Children's Acquisition of the English Cardinal Number Words:

A Special Case of Vocabulary Development

by

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Abstract

When children become able to produce the cardinal numbers from 1 to 1.000.000.000.000 in words, it is unlikely that they have encountered each and every one of these number vocabulary words, and stored them in semantic memory. Instead, researchers have assumed that children learn a finite set of number words and use their knowledge of the cardinal number system and problem solving abilities to generate the remaining words in the series. However, this assumption has not been tested empirically, and studies have not focused on children's knowledge of the number word series up to one trillion. Researchers have typically studied preschoolers' acquisition of number words up to one hundred, and suggest that after that point, the system is entirely generative. The purpose of the present investigation was to examine school-aged children's abilities to produce number words up to the billions series, document age related changes in number word knowledge, and determine the relation between children's number production skills and their mathematical ability. In two studies, children from grades one, three, five, and seven, equally divided across sex were asked to produce the number names of a randomly selected set of numerals, and then count from the numeral in a forward or backward direction. Children also completed tasks aimed to assess the size of their basic number word vocabulary and problem solving capabilities. The times taken to produce number words were also recorded in Study 2. Results revealed that children's total cardinal number word vocabularies strongly increased with grade; and children in grades one, three, five, and seven could name and count numbers as high as the hundreds, thousands, millions, and billions series, respectively. Study 2 also demonstrated that children became increasingly proficient in producing number names with grade, as the times taken to name and count numbers within each number series strongly decreased with grade. However, there was a wide range of individual differences within grade, which were related to children's mathematical achievement in most grades. Furthermore, results indicated that children's total number word vocabularies were not only dependent on the size of their basic vocabularies, but were also affected by their knowledge of the compounding rules, and their understanding of the cardinal number system. These findings are discussed in relation to children's mathematical accomplishments during the school years and have implications for the teaching of mathematics in the classroom.

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A Special Case of Vocabulary Development

The accurate estimation of vocabulary knowledge at a particular age or developmental level has been an important empirical issue for psychologists. Vocabulary development has often been used to assess language development and cognitive functioning (Hammill, Brown, Larsen, & Wiederholt, 1987; Hammill & Newcomer, 1988; Nagy & Herman, 1987; Newcomer & Hammill, 1988; Owens, 1992), to estimate reading ability (Miller, 1988; Nagy & Anderson, 1984; Nagy & Herman, 1987), and school achievement (Miller, 1988). Furthermore, it is often used as a measure of intelligence (e.g., Wechsler, 1991). Despite the importance of vocabulary knowledge, obtaining exact vocabulary estimations has been difficult.

One of the most detailed accounts of vocabulary development was conducted by Anglin (1993a) and aimed to assess both the quantitative and qualitative vocabulary accomplishments of children during the school years. Thirty-two children from each of grades one, three, and five were tested on their knowledge of a random sample of 434 words (which could be further divided into five morphological word types and three levels of morphemic complexity) from an unabridged dictionary. By multiplying the proportion of words known by children by the total number of words in the dictionary, Anglin (1993a) found a substantial increase in vocabulary estimates with grade. Grade one, three, and five children were estimated to know an average of 10,398, 19,412, and 39,994 main entry words, respectively.

However, one of Anglin's (1993a) main findings was that not all of the words that children had shown knowledge of during the experimental task had necessarily been previously encountered and stored in the mental lexicon. Anglin (1993a) suggested that children's vocabulary scores reflect knowledge of two general categories of words. There are "psychologically basic words" such as asparagus or torque whose meanings would be difficult to know unless these concepts were learned directly and stored as whole units in semantic memory. Conversely, there are words that may be "potentially knowable" because it is possible to figure out their meanings using morphological problem solving skills. For example, even though a person may not have ever encountered the word hopelessness, they may reason that "hope means to have confidence," "-less means not having," and "-ness is the quality of." Potentially knowable words have not been learned. They are constructed or constructible by considering the meanings of other words and affixes that are stored in semantic memory.

Anglin (1993a) indicated that the incidence of morphological problem solving was more common in definitions of literal compounds (e.g., snowy owl), inflected words (e.g., failed), and derived words (e.g., unlawful) than in definitions of root words (e.g., harp) and idioms (e.g., scare crow). Morphological problem solving may have been rare for root words because these words only contain single free morphemes and cannot be separated into smaller parts. It is also difficult to use morphological problem solving with idioms because the breakdown of these words into their morphological components does not generate a correct meaning of the word (e.g., a scare crow is not a type of crow that scares).

Although Anglin (1993a) found evidence of morphological problem solving at each grade level, the prevalence of problem solving increased with grade. Of the 10,398 words that grade one children were estimated to have known, about 40% of them were estimated to be potentially knowable through morphological problem solving. By grade five, over 50% of the 39,994 estimated words were estimated to be potentially knowable. Thus, both knowing "psychologically basic words" and problem solving skills are very important in the development of vocabulary during the school years.

One purpose of the current investigation was to determine the extent to which the distinction between learning psychologically basic vocabulary words and knowing them through problem solving could be applied to the English cardinal number words. Each cardinal number from 1 to 1,000,000,000,000 has a specific meaning (Anglin, 1993b; Deloche & Seron, 1982; Seron & Deloche, 1984) and can be written in words as: one; two; three; four; five; ...nine hundred and ninety-nine billion, nine hundred and ninety-nine million, nine-hundred and ninety-nine thousand, nine hundred and ninety-nine; one trillion. However, it is unlikely that children memorize all of these number words when they are learning to count. Instead, they probably memorize a small set of basic cardinal number words, and through various problem solving techniques, construct the remainder of the words in the series (Anglin, 1993b; Baroody, 1987; Boden, 1988; Deloche & Seron, 1982; Fayol, 1985; Hurford, 1975; Nunes & Bryant, 1996; Power & Longuet-Higgins, 1987; Clark & Campbell, 1991; Seron & Deloche, 1987; Seron, Noel & Deloche, 1992).

However, some people may argue that because the cardinal number words have arabic representations (e.g., 2; 312; 90,760) and are used to solve mathematical problems (e.g., 12+2=14), they are not words in the traditional sense, and should not be considered part of a vocabulary study. But the cardinal number words do satisfy Miller and Wakefield's (1993) psycholinguistic definition of what should be considered a word. Specifically, the cardinal numbers are words because they can be represented in both orthographic (e.g., twenty-four) and phonetic forms (e.g., */twenti for/*), they represent specific concepts in semantic memory (e.g., twenty-four is one more than 23 in number) and they play a syntactic role as either a noun, adjective or pronoun in English sentences (Menninger, 1969).

Furthermore, most people would contend that a word exists if it is listed in the dictionary. However, given the infinite set size of the cardinal number word sequence, it is impractical to list every number word as a lexical entry. Dictionaries have compromised and have presented all of the cardinal number words from one to a hundred as either main entries or subentries (e.g., Concise Oxford, 1990; Longman, 1984; Oxford, 1989; Random House, 1987; Webster's, 1944, 1970, 1981). Lexicographers have also listed all of the cardinal number words greater than one hundred that would be classified as root words under rules of morphology (i.e., thousand, million, etc.) as main entries. Finally, for the remaining cardinal number words not included as main or subentries (e.g., one million and twelve), some dictionaries refer readers to a number table which demonstrates the pattern for constructing the remaining words in the series (e.g., Longman, 1984; Webster's 1944, 1981).

The cardinal number words may be considered part of two morphological word type categories. Number words such as one, twelve, thirty, hundred and million may be classified as root words, because they contain only single free morphemes (Anglin, 1993a; Bauer, 1983). However, since a large percentage of the cardinal number words contain more than one root word (e.g., thirty-one, one million and thirty), these words may be classified as compound words. These number words are different from many other compound words in that they are completely rule governed, but the last constituent word in them does not necessarily denote the category or class to which the number word belongs (for a review of the compound literature, consult Bauer, 1983; Clark, Hecht, & Mulford, 1986; Clark & Berman, 1987; Marchand,1960).

For example, the number word six million, three hundred and thirty-two is not a type of two or a type of thirty-two, although it might be considered part of the "millions" category.

Some studies have indicated that problem solving strategies may be used to generate and infer the meanings of the cardinal number words. In fact, given that a large majority of cardinal number words are considered compound words, and the high repetition of basic root morphemes within these number words, problem solving strategies may be used to produce a large percentage of these words. Power and Longuet-Higgins (1987) created a computer program that could simulate the number word production process. With the input of only 30 basic number words and the programming of the compounding rules for generating number words, the computer algorithm could translate the arabic forms from 1 to 999,999 into words. A similar compounding strategy that may be used to produce the cardinal number words from 1 to 999,999,999,999 is presented in Appendix 1. Other research has indicated that preschoolers show evidence of problem solving in their overregularization errors (i.e., "fiveteen," "twenty-ten," and "tenty"), while counting (e.g., Baroody, 1987; Ginsburg, 1977; Fuson, 1988; Siegler & Richards, 1983). Finally, Fuson, Richards, and Briars (1982) have indicated that many grade two children are capable of counting well into the hundreds, even though their teachers conceded they had not formally taught every number.

If problem solving skills are used to generate some cardinal number words, it is important to determine which of the cardinal number words must be learned and stored in semantic memory, and which are "potentially knowable" through problem solving. The computer program that was created to generate the cardinal number words from one to nine hundred and ninety-nine thousand, nine hundred and ninety-nine, required the input of the conjunction _and_, plus 30 basic number names including: the number words from _one_ to _nineteen_, _twenty_, _thirty_, _forty_, _fifty_, _sixty_, _seventy_, _eighty_, _ninety_, _hundred_, and _thousand_ (Power & Longuet-Higgins, 1987). Research with children has concluded that they too must learn most, if not all of these number words by rote. Learning the first cardinal number words has been likened to a serial recall task (Fuson, 1988), and researchers contend that at a minimum, the first nineteen numbers must be memorized (Anglin, 1993b; Baroody, 1987; Fayol, 1985; Fuson, 1988, 1991, 1992a, 1992b; Fuson, Pergament, Lyons & Hall, 1985; Fuson, Richards & Briars, 1982; Gagné, 1965; Gelman & Gallistel, 1978; Ginsburg, 1977; Miller & Stigler, 1987; Miller & Zhu, 1991; Miura & Okamoto, 1989; Miura et al., 1994; Nunes & Bryant, 1996; Seron & Deloche, 1987; Seron, Noel & Deloche, 1992). Case studies have provided support that these numbers are memorized. When young preschoolers have not learned the number series from _one_ to _nine_, they can only count up to the highest number word they have memorized (Brissiaud, 1992; Ginsburg, 1977; Descoeudres, 1946).

