrieval, but has difficulty with procedural understanding, or vice versa. Nevertheless, language does not represent a homogeneous competence either, because it also consists of many sub-competences. It is therefore important to look in detail at the associations between language competences and arithmetic competences, as is impressively described in this book. This chapter is therefore devoted to specific or concrete number words (e.g., one, two, three), quantifiers or unspecific number words (e.g., many, some, a few), as well as the development of arithmetic competences and the influence or contribution of language.

What is the relationship between the development of arithmetic competences and language competences? Studies show a certain independence with regard to individual sub-competences, as also described by Dehaene (1992) in the Triple Code Model. According to several studies (cf: Wynn, 1992), the understanding or a certain sensitization in dealing with quantities (in sum a kind of innate number sense) is innate. Even infants without any understanding of language can discriminate between two quantities under certain conditions long before the development of language begins (Xu et al., 2005). Thus, at the beginning, the processing of numbers and quantities seems to be language-independent, which is also impressively demonstrated by behavioral studies with animals that are able to handle quantity differentiation very well (Ward & Smuts, 2007). However, if we look further along the time axis, it becomes clear quite quickly that one of the most effective ways to acquire mathematical or arithmetical knowledge is through language. Language competences not only represent one of the most important predictors of school success in general (Wagner et al., 2013), they also serve specifically as a predictor of mathematical skills (Preat et al., 2013). Additionally, it is possible to observe clear difficulties in this phase of the development of arithmetic competences in disadvantaged groups, such as children with a migration background or children with a language development impairment (Donlan et al., 2007). Therefore, this is a clear indication that language must fulfill a specific function in early numerical development. These contradictory results are not contradictory when viewed in a longitudinal section. Besides the innate number sense, knowledge of numbers and quantities is naturally acquired through learning as well as through social interaction. Children start to talk and use these new language skills to refine their numerical competences at the same time. Thus, at the beginning, children can only distinguish very large differences between two quantities with the help of their innate intuition for quantities. In the second year of life, they learn, parallel to this but independently of it, the number words. At this time, the word sequences are still isolated from quantities (Krajewski & Schneider, 2009a) – these two sources of information come together only later in the development. To be more precise, the first most spoken words up to the age of one and a half years already include a number word (Szagun, 2013). Looking at the main principles of acquiring vocabulary (mostly nouns) at this stage of development, this is not self-evident. The first principle that children follow in vocabulary acquisition is the "mutual exclusivity assumption," which means that a word is always assigned to an object (i.e., if a word has already been learned for that object, that word cannot mean another object; Markman, 1989). To use *two* for the number of bears and *two* for the number of cars would therefore contradict this principle. In addition, a second principle is used by the toddlers in this phase, the "whole object assumption." This means that the word "heard" covers the whole object and not any feature or part of the object. The word "shoe" is thus associated with the shoe as a whole and not just with the sole, the shoelace, or even the number of shoes (Markman, 1989). These principles make it a little difficult for children to grasp the concept of a number word at this early stage because the number word is an attribute of the object, not the object itself. As Gelman and Gallistel (1978) have already described in their Abstraction Principle, children recognize that things are countable and this in turn helps them to process the number words as specific words on another abstract level. This abstraction allows them to process these words differently and to refine them further. At first, it is just an empty collection of specific words without a stable order. Only with time children learn that number words follow a sequence, as Gelman and Gallistel (1978) also state in their counting principles. In parallel, one-to-one correspondence is discovered and applied. In this phase, counting is equivalent to reciting a poem. This means that there is not yet a cardinality understanding. One could also say that numbers are processed purely linguistically, without the quantity being processed as a semantic unit behind it. So the child can count four objects correctly, but cannot answer the question how many there actually are. This semantic knowledge about the number words is built up only very laboriously and slowly. In the last step, therefore, the linguistic information, that is, the number word, must be linked to the content or semantics (i.e., the quantity information). In concrete terms, this means that the child not only has to identify *one* as a number word and place it correctly in the number word series, but also must understand that exactly one object can be assigned to *one*. The so-called one-knowers (Sarnecka & Carey, 2008; Wynn, 1992) are thus children who have already understood the concept of *one* and can therefore semantically distinguish exactly between *one* and more. For example, if a child at the one-knower level is asked to give one of the presented objects (e.g., cars), exactly one is also given. If a one-knower is asked to give two objects, more objects are given, sometimes two, but sometimes more than two. It can be observed that language plays an important role in this step. The understanding of plural markings in nouns occurs at the same time as the children change to the one-knower-level (Barner et al., 2007). This is also supported by observations of Japanese children (Sarnecka et al., 2007), who do not acquire a plural marking at this time because this plural marking does not exist in Japanese. As a result, Japanese children achieve the transition to the one-knower-level much later. In this first phase of the acquisition of cardinality, the path via the linguistic concept of the plural seems to be beneficial. On the other hand, the path via the plural does not seem to be the only one, as the findings from Japan show. So there must also be at least one other way to acquire cardinality. With time, children gradually learn to differentiate *two*, *three*, *four*, and *five* and to assign them correctly. Only from *six* onward this understanding of cardinality generalizes and the children can transfer the knowledge to the next quantity. At this stage, children are called cardinality-knowers (Sarnecka et al., 2007). This acquisition of mapping the number word to the correct quantity is quite hierarchical (Sarnecka et al., 2007) and language seems to have a supportive function throughout numerical development. Studies such as Negen and Sarnecka (2012) show a clear correlation between the size of the vocabulary and the knowledge of number words. Pixner et al. (2018) also found a clear difference in vocabulary between subset-knowers (i.e., children who did not yet show any generalization in terms of cardinality) and cardinality-knowers. Phonological awareness proved to be another important language-related predictor for the prediction of basic numerical competences in a group of preschool children, as Pixner et al. (2017) were able to show. It is assumed that phonological awareness plays an important role in this phase, since the first number words are also very similar in sound, at least in German (e.g., *zwei* and *drei*). Krajewski and Schneider (2009b) state that a phonological processing deficit should affect mathematical domains that are verbally coded, while other domains, especially higher numerical processing, should not. In the following, they explain that the influence of a phonological awareness deficit on a mathematical impairment in early mathematical development can be mitigated or compensated (e.g., by training and manipulating the precise number words). Based on the number word sequence, children then learn to connect this number word sequences with the corresponding quantities. That means that good linguistic differentiation is necessary. All these studies show that language or linguistic competences, such as the size of the vocabulary but also phonological awareness, are helpful in this phase of the development of number words and counting as well as for cardinality knowledge. Knowledge of number words, counting, and cardinality are in turn an important building block for the successful development of arithmetic competences.