Although there is a repetitive structure to the teen words (e.g., _sixteen_, _seventeen_) that could be derived, researchers have obtained evidence indicating that even the teen words are memorized. Fuson (1988) examined the types of errors preschoolers made when asked to produce the teens on different occasions. She found that preschoolers would often consistently miss one of the number words, or produce the teens in a different order each time they counted, indicating that they did not see the regular pattern. Furthermore, children did not often substitute invented words that reflected the structure of the teen sequence (i.e., "threeteen, fiveteen") suggesting that they were not problem solving to produce the words. Finally, there were differences between a child's "best" counting trial and their mean counting score, which meant that they were not using a consistent problem solving strategy each time they produced the sequence. Likewise, Siegler and Robinson (1982) concluded that the teen words were memorized, since there were no obvious stopping patterns (or slight pauses, as they defined them) when children produced the teen sequence. These researchers found that children's responses usually contain stopping patterns at the beginning (e.g., 30-pause-31) and end (e.g., 39-pause-40) of a number set, and suggested that these stopping patterns may be associated with retrieving new number names after having generated a set of problem solved words.

Finally, several cross cultural studies have indicated that the English teen words are likely memorized since they are not compounded regularly, and do not translate directly into place value notation, compared to the number words in Asian languages (e.g., after ten comes eleven and twelve in English, as opposed to ten-one and ten-two in Chinese) (Fuson & Kwon, 1991). To support this claim, Agnoli and Zhu (1989) found that English-speaking children were slower at producing the cardinal teen words from 10 to 15 compared to their Chinese-speaking counterparts, and concluded that this performance differential was attributed to the English-speakers having to recall each teen number word separately from memory. Likewise, using a number reversing task, Miller and Zhu (1991) found that English-speaking adults showed more difficulty reversing numbers containing ones (e.g., 14, 41) compared to numbers with no ones (e.g., 43, 94), but Chinese-speaking participants did not exhibit this difficulty. Miller and Zhu (1991) attributed these findings to the morphological complexity of the English teen words, and suggested that unlike most other English two-digit number words and all of the Chinese two-digit number words, the English teen words have become lexicalized entries.

Researchers have further indicated that individuals must also learn the decade root number words (i.e., twenty, thirty...ninety) (Anglin, 1993b; Baroody, 1987; Ginsburg, 1977; Miura et al., 1994; Nunes & Bryant, 1996), and the multi-digit number words such as hundred, thousand, million, billion, trillion, quadrillion and so forth, by rote (Anglin, 1993b; Baroody, 1987; Ginsburg, 1977). Since there is a pattern to the decade numbers and even for the larger numbers (i.e., billion, trillion, quadrillion), it may seem possible that people do not find it necessary to memorize all of these words. However, when adult participants were required to rapidly rote count backward from 100, Seron and Deloche (1986) noticed that omissions and errors in counting tended to occur on decade boundaries. These researchers suggested that the errors reflected sections of the number sequence where participants had to retrieve appropriate basic number words. Finally, many researchers have noted that the irregularities of the English decade number words (i.e., twenty instead of two-ten or twoty; thirty instead of three-ten or threety) obfuscate the simplicity of the series (Fuson & Kwon, 1992a, 1992b, Ifrah, 1985; Miller, Smith, Zhu, & Zhang, 1995; Miura et al., 1994; Menninger, 1969) making the pattern of the decade number sequence difficult for most adults to describe (Fuson & Kwon, 1992b). In fact, pilot testing by the current experimenter revealed that even adults did not often notice the pattern in the large multi-digit basic number words and did not select the correct large number words (e.g., quadrillion, sextillion) from a set of distractors.

Hence, in order to produce the number word equivalents for the numbers from 1 to 1,000,000,000,000, individuals have probably learned a minimum of 32 basic vocabulary words from which the remainder of the series can be derived (Anglin, 1993b). In other words, by learning the number words from one to nineteen, twenty, thirty, forty, fifty, sixty, seventy, eighty, ninety, hundred, thousand, million, billion, and trillion, and by having knowledge of the relevant morphological compounding rules, an additional 999,999,999,999,967 new words are constructible through problem solving![1] In this respect, the cardinal numbers are a very special case of vocabulary development because they clearly demonstrate the potentially large role that problem solving skills play in developing word knowledge.

Thus, it would be interesting to determine how many cardinal number words children know at particular grade levels, whether children use problem solving to generate additional words in the number sequence, and the extent to which problem solving enhances their number word vocabularies. Many vocabulary studies have concentrated on determining estimates of word knowledge at different developmental levels (e.g., Anglin, 1993a; D'Anna, Zechmeister, & Hall, 1991; Goulden, Nation, & Read, 1990; Seashore & Eckerson, 1940). Although some studies have focused on the vocabulary acquisition of special domains such as first words (e.g., Fenson, et. al, 1994), deictic terms (deVilliers & deVilliers, 1974), color terms (Bartlett, 1977), kinship terms (e.g., Benson & Anglin, 1987), superordinates (e.g., Skwarchuk & Anglin, 1997) and the differential organization of different verbal concepts in semantic memory (e.g., Miller, 1991; Skwarchuk & Clark, 1996), children's acquisition of the cardinal number words has not often been investigated in studies which specifically focus on lexical knowledge.

In addition to studying children's acquisition of the English cardinal number words from a vocabulary perspective, a second goal of the present investigation was to examine normative developments in children's number production skills with grade from a mathematics education research perspective. Previous work in this area has most often focused on preschoolers' and early school aged children's knowledge of the number word series up to one hundred, their developing understanding of numeracy and the basic "how to count" principles (e.g., Baroody & Price, 1983; Becker, 1993; Brissiaud, 1992; Fuson, Pergament, Lyons & Hall, 1985; Fuson, Secada & Hall, 1983; Gelman & Gallistel, 1978; Ginsburg, 1977; Michie, 1984; Resnick, 1989; Saxe, Becker, Sadeghpour & Sicillian, 1989; Shannon, 1978; Shipley & Shepperson, 1990a, 1990b; Wagner & Walters, 1982). Only a few studies have examined older children's acquisition of the number sequence into the hundreds and thousands (Bell & Burns, 1981; Kar & Dash, 1991; Siegler & Richards, 1983). Researchers have commonly made the assumption that after children acquire the number words up to one hundred, the remainder of the cardinal number sequence is entirely generative (Ginsburg, 1977; Baroody, 1987).

However, the ability to produce the cardinal number words greater than one hundred is a complicated process and has not been well described in the psychological literature. Naming an arabic numeral form in words is dependent on at least four factors: 1) knowledge and retrieval of appropriate vocabulary words, 2) knowledge of compound rules needed to order vocabulary words correctly within a compound number word, 3) knowledge of place value conventions necessary to translate numbers from their arabic to spoken forms, and 4) problem solving skills to orchestrate the above knowledge. The process of counting forward or backward from a number indefinitely is further complicated, because in addition to naming a number, children must also have an understanding of the cardinal number system to generate the next number in the sequence. It is possible that little research has focused on this topic because number naming and counting skills are assumed to be very automatic and tacit by adulthood and may have been taken for granted.

It would be beneficial to examine the normative developments of school aged children's number naming and counting skills into the thousands, millions, and billions series, to obtain an understanding of the cognitive processes underlying number production, and to determine how children develop this knowledge. Even though researchers have claimed that the words in the cardinal number system are entirely generative after acquiring the word one hundred, the validity of this assumption should be tested empirically, to determine the critical grade level and point in the number series where children can automatically continue the number series indefinitely. It seems unlikely, that by the age of five or six (when most researchers claim children can count by rote up to one hundred) (e.g., Baroody, 1987; Fuson, 1988) that children have acquired the above implicit knowledge for naming and counting numbers and (even when supplied with relevant vocabulary terms), would be able to generate number words in the millions and billions series.

In studying the development of children's number naming and counting skills, it would also be beneficial to determine the order in which the number words are acquired, and relatedly, the characteristics of a number word that are responsible for its early or late acquisition. The only order of acquisition factor that has been implicated in previous research is the cardinal position of the number word within the number series. Many researchers have suggested that children learn the names of the smaller numbers first, not only because they are not as cognitively or morphologically complex as later occurring number words, but because they constitute part of other, larger number words. Then, since the cardinal number system is cumulative and inductive, new words are "added on" to the smaller cardinal number words to generate the names of the larger number words in the series (Baroody, Gannon, Berent, & Ginsburg, 1984; Crossley, 1987; Fayol, 1985; Fuson, 1992a; Fuson & Fuson, 1992; Gellert, Kustner, Hellwich & Kastner, 1977; Holender & Peereman, 1987; Hurford, 1987; McCloskey, 1993). However, more empirical studies are needed to determine the extent to which the cardinal position of the number word is an important acquisition factor, especially with respect to the larger numbers.

Finally, substantial individual differences in counting ability during the preschool and early school aged years have been obtained and then discounted or reported parenthetically in some studies (Hubbard, 1995; Fuson, 1988; Fuson, Richards, & Briars, 1982). These individual differences are important from a developmental perspective in that good preschool and early school-aged counting abilities have been linked to numerical fluency (Baroody, 1987; Gelman & Gallistel, 1978; Hubbard, 1995; Nunes & Bryant, 1996), they have been associated with basic mathematical ability (Baroody, 1987; Hubbard, 1995), and they are used as a strategy to solve mental arithmetic problems (Bisanz, Morrison, & Dunn, 1995; Bisanz & LeFevre, 1990; Hubbard, 1995; Siegler, 1987a; Siegler, 1987b; Siegler & Jenkins, 1987). Furthermore, counting abilities are usually used to ascertain children's knowledge of place value and the base 10 number system (Fuson & Kwon, 1992c; Geary, 1996). However, little research has concentrated on whether the relation between counting, basic mathematical achievement, and place value knowledge is relevant at older grade levels, when counting skills presumably become more automatic. It would be interesting to measure the individual differences in children's counting abilities within different developmental levels, and provide a more thorough understanding of the developing relation between children's counting abilities and mathematical achievement. Since previous work has reported some individual differences in counting ability within a particular age group, it would be relevant to educational curricula to determine the underlying reasons why these differences occur, and whether they disappear at a particular age.

In two studies, children from grades one, three, five, and seven (i.e., ages 6, 8, 10, and 12 years respectively) were asked to name Arabic numerals up to one trillion, and then count from them (i.e., without the aid of any physically present objects) in a forward or backward direction. The primary goal of this research was to document developmental changes in: 1) the number of psychologically basic number words known; 2) the number of cardinal number words known; and 3) children's use of problem solving strategies while naming and counting numbers. In the first study, developmental differences in children's number naming and counting abilities were examined both within and across grade. In the second study, children's times to produce the basic and non-basic cardinal number words were studied in addition to the above abilities in an attempt to understand the cognitive processes that underlie their number naming and counting abilities. It was anticipated that children's number word production skills would not solely depend on the size of their number word vocabulary, but also on their knowledge of the compounding rules and place value conventions requisite for converting the cardinal numerals into words. Furthermore, it was expected that problem solving skills would play an important role in children's abilities to extend the number word series. The current investigation was an extension of previous research since it considered the number production abilities of older children, and related children's number knowledge to the study of language development.

STUDY 1

In the first study, school-aged children completed a basic number word knowledge task. a forward and backward number naming and counting task, and a numerical problem solving task. The tasks attempted to measure developmental differences in children's number naming and counting skills, provide estimates of children's psychologically basic and total cardinal number word vocabularies, and determine the kinds of problem solving techniques children use while producing numbers. Performance differences were measured both within and across grade.

Consistent with Anglin's (1993a) vocabulary findings, it was expected that children's psychologically basic number word vocabularies and consequently their total cardinal number word vocabularies would increase with grade. According to various school curricula (Ministry of Education, 1985; Simcoe County Board of Education, 1988a; Simcoe County Board of Education, 1988b; Waterloo County School Board, 1985a; Waterloo County School Board, 1985b; Waterloo County School Board, 1985c; Waterloo County School Board, 1985d: Waterloo County School Board, 1985e), grade one children should have experienced all two digit numbers and be able to count up to 100, and they should have encountered the first 27 basic number words up to ninety at a minimum. By grade three, children should be able to read and order numerals up to 999, and thus should have added at least one new basic term, hundred to their vocabulary. At the grade five level, children should have gained knowledge of the number word thousand and thus be able to continue the sequence into the thousands series. Finally, grade seven students should have added the basic term million to their vocabularies, and thus should be able to demonstrate knowledge of the millions series.

During the testing, both a forward and a backward counting task were used to assess children's fluency in producing number words and to increase the validity of estimating children's number word vocabulary. That is, if children know the relevant basic number words, the requisite compounding rules and place value conventions, they have the capability of producing additional number words in the series without the presence of any objects, and should be able to do so in either a forward counting or a backward counting direction. Difficulties in producing the cardinal number word sequence in either direction may indicate that children are still learning the structure of the cardinal number sequence, or that they are not able to use their problem solving skills to orchestrate different areas of knowledge.

However, because the forward and backward tasks involve the use of slightly different strategies, children's counting ability may vary as a function of these tasks. Consistent with some previous research (Steinberg, 1985; Thornton & Smith, 1988; Wright, 1994), children may produce more cardinal number words correctly on the forward than the backward counting task, because it is assumed children use "counting on" addition strategies when counting forward (Ashfield, 1989). These addition strategies are taught earlier in school, and are assumed to be easier than the subtraction strategies that are considered requisite for backward counting. Nevertheless, not all studies have supported the performance differential between forward and backward counting (Bell & Burns, 1981; Fuson, 1986; Fuson, 1992c; Fuson & Fuson, 1992).

The numerical problem solving task was designed to determine whether children use problem solving strategies to generate additional number words in the series. Problem solving strategies were assessed using a modified version of Berko's (1958) "wug" test, traditionally used to measure grammatical accomplishments. In this procedure, nonsense words are embedded in sentences, and children are asked to produce grammatical morphemes by filling in missing portions of sentences. Furthermore, children's knowledge of the implicit grammatical rules is assessed independently of words that they may have previously encountered. It was anticipated that if children are using problem solving skills and have knowledge of the compounding rules for generating words in the number series, they should use these strategies, and show knowledge of the compounding rules, when presented with novel basic number words, as did the children who participated in the Berko (1958) study. It was hypothesized that all children would use some form of problem solving while completing the number production tasks. Thus, when presented with the name of a pseudo number word for a number they have not expressed previous knowledge of in earlier tasks, children would be able to use their problem solving capabilities, show knowledge of the compounding rules, and continue labelling number words in the series.

Finally, consistent with previous research (Fuson, 1988; Hubbard, 1995) it was anticipated that there would be considerable individual differences in number naming and counting performance within each grade. In an attempt to account for some of the within grade variability, teacher ratings of the children's mathematical and reading ability were obtained, and children's attitudes towards these subject areas were assessed. Since the tasks in this study may be perceived as both "vocabulary assessments" and as "mathematical tasks," it was expected that children who are proficient in both mathematics and language arts, and who have positive attitudes toward each of these subjects would score higher on the counting tasks compared to their lower achieving agemates.

Method

Participants

Sixteen children from each of grades one, three, five, and seven, from one public school in a moderately large community in Southwestern Ontario participated. Across grade, the children were equally divided across sex. However, at the grade one level there were ten males and six females, and at the grade three level there were six males and ten females. There were equal numbers of males and females in grades five and seven. The mean ages of the children were 6 years, 11 months in grade one, 8 years, 10 months in grade three, 10 years, 11 months in grade five, and 12 years, 10 months in grade seven. Since none of the children had failed or skipped any grades, children's grade levels were consistent with their chronological ages. All children whose parents gave consent for them to participate in the experiment were included in the testing phases of the project. However, the data from children for whom English was not the primary language spoken at home (as assessed by asking parents: Is English the primary language spoken in your home?) were excluded. Likewise, the data of participants were excluded if their teachers reported a particular student had a serious speech or language impediment (i.e., Is the child currently undergoing therapy from a speech and language pathologist?) or an extreme learning disability (i.e., Does the child suffer from any developmental condition that might result in an extreme learning disability?). As a result of these selection criteria, a total of four participants (all in grade seven) were replaced because they did not meet at least one of the requirements.

Materials

For the basic number knowledge task, all cardinal number words that could at a minimum, be considered psychologically basic according to Anglin (1993b), were printed in numeral form on 4 x 6 inch laminated index cards. These basic numbers are listed in Appendix 2. Although participants were not directly tested on the cardinal number words higher than one trillion in subsequent tasks, the last six numbers were included in this task to determine whether the participants had any knowledge of the words representing these less frequently occurring numerical values. The number cards were divided into four sets and randomized within each set for each participant. Specifically, set one contained the basic numbers below 20; set two was composed of the basic decade numbers (20, 30, 40,...90); set three contained the basic numbers from 100 to 1,000,000,000,000; and set four was comprised of the basic numbers greater than 1,000,000,000,000. These sets were presented in ascending order to prevent children from receiving a very large number word at the beginning of the study. Furthermore, the randomization within each set would eliminate any possibilities that children would receive credit for knowing a word simply because it was presented in a standard numerical order.

In the forward and backward counting tasks combined, children were tested on their knowledge of 156 number words ranging from ten to one trillion. Of the 156 words tested, there were 36 special case numbers that occur at certain transition points in the number series. All of these special case numbers were included in the tasks to determine whether children could continue the cardinal number sequence from one level of number words (e.g., hundred millions) to the next (e.g., billions), given changes in the number of digits associated with an arabic representation of the numeral (e.g., 999 to 1,000), and/or changes in the large basic element of the compound (e.g., "nine hundred and ninety-nine" to "one thousand," or "thirty-nine" to "forty"). The list of 36 special case numerals is presented in Appendix 3. However, in order to determine whether children were successful in extending the number series across a transition point where there is a change in the number of digits (i.e., 99 to 100), only half of the special cases (i.e., numbers containing series of nines such as 99, 999) were always included on the forward task while the remaining half (i.e., numbers containing many zeros such as 100, 10,000) were always included on the backward task. This procedure was adopted such that the transition between numbers differing in digit length could be measured for all children on all tasks. Furthermore, counting backward from numbers with several nines (e.g., the number before 99 is 98), or counting forward from a number with many zeros (e.g., the number after 1,000 is 1,001) does not reflect a change in digit length, and thus, would not measure children's abilities to continue the number sequence as the number of digits changes.

It should be noted that although many basic number words are included in the special case number word list, basic number words and special case number words are not considered the same set of words. For clarification, please consult Appendix 2 for the list of the basic number words and Appendix 3 for the 36 special case numerals.

The remaining 120 cardinal number words in the forward and backward tasks were randomly selected from a random numbers table. However, in order to ensure that the cardinal number words were selected from the entire range of one trillion words, the range was divided into five numerical sets (i.e., decades, hundreds, thousands, millions, and billions). Each of these sets was then further divided into three main levels, creating fifteen levels in total and eight cardinal numbers were selected at random from each of these fifteen levels. This selection process ensured that participants were tested on the same number of cardinal number words from each of the five main sets. Furthermore, it facilitated random selection procedures for the thousands, millions, and billions sets. That is, since a random number table was used to select number words, it was easiest to generate an equal number of words for each increasing digit (e.g., 1,000s, 10,000s, 100,000s), beginning with number words that are represented numerically by two digits and continuing up to and including number words represented by 12 digits.