1 Quantifiers: Their development and their influence on cardinality

One aspect of the association between language and arithmetic skills is mathematical language. This includes terms that are strongly domain-specific and related to the mathematical context (Purpura & Reid, 2016). Understanding mathematical language is essential in school. Even "simple" quantifiers like "more" or "less" can cause massive problems in solving word problems (Dresen et al., submitted). Children usually associate "more" with an addition and "less" with a subtraction. If these terms are used inconsistently to the "anticipated" arithmetic operation, the probability of solving such problems decreases significantly. This phenomenon can be observed not only in children but also in adults. Therefore the development of an understanding of mathematical language, especially of quantifiers, is of essential importance.

Quantifiers are unspecific number words, which play a special role in the development of number words as well as cardinality. In line with Gleitman's bootstrapping theory (1990), Carey (2004) postulated that children derive the meaning of number words from their understanding of quantifiers. Resnick (1989) also assumes that children first have an imprecise association between quantifiers and the corresponding quantities, which becomes more specific and precise with the length of their experience. Quantifiers represent unspecific number words (e.g., more, many, a few) and – as specific number words – represent a quantity (Sullivan & Barner, 2011). Additionally, exact quantifiers (e.g., both) or non-exact quantifiers (e.g., some) can be distinguished. However, to understand the meaning of quantifiers, it is important to grasp semantic and pragmatic restrictions (i.e., language knowledge) as well as the quantificational meaning of each quantifier (i.e., domain-specific numerical knowledge; Dolscheid & Penke, 2018). In this sense, Sullivan and Barner (2011) argued that to get the meaning of quantifier successfully, children need to understand that quantifiers are arranged on a shared scale. This scaling allows children to draw pragmatic conclusions about the individual significance of the quantifiers. Accordingly, Hurewitz et al. (2006) investigated linguistic similarities and differences of both specific and unspecific number words. They argued that specific number words (as, for example, *two*) are always independent from the context (e.g., *two* is always *two*). In contrast – regarding quantifiers as unspecific number words – in a set of three objects many could already be *two*, whereas in a set of thousand objects many is clearly more than *two*. At the same time, similarities regarding the embedment in the syntax are described as well. For instance, both specific and unspecific number words can be sequenced in an order (e.g., all is always more than most and 7 is always more than 4). Furthermore, findings of Dolscheid et al. (2015) demonstrated an association between unspecific quantifier knowledge and numerical skills such as specific cardinality knowledge and counting skills at the age of 4.6 years – without, however, being able to answer the extent to which these skills are interdependent.