The eight randomly selected numbers from each level were randomly divided into two lists; thus there were four numbers from each level on each of the lists. These two lists are presented in the Appendix 4. For half of the participants at each grade and sex level, list one served as the stimuli for the forward task and list two served as stimuli in the backward task. When list one was used in the forward task, all of the special cases ending in 9 were inserted into list one (and all others were inserted into list two). The lists were reversed for the other half of the participants. However, the special cases were not reversed. Special case numbers ending in 9 were always kept in the forward task, and numbers ending in 0 were always placed within the backward task.

The 156 cardinal numbers (120 random selections and 36 special cases) were printed in numeral form on 4 x 6 inch laminated cards. The cards containing the random numbers were divided into two lists (described earlier) and the number sets were placed in ascending order beginning with the decades set and ending with the billions set. However, the order of the number cards within each set was randomly determined for each participant. The special case numbers at the beginning of each of the five numerical sets (e.g., 99, 100; 999, 1000, etc.) were slotted in according to their numerical position as transition points between number sets. However, the remaining special case numbers not associated with the beginning or end of a number set (e.g., 29; 9,999; 100,000) were grouped with the random numbers from the same number set, and the order of these cards was randomly determined for each participant.

It should be noted that due to discrepancies in the presentation of numbers according to the International and Imperial systems, two sets of number cards were created for all large multi-digit number words. The first set was consistent with the Imperial system, and the groups of three digits in larger numbers were separated by commas. The second set of cards was consistent with the International system, and groups of three digits were separated by spaces. Although this second set was created, the first ten children tested indicated that they had a preference for the numbers contained on the first set of cards, and thus, the first set was used on the number production tasks for all students.

Finally, to assess children's mathematical and linguistic abilities, four classroom teachers completed two five-point rating scales. Specifically, the teachers were asked to rate overall mathematical ability and overall reading ability of each child who participated in the project. Ratings of five indicated that the child was highly above average compared to the children in the class, while ratings of one indicated that the child was highly below average compared to their same aged peers.

Procedure

Participants were tested individually by a female experimenter and all sessions were tape recorded. The experimenter also recorded participants' responses on a scoring sheet. Participants were asked to complete several number naming and counting tasks to determine how high they could name and count numbers. They completed the basic number task, the forward/backward counting tasks, and the numerical problem solving task in that order. These tasks will be described in detail below.

Basic Number Knowledge Task

For the basic number knowledge task, participants were shown 39 index cards with the "psychologically basic" numerals written on them, beginning with the first set of basic number words and continuing on up to the fourth set. The participants were asked to orally identify the name of the number on each card. If they did not know the name of the number on the card, they were told they could either guess or indicate that they did not know. All children were asked to demonstrate their knowledge of all 39 numerals on the cards. Incorrect responses were tallied on the scoring sheet.

When the first large multi-digit number appeared in the basic number knowledge task (that could be represented using either commas or spaces), children were shown the number written according to the conventions of the International (e.g., 10 000) and Imperial systems (e.g., 10,000), and were asked to indicate their preference. The first ten children in the study all indicated that they had a preference for the Imperial system of writing numbers or that it did not matter, and thus, the numbers were presented with commas for the remaining children.

Forward and Backward Naming and Counting Tasks

For the forward and backward tasks, participants were shown an index card containing a numeral and were asked to state the name of the number on the card. Then, for the forward counting trials, participants were asked to state the number that immediately follows the cardinal number on the card, as if they were counting forward by ones. Conversely, for backward counting trials, participants were asked to verbally state the cardinal number that immediately precedes the number on the card, as if they were counting backward by ones. If children indicated that they did not know how to name a number, the counting trial was skipped. Participants were allowed to make corrections while completing the tasks and their last response was evaluated for correctness. If the experimenter felt that the children made an error through lack of concentration or clumsiness, the children were asked to state their answer again, as if the experimenter had not heard part of their original response, and the response on this second trial was evaluated for correctness. A second trial was uncommon, occurring in less than three percent of all responses. The children did not receive feedback as to whether their responses were correct or not. Participants were explicitly instructed that ordinal numbers (e.g., second, fourth), fractions, decimals and other numerical expressions (e.g., many, twice) were not acceptable responses. The children completed four practice trials for each of the forward and backward tasks to ensure that they correctly understood the testing procedure. The forward and backward tasks were continued until participants either completed all of the number cards or they failed naming a number on eight consecutive cards (i.e., through either errors or omissions). Children's incorrect responses to name the number words, and to correctly produce the next number in the forward and backward tasks were tallied on the answer sheet.

Although all participants were asked to complete the forward and backward tasks, the order of these two tasks was randomly determined for each participant. Half of the participants at each grade level completed the forward task first, immediately followed by the backward task. The remaining half of the participants at each grade level completed the tasks in the reverse order.

Responses on the forward and backward counting tasks were considered correct if they conformed to the names of the denominations in the American number system. Using the American counting system did not pose a problem since interviews with the teachers revealed that the children were taught mathematics using this counting system in school. Inclusion of the conjunction "and," within each number word (e.g., one hundred and twenty-five), as well as the article "a" in place of "one" in responses such as "a hundred" were considered acceptable. Basic multi-digit number names were also accepted in responses omitting the word "one." For example, hundred was accepted as a response for 100. Finally, short forms of the cardinal number words (e.g., two sixty-one, for 261; or fourteen ninety-two for 1492) were not accepted. Children were asked to produce the longer form of the word.

Numerical Problem Solving Task

For the numerical problem solving task, children were told that they would be asked about their knowledge of some very difficult number words. Children were shown the first basic number word that they were unable to identify during the forward and backward counting tasks. To eliminate any possibility that the number word had been encountered previously, children were told the name of a pseudo number word, one guggle. Although the targeted basic number word was different for different children, the same pseudo label was used for all basic number words. Given knowledge of this "new" number word, children were asked to produce the next five number words in the series.

Finally, children were asked if they used any strategies (i.e., "How did you know all of these numbers?," "How did you know what number came before/next?," "Did you memorize all of these numbers?") after completing the counting tasks. They also answered some questions that attempted to assess their attitude (i.e., Do you like math/reading?) and self perceived ability (i.e., Are you good at math/reading?) with respect to mathematics and reading using categorical "yes" or "no" questions.

Scoring

Raw Number Production Data

The number of correct responses on each of the basic number knowledge, forward counting, backward counting, and numerical problem solving tasks was tallied for each participant. Mean scores were then calculated for children at each grade level. They could range from 0 to 39 on the basic number knowledge task, and from 0 to 5 on the numerical problem solving task.

For each of the forward and backward tasks, two scores were determined for each participant: 1) a number naming score and 2) a counting score. The number naming score reflects the total number of cardinal number words produced correctly when the number was presented in arabic form. The counting score indicates the total number of trials for which children were capable of generating the next number word or the preceding number word correctly in the series. The naming and counting scores were summed independently; thus, it was possible for children to name a number incorrectly, but receive credit for the counting trial for that number. Children's forward and backward scores on each of the naming and counting variables could range from 0 to 78. The forward and backward scores were then added together, to produce a total naming score and a total counting score for each participant. Both of the total naming and counting scores could range from 0 to 156.

Since the forward and backward counting tasks contained sets of randomly selected and special case number words, the number naming and number counting scores were further divided into these components. There were 60 randomly selected numbers in each task, and thus each naming and counting score could range from 0 to 60 for these numbers on each of the forward and backward tasks. The special case number word score could range from 0 to 18 on each of the forward and backward counting tasks. Once again, the forward and backward scores were collapsed, to produce a total random naming score (maximum score of 120), a total random counting score (maximum score of 120), a total special case naming score (maximum score of 36), and a total special case counting score (maximum score of 36) for each participant.

To determine how consistent children were at producing number words correctly on both the basic number knowledge task, and on the total number production tasks (including the forward and backward number naming and counting tasks), children's stopping points (i.e., the largest correctly produced number on each task) were recorded for each participant. Participants then received a categorical rating according to the consistency of their responses across the two tasks. More specifically, children received a "consistent" rating if their stopping points were within the same number series for both the basic number knowledge and the number production tasks. Responses were also coded "basic score greater" when children received credit for knowing numbers from a higher number series on the basic number knowledge task, than on the number production tasks. Conversely, "number production score greater" was coded when children received credit for a number in a higher number series on the number production task, compared to the basic number knowledge task.

Estimating Children's Cardinal Number Word Vocabularies

Since the cardinal number words were randomly sampled on the total, forward and backward counting tasks, it is possible to estimate children's number naming and counting abilities of the entire cardinal number word sequence (up to one trillion) using their scores from these tasks. Estimation scores of children's total cardinal number word knowledge were obtained by multiplying the proportion of number words answered correctly on the counting tasks by the total population of cardinal number words sampled (i.e., up to one trillion). However, since the number of cardinal number words within each set multiplies from one series to the next, different multipliers were used to determine an estimated score for each set of the number series. These scores were then summed across the five number series to produce a total estimated cardinal number word score at each grade level. A list of the number ranges from which numerals were randomly sampled, and the corresponding multipliers used to derive the estimates for each set of numbers is presented in Appendix 5.

For the range of decade numbers from 10 to 99, 15 numerals were included in the special case list, leaving 75 numbers from which the remaining numbers on the forward and backward tasks were randomly selected (see Appendices 3 and 4). In order to estimate children's number naming and counting abilities at the decade level, the proportion of correct random numbers on the number production tasks was multiplied by 75. A similar procedure was followed for number words occurring within the hundreds series. Since there are 898 random number words from one hundred and one to nine hundred and ninety-eight in the hundreds sequence population, the proportion of random numbers on the number production tasks answered correctly by the children in the hundreds series was multiplied by 898.

However, since the number of cardinal number words increases exponentially within each of the thousands, millions and billions series, different constants were used to estimate children's cardinal number knowledge at each level of these three number series. At the first level of the thousands series, there are 8998 number words from one thousand and one to nine thousand, nine hundred and ninety-eight. Thus, the proportion of correct scores on the random component of the number naming and counting tasks at the first level of the thousands series was multiplied by 8998. At level two of the thousands series, there are 89,998 number words from ten thousand and one to ninety-nine thousand, nine hundred and ninety-eight. As a result, the proportion of correct responses at level two of the thousands series was multiplied by 89,998. Finally, because there are 899,998 number words from one hundred thousand and one to nine hundred and ninety-nine thousand, nine hundred and ninety-eight, correct scores at this level were multiplied by 899,998. Using similar logic, the proportions of correct random scores at levels one, two, and three of the millions set were multiplied by 8,999,998; 89,999,998; and 899,999,998 respectively. Likewise, the proportion of correct random scores on the counting tasks at levels one, two, and three of the billions set were multiplied by 8,999,999,998; 89,999,999,998; and 899,999,999,998 respectively.

Finally, since the special case number words were not included in the random scores, and knowledge of them was directly assessed on the naming and counting tasks, the number of special case words children correctly responded to on the naming and counting tasks was added to their final estimated counting and naming scores. Thus, in total, the sum of children's total number naming and counting scores could range from 10 to 1,000,000,000,000.[4]

Individual Differences Data

To determine how proficient individual children were at naming and counting numbers at a particular series within the cardinal number system, their total scores on the number naming and counting tasks were converted into a four point number production proficiency ordinal scale. Children received a score on the number production proficiency scale for both their number naming and counting performance at each of the number series tested (i.e., decades, hundreds, low thousands, ten thousands, hundred thousands, low millions, ten millions, hundred millions, low billions, ten billions, hundred billions). Scores of "one" indicated that children did not have any knowledge of how to produce the numbers within a particular series, evidenced by the fact that they did not receive any credit for the numbers in that series. Children received scores of "two" if they showed some knowledge of how to name or count numbers within a number series, and received credit for at least one, but not more than 74% of the numerals presented within that series (which translates into receiving credit for at least one number in a particular number series, but making more than two mistakes on the eight trials of both the forward and backward tasks for each specific number level). Scores of "three" represented children who showed good (but not perfect) knowledge, and received credit for 75% to 99% of the number words at a particular level (which translates into making only one or two mistakes on each of the forward and backward tasks for a particular number series). Finally, scores of "four" indicated that children had mastered the numbers within a particular number series, and they made no errors while naming or counting the numbers.

Results

The results section is divided into four main parts. In the first section, the outcomes of several ANOVAs and dependent t-tests on children's number naming and counting scores are reported as a function of grade and sex. In the second section, children's total number naming and counting scores are used to obtain estimates of their basic, problem solved, and total number word vocabularies. The third section contains a discussion of the individual differences in children's number naming and counting performance within each grade. Finally, in the fourth section, correlation coefficients examining the relation between children's number production abilities and teacher ratings of children's academic abilities are reported. Since preliminary analyses did not yield any significant main effects or interactions for the word list or task order variables, these two conditions were collapsed, and analyses are conducted across them.

Number Naming, Counting and Problem Solving Analyses

Table 1 illustrates children's mean scores on the basic number knowledge task, total number naming and counting tasks, and numerical problem solving task as a function of grade and sex. A grade by sex ANOVA conducted on children's mean basic number knowledge scores revealed a statistically significant effect of grade, $F(3, 56) = 11.21$, $p < .001$. Most children in grades one, three, five, and seven could correctly produce all basic number words up to fifty, one thousand, one million, and one billion respectively. However, Tukey (HSD) post hoc procedures indicated that only the grade one level mean differed significantly from the means at the other grade levels ($p < .05$).

A repeated measures ANOVA with grade and sex as the between subjects measures, and task direction (i.e., forward versus backward) as the within subjects measure conducted on children's total number word naming ability revealed a statistically significant grade effect $F(3, 56) = 57.42$, $p < .001$, and a sex effect, $F(1, 56) = 4.69$, $p < .035$. The average grade one score

Table 1

Children's Mean Basic Number Knowledge, Total Naming and Counting, and Numerical Problem Solving Scores in Study 1 as a Function of Grade and Sex

	Grade				
Basic Number Knowledge	1	3	5	7	Total
(out of 38)					
Boys	27.10	29.67	29.88	31.75	29.67
Girls	24.17	29.60	30.75	30.50	29.09
Overall	26.00	29.63	30.31	31.13	29.27
Naming Task					
(out of 156)					
Boys	50.10	86.17	112.63	153.50	98.34
Girls	31.50	76.60	106.63	137.13	90.78
Overall	43.13	80.19	109.63	145.31	94.56
Counting Task					
1) OVERALL COUNTING					
(out of 156)					
Boys	42.70	84.67	109.25	152.00	94.53
Girls	23.17	73.30	102.75	131.25	85.75
Overall	35.38	77.56	106.00	141.63	90.14

Table 1 (Continued)

2) FORWARD COUNTING					
(out of 78)					
Boys	23.60	42.67	55.00	77.88	48.59
Girls	13.00	36.90	53.13	68.38	44.34
Overall	19.63	39.06	54.06	73.13	46.47
3) BACKWARD COUNTING					
(out of 78)					
Boys	19.10	42.00	54.25	74.13	45.94
Girls	10.17	36.40	49.63	62.88	41.41
Overall	15.75	38.50	51.94	68.50	43.67
Problem Solving Task					
(out of 5)					
Boys	2.40	2.50	3.75	5.00	3.41
Girls	1.33	1.50	2.50	4.38	2.44
Overall	2.00	1.88	3.13	4.69	2.92

fell within the hundreds series, with 50% of grade one students being able to name at least one number at this level. At the grade three level, 56% of children were able to name numbers at the ten thousands level, and thus, the mean score fell within the ten thousands range. The average grade five naming score fell within the ten millions, with 56% of the grade five students correctly identifying at least one number word at this level. Finally, the grade seven mean number naming score fell within the ten billions series, and 94% of grade seven students were able to name a number word at this level. Tukey (HSD) post hoc tests indicated that all grade means differed significantly ($p < .05$). With respect to the sex effect, boys named more number words correctly than girls, and post hoc tests revealed that the difference between boys and girls was only statistically significant at the grade one and seven levels ($p < .05$).[5]

Results of the analyses on children's total counting ability were quite consistent with the total naming data, indicating that most children could generate the next number word in the series. A repeated measures ANOVA with grade and sex as the between subjects factors and task direction as the within subjects factor on children's total counting ability revealed a grade effect, $F(3, 56) = 61.45$, $p < .001$, a sex effect, $F(1, 56) = 6.20$, $p < .016$, and counting direction effect, $F(1, 56) = 10.66$, $p < .002$. Children counted higher during the forward than the backward counting tasks. However, t-test comparisons made at each of the four grade levels indicated that the advantage for forward counting existed only at the grade one ($t(15) = 2.19$, $p < .015$ (one-tailed) and grade seven levels ($t(15) = 2.36$, $p < .016$ (one-tailed).

The relative advantage of forward over backward counting was also observed when the randomly selected number words ($t(63) = 2.03$, $p < .047$) and the special case number words ($t(63) = 4.85$, $p < .001$) were considered separately. However, close examination of the data at each grade level revealed that the counting direction was more influential in predicting correctness for the special case than the randomly selected numbers. More specifically, although none of the forward versus backward comparisons at each grade level for the random trials was significant, all respective pairwise comparisons for the special case trials were highly significant in favoring forward counting ($t(15) = 2.95$, $p < .001$; $t(15) = 3.47$, $p < .003$; $t(15) = 2.49$, $p < .025$; $t(15) = 2.46$, $p < .026$, at the grade one, three, five and seven levels respectively).

As indicated by the previously cited ANOVA and consistent with the naming data, children's counting performance increased significantly with grade. In grade one, 94% and 88% of the children could count forward and backward from at least one number in the decades respectively, and the average grade one scores fell in the seventies. By grade three, 44% could count forward and 38% could count backward from numbers into the ten thousands, placing the grade three mean for both forward and backward counting in the ten thousands series. At the grade five level, the forward counting mean was at the ten millions series, with 44% of grade five students being able to count forward from at least one number in the ten millions series. The backward counting mean fell in the low millions, and 31% of the grade fives could count backward from numbers at this level. Finally, at the grade seven level, 88% and 75% of children could count forward and backward from a number in the ten billions, respectively, placing the means for these counting tasks in the ten billions. Tukey (HSD) post hoc procedures revealed that the differences between means across all grade levels were significant ($p < .05$).

With respect to the sex effect, boys were more likely on average to count higher than girls. However, when the children were compared within grade, only the difference between means at the grade one level for boys and girls, and the means at the grade seven level for boys and girls differed significantly (p <.05).[6]

The consistency of children's scores on the basic number knowledge and the number production tasks are presented as a function of grade in Table 2. As illustrated in the table, approximately half of the children produced number words correctly from the same number series on both tasks. However, 23% of students received credit for larger numbers on the basic number knowledge than the number production task, while the remaining 30% of students produced larger numbers on the number production than the basic number knowledge task. Furthermore, it is interesting that the children in grades one and three who were inconsistent tended to perform better on the basic number knowledge than the number production task. However, the opposite inconsistency pattern was found for children in grades five and seven who tended to score higher on the number production than the basic knowledge task.

Table 1 illustrates the mean scores on the numerical problem solving task and Table 3 contains the frequency of children's scores on the numerical problem solving task as a function of grade. As illustrated in Table 3, children's scores on the task were either 0, 4, or 5 (out of a possible score of 5), indicating that children were very consistent in their responding and they either received credit for all, almost all, or none of the questions on this task. A grade by sex ANOVA conducted on the mean numerical problem solving data revealed a statistically significant grade effect, $F(3, 56) = 27.22$, p <.002. However, Tukey post hoc tests indicated that only the grade one and three means differed significantly from the grade seven mean. Across grade, 26 children did not receive any credit for any items on the numerical problem solving task. Close observations of their errors revealed that 58% (i.e., 15) of these children

Table 2

Percentage of Children who Produced Consistent Scores on Both the Basic Number Knowledge Task and the Number Production Tasks in Study 1.