A recent study of Dresen et al. (2020) evaluated potential associations between the acquisition of cardinality knowledge and quantifier knowledge (i.e., unspecific number words) in children. The study followed a total of 76 (34 boys and 42 girls) monolingual German-speaking children aged between 3.6 and 4.6 years at the first measurement time for two more measurement times 6 months and one year later. Children were tested with two relevant tasks: a give-N task assessing specific cardinality knowledge of numbers from 1 to 10 and a give-N task measuring unspecific quantifier knowledge (more than, less than, all, a lot of, etc.). Results clearly indicated that children's cardinality knowledge correlated over all three measuring times. Children who already had better cardinality knowledge at an earlier measurement time also performed better at later measurement times and vice versa. Therefore, it makes sense to monitor children's cardinality knowledge already at early stages of their numerical development because it is considered as one important basic numerical competence for the development of further numerical competences (e.g., Brannon & Van de Walle, 2001). A little different was the picture for the case of quantifiers. No correlation between quantifier knowledge at the first and second measurement time was found. This may indicate that the development of quantifier knowledge is not linear but may rather be influenced by other factors such as language development, for instance. It was only between the second and third measurement time that a significant correlation for quantifier knowledge was observed.

More interesting, however, were the observed associations of specific cardinality knowledge and unspecific quantifier knowledge. Quantifier knowledge assessed at the first measurement time was not associated with actual and/or future cardinality knowledge. This seems to imply that there may be no further disadvantage for children's development of the cardinality knowledge when they do not yet master the quantifiers at the ages of 3.6 to 4.6. Interestingly, however, there was a significant association between cardinality knowledge and quantifier knowledge at the second measuring time. Furthermore, there were significant bidirectional associations of cardinality knowledge and quantifier knowledge from the second to the third measurement times (when children were on average 4.4 and 4.10 of age, respectively). Importantly, mediation analyses specified that the association between cardinality knowledge at measurement times two and three was fully mediated by children's quantifier knowledge at measurement time two. Interestingly, on the other hand, there was no mediation of the development of quantifier knowledge between measurement times two and three by children's cardinality knowledge at measurement time two. Based on these results, it can be assumed that – at this particular age – quantifier knowledge seems to facilitate further development of children's cardinality knowledge. In turn, this may mean that children should have acquired an understanding of quantifiers up to this age because this helps them to further develop their cardinality knowledge.

In summary, these results show how differentiated one has to consider associations between the early development of specific cardinality knowledge and unspecific quantifier knowledge reflecting less precise numerical magnitude information. In particular, quantifier knowledge seems to facilitate cardinality knowledge at a specific age, which might indicate the specification of less precise and thus approximate magnitude representations as reflected by quantifiers.

2 Concept and characteristics of zero and negative quantifiers

As described above, the development of arithmetic competences involves many sub-competences and a wide range of influences. If we concentrate on the specific number words on the one hand and on the unspecific number words, quantifiers, on the other hand, we can discover additional specific characteristics. Both *zero* and negative quantifiers (e.g., nothing) differ from the concepts presented, although by definition they belong to these two groups. Let us first take a closer look at *zero*. As discussed at the beginning, children between the ages of 22 and 24 months learn to distinguish between *one* and more, at the same time as they mark nouns with the correct plural. This means that the understanding of quantities greater than *one* is supported by the language, thus facilitating differentiation. But what does this look like with *zero*? Also with *zero*, the following noun is marked with plural (e.g., I have *zero* apples). This phenomenon can be found in many languages. The supporting principle of quantity differentiation by plural marking is thus overridden or violated at *zero*. Concretely, this means that a quantity which is less than *one* is nevertheless marked with the plural at nouns. This may therefore be one of the explanations why *zero* is associated with a lot of difficulties in children, but also later in adults (Brysbaert, 1995; Wellman & Miller, 1986). The first, frequently described difficulty with *zero* is the implementation of arithmetic rules when calculating with zero ($2*0 = 0$ but $2 + 0 = 2$). The second difficulty has to do with the placeholder function of *zero* in multi-digit numbers. In evolutionary terms, *zero* is a relatively young number (Butterworth, 1999). Most primitive number word systems and also the symbol-x-value systems such as the Roman system did not need *zero*, since only one number was needed to represent a quantity. All of the above-mentioned number word systems begin with the number *one*, and since they do not need a placeholder due to their structure (e.g., in Roman 5 is represented as V and 10 as X), *zero* is not necessary either. In the current Arabic notation system, however, *zero* has this very important placeholder function. In concrete terms, this means that if in a multi-digit number a position is not existing (e.g., no tens), a *zero* must be entered in the missing place; otherwise, the quantity is no longer correct (e.g., there is no ten in 302, but the ten's place cannot simply be omitted, since otherwise the 302 would result in a 32, i.e., a completely wrong quantity).

Looking at these difficulties with *zero*, the question arises how the understanding of negative quantifiers, for example, no/none/nothing, looks like in child development. The concept of nothing may pose difficulties at a more general level – not only referring to the numerical value of zero. This means the understanding of the concept of no objects differs from the understanding of one or more objects as an experiment of Wynn and Chiang (1998) could show. In this experiment, 8-month-old infants were irritated when an object disappeared in a location in which this item had been shown before. This was not the fact when an object appeared where no object was before. Although young infants already have a distinct knowledge of material objects, they are not able to understand *no objects*. Only later on, children acquire the words "nothing"/"none"/"no" (objects) and their semantical meaning, without considering it as a numerical value and combining it with the symbol of *zero* (Pixner et al., 2018).

In a study by Pixner et al. (2018) 65 kindergarten children aged 4 to 5 years ($M = 4$ years and 4 month; $SD = 3$ months) were examined with regard to their understanding of small numbers and *zero* as well as their visual-spatial skills (measured with the subtest visual perception of the Visual Motor Integration (VMI), Beery, 2004), general language (measured with a standardized active vocabulary test, AWST-R, Kiese-Himmel, 2005), counting skills, knowledge of Arabic numbers, and finger knowledge. To identify children´s finger knowledge, the children were asked to present a different configuration of fingers. All quantities between 0 and 10 were asked in random order. Participating children were recruited from local public kindergartens and all of them were monolingual native German speakers. Thirty-one boys and 34 girls were included in this study. Most of the children were right-handed (81.5%). No child in this study showed an intellectual or language impairment. Significant correlations were observed between vocabulary, numeracy, finger knowledge, and counting skills, both with understanding of the cardinality of small numbers and with knowledge of *zero*. Subsequent regression analyses, however, only showed the importance of counting skills on knowledge of *zero*. General vocabulary, spatial skills, as well as the cardinality understanding of small numbers showed no independent predictive value in this regression. It is interesting to note that *zero* and the negative quantifiers, like "nothing"/"no"/"none," had a negative correlation at this age. An explanation can be derived from the general principles in the vocabulary development, specifically from the mutual exclusivity assumption, which means that if you already have a term for nothing/zero at this age, you do not need another term for this state.

3 Conclusion

In summary, it can therefore be said that language or linguistic competences, as cross-domain competences, fulfil strongly supportive functions at many stages of the development of arithmetic competences. This should be kept in mind especially for children at risk with limited linguistic development, for whom there is an additional risk that arithmetic competences will not develop in line with age. However, despite the linguistic influence, the results of some studies also show that domain-specific numerical precursor skills appear to be more important for the acquisition of cardinality understanding and zero than more cross-domain skills. An intervention should therefore cover both aspects equally.

If we look in particular at specific mathematical vocabulary, such as the quantifiers in this chapter, results indicate that understanding quantifiers contribute significantly to the acquisition of children's understanding of cardinality. However, mathematical vocabulary is also important in later life for the acquisition of various mathematical skills and the successful solution of mathematical tasks, such as mathematical word problems, and should, therefore, also be a focus in the school context.

An important and often neglected aspect is the extraordinary role of *zero*, both in acquisition and later in implementation in the mathematical sense. In order to minimize the numerous difficulties with *zero* in children as well as in adults, the corresponding arithmetic rules and also the placeholder function should not be neglected and should be repeated continuously.

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