Grade	Consistent	Inconsistent #1 (Basic Score greater)	Inconsistent #2 (Number Production Score Greater)
1	63	37	0
3	44	31	25
5	56	6	38
7	25	19	56
Total	47	23	30

Table 3

Frequency of Children's Problem Solving Scores as a Function of Grade on the Numerical Problem Solving Task in Study 1

Problem Solving	Grade 1	Grade 3	Grade 5	Grade 7	Overall
0	9	10	6	1	26
1	0	0	0	0	0
2	0	0	0	0	0
3	0	0	0	0	0
4	3	0	0	0	3
5	4	6	10	15	35

produced the incorrect problem solving variation of "two guggle, three guggle, four guggle, five guggle." An additional 19% (i.e., 5) of the children indicated that they did not know the answers to the questions, and 23% (i.e., 6) of the children (mostly at the grade one level) produced other idiosyncratic problem solving errors. For example, one grade one child indicated that after one guggle came "two, three, four, five." Another grade one student indicated that one guggle was followed by "one guggle and one guggle, one guggle and two guggle, one guggle and three guggle," and so forth.

Estimates of Children's Number Naming and Counting Knowledge

Children's median estimated number naming and total counting scores as a function of grade are presented in Table 4. Counting performance is further divided into forward and backward counting estimates in Table 5. Since there were 16 children per grade, the median score is the average of the eighth and ninth ranked children's estimates. It should be noted that in most cases, the medians for total naming, total counting, forward counting and backward counting do not necessarily contain data from the same children. Medians are reported (instead of means and ANOVAs) due to extreme variability in the scores (i.e., estimates ranged from 15 to 1,000,000,000,000 for naming, and from 9 to 1,000,000,000,000 for counting).

From these estimates, the median number of cardinal number words that could at a maximum be constructed through problem solving was determined for children at each grade. These scores were computed by subtracting the mean number of words known on the basic number knowledge task from the total median number word naming and counting estimates and are presented in Table 6. Once again, means and ANOVAs were not computed on the estimates of words generated through problem solving due to variability in the scores.

Table 4

Median Estimated Number (and Range) of Cardinal Number Words Nameable and Countable at Each Grade in Study 1

Grade	Naming Estimate	Counting Estimate
1	156	96
	(15 - 2125)	(9 - 2082)
3	52,187	19,560
	(999 - 988,749,887,500)	(999 - 988,637,387,499)
5	67,644,440	18,031,372
	(1000 - 1,000,000,000,000)	(999 - 999,999,999,997)
7	1,000,000,000,000	999,999,999,995
	(88,750- 1,000,000,000,000)	(88,748- 1,000,000,000,000)

Table 5

Median Estimated Number (and Range) of Cardinal Number Words and Range of Estimated Scores Countable on the Forward and Backward Tasks at Each Grade Level in Study 1

Grade	Forward Counting Estimate	Backward Counting Estimate
1	87	98
	(9 - 1000)	(9 - 3175)
3	8873	6,623
	(999 - 999,999,774,999)	(999 - 977,274,999,999)
5	2,012,497	774,998
	(999 - 999,999,999,997)	(999 - 999,999,999,997)
7	999,999,999,995	999,988,749,995
	(99,998 - 1×10^{12})	(77,499 - 1×10^{12})

Table 6

Median Estimated Number of Words Deducible Through Problem Solving at Each Grade in Study 1

Grade	Mean Basic Number Knowledge Score	Naming Estimate	Counting Estimate
1	26.00	130	70
3	29.63	52,157	19,530
5	30.31	67,644,410	18,031,342
7	31.13	999,999,999,969	999,999,999,964

Individual Differences in Number Naming and Counting Abilities

The percentages of children who fell at each of the four levels on the number production proficiency scale at each grade level are presented as a function of the five number levels (i.e., decades, hundreds, thousands, millions, billions) in Table 7, and then at more specific levels (e.g., ten thousands, hundred thousands and so forth) in Tables 8, 9, 10, and 11. Close examination of the data in these tables illustrates the large variability in children's number naming and counting performance within each grade. Specifically, although 50 percent of the grade one children had mastered all of the decade level numbers and were working on learning the number words at the hundreds level, one child had limited number naming and no counting knowledge of the decades sequence. Conversely, another grade one child demonstrated some ability to name and count numbers into the low thousands. At the grade three level, most children could name and count numbers at various levels of the thousands series, but there was one child who was able to name some numbers and count from them without any errors into the hundred billions. Although over 50 percent of the grade five children were working on naming and counting from numbers in the millions series, one grade five student had no knowledge of how to compound number words in the low thousands, while four grade five children (i.e., 25 percent) had reached the mastery level for the hundred billions. Finally, even though over 60 percent of the grade seven students mastered naming and counting number words in the billions, one student had difficulty producing number words in the hundred thousands.[7]

Table 7

Percentage of Children Falling in the Four Categories of the Number Production Proficiency Scale for Overall Naming and Counting at the Five Number Series in Study 1

Grade 1

	Naming				Counting			
Series	1*	2	3	4	1	2	3	4
Decades	0.0**	6.3	43.8	50.0	6.3	12.5	50.0	31.3
Hundreds	50.0	25.0	18.8	6.3	56.3	25.0	18.8	0.0
Thousands	93.8	6.3	0.0	0.0	93.8	6.3	0.0	0.0
Millions	100.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0
Billions	100.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0

Grade 3

	Naming				Counting			
Series	1	2	3	4	1	2	3	4
Decades	0.0	0.0	0.0	100.0	0.0	0.0	0.0	100.0
Hundreds	0.0	0.0	0.0	100.0	0.0	0.0	0.0	100.0
Thousands	25.0	68.8	6.3	0.0	31.3	62.5	6.3	0.0
Millions	87.5	6.3	0.0	6.3	87.5	6.3	6.3	0.0
Billions	93.8	0.0	6.3	0.0	93.8	0.0	6.3	0.0

*1 = No Knowledge (0% Correct)

2 = Some Knowledge (1% to 74% Correct)

3 = Still Learning (75% to 99% Correct)

4 = Mastery (100% Correct)

**Please note that approximately 6.3% = One Child

Table 7 (continued)

Grade 5	Naming				Counting			
	1*	2	3	4	1	2	3	4
Series								
Decades	0.0**	0.0	0.0	100.0	0.0	0.0	0.0	100.0
Hundreds	0.0	0.0	0.0	100.0	0.0	0.0	0.0	100.0
Thousands	6.3	37.5	18.8	37.5	6.3	37.5	25.0	31.3
Millions	37.5	31.5	6.3	25.0	43.8	31.3	0.0	25.0
Billions	62.5	12.5	0.0	25.0	62.5	12.5	0.0	25.0

Grade 7	Naming				Counting			
	1	2	3	4	1	2	3	4
Series								
Decades	0.0	0.0	0.0	100.0	0.0	0.0	0.0	100.0
Hundreds	0.0	0.0	0.0	100.0	0.0	0.0	0.0	100.0
Thousands	0.0	12.5	12.5	75.0	0.0	12.5	12.5	75.0
Millions	6.3	6.3	6.3	81.3	6.3	6.3	31.3	56.3
Billions	6.3	18.8	6.3	68.8	12.5	12.5	12.5	62.5

*1 = No Knowledge (0% Correct)

2 = Some Knowledge (1% to 74% Correct)

3 = Still Learning (75% to 99% Correct)

4 = Mastery (100% Correct)

**Please note that approximately 6.3% = One Child

Table 8

Percentage of Grade One Students Falling in the Categories of the Number Production Proficiency Rating (Rtg) Scale in Study 1

	Total Naming Data				Total Counting Data			
Number Series	Rtg= 1	Rtg= 2	Rtg= 3	Rtg= 4	Rtg= 1	Rtg= 2	Rtg= 3	Rtg= 4
Decades	0.0*	6.3	43.8	50.0	6.3	12.5	50.0	31.3
Hundreds	50.0	25.0	18.8	6.3	56.3	25.0	18.8	0.0
Low Thousands	93.8	6.3	0.0	0.0	93.8	6.3	0.0	0.0
Ten Thousands	100.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0
Hundred Thousands	100.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0
Low Millions	100.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0
Ten Millions	100.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0
Hundred Millions	100.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0
Low Billions	100.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0
Ten Billions	100.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0
Hundred Billions	100.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0

*Please note that approximately 6.3% = One Child

Table 8 (continued)

	Forward Counting				Backward Counting			
Number Series	Rtg= 1	Rtg= 2	Rtg= 3	Rtg= 4	Rtg= 1	Rtg= 2	Rtg= 3	Rtg= 4
Decades	6.3*	18.8	37.5	37.5	12.5	18.8	12.5	56.3
Hundreds	62.5	6.3	6.3	25.0	68.8	12.5	18.8	0.0
Low Thousands	100.0	0.0	0.0	0.0	93.8	6.3	0.0	0.0
Ten Thousands	100.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0
Hundred Thousands	100.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0
Low Millions	100.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0
Ten Millions	100.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0
Hundred Millions	100.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0
Low Billions	100.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0
Ten Billions	100.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0
Hundred Billions	100.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0

*Please note that approximately 6.3% = One Child

Table 9

Percentage of Grade Three Students Falling in the Categories of the Number Production Proficiency Rating (Rtg) Scale in Study 1

	Total Naming Data				Total Counting Data			
Number Series	Rtg= 1	Rtg= 2	Rtg= 3	Rtg= 4	Rtg= 1	Rtg= 2	Rtg= 3	Rtg= 4
Decades	0.0*	0.0	0.0	100.0	0.0	0.0	0.0	100.0
Hundreds	0.0	0.0	0.0	100.0	0.0	0.0	0.0	100.0
Low Thousands	31.3	18.8	12.5	37.5	37.5	12.5	18.8	31.3
Ten Thousands	43.8	25.0	6.3	25.0	43.8	31.3	0.0	25.0
Hundred Thousands	75.0	18.8	6.3	0.0	75.0	18.8	6.3	0.0
Low Millions	87.5	6.3	0.0	6.3	87.5	6.3	0.0	6.3
Ten Millions	87.5	6.3	0.0	6.3	87.5	6.3	0.0	6.3
Hundred Millions	87.5	6.3	0.0	6.3	93.8	0.0	0.0	6.3
Low Billions	93.8	0.0	0.0	6.3	93.8	0.0	0.0	6.3
Ten Billions	93.8	0.0	6.3	0.0	93.8	0.0	6.3	0.0
Hundred Billions	93.8	0.0	0.0	6.3	93.8	0.0	0.0	6.3

*Please note that approximately 6.3% = One Child

Table 9 (continued)

Number Series	Forward Counting				Backward Counting			
	Rtg= 1	Rtg= 2	Rtg= 3	Rtg= 4	Rtg= 1	Rtg= 2	Rtg= 3	Rtg= 4
Decades	0.0	0.0	0.0	100.0	0.0	0.0	0.0	100.0
Hundreds	0.0	0.0	0.0	100.0	0.0	0.0	0.0	100.0
Low Thousands	37.5	18.8	12.5	31.3	43.8	6.3	6.3	43.8
Ten Thousands	56.3	12.5	6.3	25.0	62.5	6.3	6.3	25.0
Hundred Thousands	87.5	6.3	6.3	0.0	81.3	6.3	6.3	6.3
Low Millions	87.5	6.3	0.0	6.3	93.8	0.0	0.0	6.3
Ten Millions	87.5	6.3	0.0	6.3	87.5	6.3	0.0	6.3
Hundred Millions	93.8	0.0	0.0	6.3	87.5	6.3	6.3	0.0
Low Billions	93.8	0.0	0.0	6.3	93.8	0.0	0.0	6.3
Ten Billions	93.8	0.0	0.0	6.3	93.8	0.0	0.0	6.3
Hundred Billions	93.8	0.0	0.0	6.3	93.8	0.0	0.0	6.3

*Please note that approximately 6.3% = One Child

Table 10

Percentage of Grade Five Students Falling in the Categories of the Number Production Proficiency Rating (Rtg) Scale in Study 1

	Total Naming Data				Total Counting Data			
Number Series	Rtg= 1	Rtg= 2	Rtg= 3	Rtg= 4	Rtg= 1	Rtg= 2	Rtg= 3	Rtg= 4
Decades	0.0*	0.0	0.0	100.0	0.0	0.0	0.0	100.0
Hundreds	0.0	0.0	0.0	100.0	0.0	0.0	0.0	100.0
Low Thousands	6.3	0.0	18.8	75.0	6.3	0.0	18.8	75.0
Ten Thousands	12.5	6.3	6.3	75.0	12.5	6.3	6.3	75.0
Hundred Thousands	25.0	31.3	0.0	43.8	25.0	31.3	6.3	37.5
Low Millions	56.3	12.5	0.0	31.3	50.0	18.8	6.3	25.0
Ten Millions	43.8	25.0	6.3	25.0	43.8	25.0	6.3	25.0
Hundred Millions	50.0	25.0	0.0	25.0	68.8	6.3	0.0	25.0
Low Billions	62.5	6.3	0.0	31.3	62.5	6.3	0.0	31.3
Ten Billions	62.5	6.3	6.3	25.0	62.5	12.5	0.0	25.0
Hundred Billions	68.8	6.3	0.0	25.0	68.8	6.3	0.0	25.0

*Please note that approximately 6.3% = One Child

Table 10 (continued)

Number Series	Forward Counting Rtg= 1	Forward Counting Rtg= 2	Forward Counting Rtg= 3	Forward Counting Rtg= 4	Backward Counting Rtg= 1	Backward Counting Rtg= 2	Backward Counting Rtg= 3	Backward Counting Rtg= 4
Decades	0.0	0.0	0.0	100.0	0.0	0.0	0.0	100.0
Hundreds	0.0	0.0	0.0	100.0	0.0	0.0	0.0	100.0
Low Thousands	6.3	6.3	12.5	75.0	6.3	0.0	0.0	93.8
Ten Thousands	18.8	0.0	0.0	81.3	12.5	6.3	0.0	81.3
Hundred Thousands	37.5	6.3	12.5	43.8	31.3	25.0	0.0	43.8
Low Millions	50.0	6.3	6.3	37.5	68.8	0.0	0.0	31.3
Ten Millions	56.3	12.5	0.0	31.3	56.3	12.5	0.0	31.3
Hundred Millions	62.5	0.0	6.3	31.3	68.8	0.0	0.0	31.3
Low Billions	62.5	0.0	0.0	37.5	68.8	0.0	0.0	31.3
Ten Billions	62.5	6.3	0.0	31.3	68.8	0.0	6.3	25.0
Hundred Billions	68.8	0.0	0.0	31.3	75.0	0.0	0.0	25.0

*Please note that approximately 6.3% = One Child

Table 11

Percentage of Grade Seven Students Falling in the Categories of the Number Production Proficiency Rating (Rtg) Scale in Study 1

	Total Naming Data				Total Counting Data			
Number Series	Rtg= 1	Rtg= 2	Rtg= 3	Rtg= 4	Rtg= 1	Rtg= 2	Rtg= 3	Rtg= 4
Decades	0.0*	0.0	0.0	100.0	0.0	0.0	0.0	100.0
Hundreds	0.0	0.0	0.0	100.0	0.0	0.0	0.0	100.0
Low Thousands	0.0	0.0	0.0	100.0	0.0	0.0	0.0	100.0
Ten Thousands	0.0	0.0	6.3	93.8	0.0	0.0	6.3	93.5
Hundred Thousands	6.3	6.3	12.5	75.0	6.3	6.3	12.5	75.0
Low Millions	6.3	6.3	0.0	87.5	6.3	6.3	0.0	87.5
Ten Millions	6.3	6.3	0.0	87.5	6.3	6.3	18.8	68.8
Hundred Millions	6.3	6.3	6.3	81.3	12.5	12.5	0.0	75.0
Low Billions	12.5	12.5	0.0	75.0	12.5	12.5	12.5	62.5
Ten Billions	6.3	18.8	6.3	68.8	12.5	12.5	0.0	75.0
Hundred Billions	12.5	12.5	0.0	75.0	12.5	12.5	0.0	75.0

*Please note that approximately 6.3% = One Child

Table 11 (continued)

Number Series	Forward Counting				Backward Counting			
	Rtg= 1	Rtg= 2	Rtg= 3	Rtg= 4	Rtg= 1	Rtg= 2	Rtg= 3	Rtg= 4
Decades	0.0	0.0	0.0	100.0	0.0	0.0	0.0	100.0
Hundreds	0.0	0.0	0.0	100.0	0.0	0.0	0.0	100.0
Low Thousands	0.0	0.0	0.0	100.0	0.0	0.0	0.0	100.0
Ten Thousands	0.0	0.0	0.0	100.0	0.0	0.0	6.3	93.8
Hundred Thousands	6.3	6.3	0.0	87.5	12.5	0.0	12.5	75.0
Low Millions	6.3	6.3	0.0	87.5	12.5	0.0	0.0	87.5
Ten Millions	6.3	0.0	6.3	87.5	12.5	0.0	12.5	75.0
Hundred Millions	6.3	0.0	0.0	93.8	12.5	0.0	12.5	75.0
Low Billions	12.5	0.0	6.3	81.3	25.0	6.3	6.3	62.5
Ten Billions	12.5	0.0	0.0	87.5	25.0	0.0	0.0	75.0
Hundred Billions	12.5	0.0	0.0	87.5	25.0	0.0	0.0	75.0

*Please note that approximately 6.3% = One Child

Relation between Number Production Performance and Academic Abilities

The Pearson product moment correlation coefficient was used to examine the relation between children's performance on the number production measures, and teachers' ratings of children's mathematical and reading abilities. Given a priori predictions, all correlations were conducted using one-tailed tests. At the grade one level, teacher ratings of children's mathematical performance were significantly correlated with children's total number naming [$r(14) = 0.76$, $p < .001$] and counting abilities [$r(14) = 0.88$, $p < .001$]. Teachers' mathematical ratings at the grade five level were also significantly correlated with children's basic number knowledge [$r(14) = 0.59$, $p < .01$], total number naming abilities [$r(14) = 0.59$, $p < .01$], and their abilities to count random numbers [$r(14) = 0.58$, $p < .01$]. However, although the relations between teacher ratings of mathematical abilities and the children's performance on the number production tasks for the grade three and seven children were positive [with $r(14)$'s ranging from 0.29 to 0.42], the correlations between these variables were not statistically significant.

Teacher ratings of reading ability were not as strongly correlated with the children's number naming and counting skills as the ratings of mathematical ability, although the analyses yielded some statistically significant findings at the grade one level. Specifically, teacher ratings of grade one students' reading ability were significantly correlated with children's number naming [$r(14) = 0.64$, $p < .01$] and counting abilities [$r(14) = 0.75$, $p < .001$]. Finally, children's responses to questions on mathematical and reading anxiety and the strategies they claimed to have used during the testing did not reveal any obvious differences within or between age groups.

Discussion

Results clearly revealed strong increases in children's basic number word vocabularies with grade. Older children may have produced more number words correctly because they have larger vocabularies (Anglin, 1993a), and they have been exposed to more mathematics curricula where number words are taught, compared to their younger counterparts (Ministry of Education, 1985; Simcoe County Board of Education, 1988a; Simcoe County Board of Education, 1988b; Waterloo County Board of Education, 1985a; Waterloo County Board of Education, 1985b; Waterloo County Board of Education, 1985c; Waterloo County Board of Education, 1985d; Waterloo County Board of Education, 1985e). Furthermore, older children may have developed a better understanding of the cardinal number system, which may have enhanced their knowledge of the meaning of each basic number word. For example, older children may know that one million follows the thousands and it contains six zeros, as opposed to simply knowing it is the name of a very large number word. Thus, older children may have been more capable of using their numerical knowledge to distinguish between each large multi-digit number, as opposed to using the name of the same basic number for all large basic numbers, as young children often did.

Results further indicated that children's cardinal number production tasks scores strongly increased with grade, reflecting substantial increases in the size of children's number word vocabularies. For the most part, scores exceeded curriculum guidelines proposed by the Ministry of Education (1985) (see also Simcoe County Board of Education, 1988a; Simcoe County Board of Education, 1988b; The Waterloo County Board of Education, 1985a; The Waterloo County Board of Education, 1985b; The Waterloo County Board of Education, 1985c; The Waterloo County Board of Education, 1985d; The Waterloo County Board of Education, 1985e) possibly because children were tested near the end of the school year. Results were also consistent with a handful of studies (Baroody, 1987; Bell & Burns, 1981; Siegler & Robinson, 1982) that have documented age-related changes in children's counting abilities up to grade three. The results of the project add to the literature by demonstrating that children's number knowledge continues to develop exponentially beyond grade three.

Although the aforementioned results have clear implications for children's mathematical development, the findings also contribute to research on vocabulary development. Specifically, the findings exemplify how the interplay between "psychologically basic" and "potentially knowable" vocabulary words contribute to the development of children's cardinal number word vocabularies during the school years. In the most extreme case, although "average" grade seven students received credit for learning only 31 or 32 psychologically basic vocabulary words, they were estimated to know almost one trillion words through problem solving.

Close examination of children's stopping points (i.e., critical points in the cardinal number series, beyond which for whatever reason, children were no longer capable of producing number words correctly) on the basic number knowledge task and on the total number production tasks revealed that children's abilities to continue the cardinal number sequence were dependent on the size of their individual basic number word vocabulary. The data from about one half of the children supported the hypothesis that when they did not know the name of a basic number word on the basic number knowledge task, they were unable to produce any number words beyond that point in the number series; however when they did, they could produce at least one number word from the same series, on the number production tasks. The findings provide some support for the assumption that a basic number word vocabulary is necessary to produce cardinal number words.

However, the stopping point data for about half of the children did not manifest the above pattern. In 30 percent of the cases (and especially for the older two grades), children received credit for several compound cardinal number words on the total number production tasks, even though they were not credited with knowing all of the basic number words contained in those compound words in isolation on the basic number knowledge task. For these children, it is possible that they required several practice trials to retrieve and coordinate their number knowledge. The basic number knowledge task may have enabled these students to retrieve and organize their number knowledge to a considerable extent, while familiarizing themselves with task demands. With practice, these children may have been able to recall more of their cardinal number knowledge, and score higher on subsequent tasks.

Conversely, 23 percent of the children knew the basic vocabulary words in isolation on the basic knowledge task, even though they were unable to produce words requiring them correctly on the number production tasks. In these cases, children (especially younger children) may still be learning the fundamentals of number production. Thus, even though children may demonstrate knowledge of the requisite vocabulary (on the basic number knowledge task), they may not be able to produce all the numbers for a particular series (on the total number production tasks) because they have not mastered the requisite compounding rules, and/or they are not proficient at coordinating their compound construction and vocabulary knowledge. These findings seem to support the hypothesis that children do not simply learn the basic number words that are part of a number word compound. The process of naming numbers and counting them is more complicated and at a minimum, involves the coordination of knowledge on how to compound vocabulary words correctly given the structure of the cardinal number word system.

Consistent with the hypotheses and some previous research (i.e., Siegler, 1987a; Steinberg, 1985; Thornton & Smith, 1988), children were more proficient at counting in a forward than backward direction, especially at grades one and seven. These findings may have occurred because children learn to count numbers in a forward direction first, and they have had more opportunities to memorize and master the cardinal number sequence when counting forward. Furthermore, counting forward may require children to use various "counting on" and "adding one" strategies (Ashfield, 1989) that are taught earlier than the subtraction strategies assumed to be important in counting backward (e.g., Fuson & Fuson, 1992).

The quality of responses on the numerical problem solving task (and also on the other number production tasks) indicated that most children used problem solving to produce number words. However, as predicted, older children were more likely to produce correct problem solving attempts compared to their younger agemates. Children's overall willingness to produce various forms of the pseudo number words may indicate that most children were aware of the generativity of the cardinal number system. However, older children were more proficient at producing words correctly because they have been exposed to more examples of compounding rules, and may have had more practice constructing numbers in the cardinal system than younger children.

Consistent with the hypotheses and some previous research (Hubbard, 1995; Fuson, Richards, & Briars, 1982; Fuson, 1988), results demonstrated strong individual differences in children's number production skills within each grade. These individual differences are important from a mathematics achievement perspective, in that the high scores on the number production tasks were significantly correlated with teacher ratings of children's mathematical ability in grades one and five.

Although correlations between children's number production performance and teacher's ratings were positively related at grades three and seven, it is interesting to speculate why the correlations were not significant at these grades. One possibility is that the experiment had low power with respect to finding an effect at a specific grade, given the small sample size of 16 children per grade. More specifically, assuming a moderate relation between mathematical performance and counting ability, there was only a 36% chance of finding the effect, given that it exists. Furthermore, the correlations at the grade three and seven levels were similar to the significant correlations at the other two grades, and larger variations within students at grades three and seven likely affected the significance of the ratings.

Another possible explanation that may have contributed to the non-significant findings is that since children of different grades had different teachers for mathematics (and reading), different raters were used at each grade to assess mathematical performance. Although all teachers received the same instructions to rate students, qualities inherent in each teacher, such as teaching style, expectations, and class structure, may have influenced the ratings.

However, the positive, but non-significant correlations at the grade three and seven levels may indicate that there are other factors contributing at least in part, to the extent of the individual differences within grade. One such factor that has not been thoroughly investigated in previous research, is the speed at which children are able to produce numbers in the cardinal number system. Informal observations during the current investigation suggested that there are likely differences both within and across grade in how automatically children are able to generate the number words. Furthermore, these number production times may be related to children's achievement scores as some research has shown that children's abilities to produce single digits quickly are related to their reading achievement (Bowers, Steffy & Swanson, 1986; Bowers, Steffy & Tate, 1988). Study 2, in addition to replicating and extending Study 1 in other ways, sought to investigate the variability in the number naming and counting times among participants both within and across grade, in order to provide a further understanding of the development of children's number production abilities.

STUDY 2

In Study 2, children completed the basic number knowledge task and two number production tasks. Times to name and count the numbers were also recorded on a laptop computer. It was anticipated that these data would: 1) replicate the overall number naming and counting findings of Study 1; 2) shed light on the role of automaticity in the development of children's number production abilities; 3) provide further support for the hypothesis that children's number production abilities are related to mathematical achievement; and 4) provide some evidence in support of the assumption that basic number words are stored in semantic memory but that regular compound number words are not.

To obtain measures of children's number naming and counting times, the same number production tasks from Study 1 were used in Study 2. Based on the informal observations made in Study 1, it was predicted that children's times to produce number words correctly within each number series would decrease with grade. These findings were predicted because, in addition to older children being in school longer to practice the names of the number words, their semantic networks for the cardinal number words may be more developed and efficiently organized, as they are for other categories of words (e.g., Anglin, 1977; Miller, 1991), compared to those of the younger children. Thus, older children may be faster at retrieving and coordinating basic number words into a number word compound compared to their younger agemates.

It was further hypothesized that individual variations in children's number production times would be related to their mathematical achievement scores. In addition to teacher ratings, children's mathematical abilities were assessed more objectively in Study 2, using two mathematical subtests from the Woodcock Johnson (Revised) Tests of Achievement. Given this more formal and unbiased assessment, it was predicted that children who were automatic at producing numbers correctly, may have a greater understanding of place value and the cardinal number system, the information in their semantic memories for mathematical knowledge may be better organized, and this would lead to the automatic retrieval of both number words on the number production tasks and mathematical facts and procedures on the achievement measures.

A number naming reaction time task was used to examine the speed at which children were able to react to and name basic number words versus non-basic comparisons containing similar numbers of digits and syllables. Times on this task were used to provide preliminary support for the assumption made in this project, and in others, that the basic number words must be learned and stored in semantic memory in contrast with the regular complex number words which could be generated through knowledge of the compounding rules underlying their construction. That is, if the basic number words are stored in semantic memory while non-basic number words are likely constructed, children's times to react to, and name the basic numbers should be quicker than the non-basic times. Basic number times should be quick because children only have to retrieve the basic words from memory, and do not need to use their problem solving capabilities to construct these words.

In addition to measuring children's number naming and counting times, two modifications were made to the testing procedure in Study 2 to improve the quality of the project, and clarify the interpretation of the findings. First, in Study 1, children were asked to produce the names of the number words up to the billions, and vocabulary estimates were derived from these data. However, from a vocabulary perspective, children did not explicitly express their knowledge of these words. Given that children could usually count forward or backward from the number names they produced, a case could be made that they did have some important knowledge of their meanings.

It may be possible to demonstrate that children understand another important aspect of the meanings of the number words by ascertaining that they use the cardinality rule (Schaeffer. Eggleston, & Scott, 1974) or the principle of cardinality (Gelman & Gallistel. 1978) when counting larger numbers. The cardinality principle refers to the understanding that the last number produced when objects are counted denotes the total number of objects in the set. Some researchers have demonstrated that it is mastered with smaller numbers by the preschool years (Dehaene, 1993; Fuson, Pergament, Lyons, & Hall, 1985; Fuson & Hall, 1983; Gelman & Gallistel, 1978; Gelman & Meck, 1986). Theoretically, if children understand the principle of cardinality, they could illustrate the meaning of each number word by counting actual objects, and each successive number word in the cardinal number series would be represented by the addition of one object to the already counted set.

A cardinality task was introduced in Study 2 to determine whether children could apply the cardinality principle in an abstract scenario using pseudo number words. On the assumption that children could show knowledge of the cardinality rule, they should be able to apply the rule when counting any number of objects, provided they know all the vocabulary words to label all the objects. Since all children in the study were older than the preschoolers tested in previous research, it was hypothesized that all children would show some knowledge of the cardinality principle during testing.

The second modification in Study 2 was made to the numerical problem solving task. Specifically, given the structure of the cardinal number words beyond the thousand series, many children may believe that all of the large number words end in illion. Thus, some children may have received low scores on the numerical problem solving task in Study 1 because the pseudo number word used (i.e., one guggle) did not conform to the above convention. To determine whether children are sensitive to the sound pattern of large basic number words, the pseudo word was changed from one guggle to one gillion for half of the students at each grade.

Method

Participants

Twenty-four children from each of grades one, three, five, and seven, from two public schools in a moderately large community in Southwestern Ontario participated. The mean ages of the children were 6 years, 6 months in grade one, 8 years, 8 months in grade three, 10 years, 8 months in grade five, and 12 years, 8 months in grade seven. All participants were fluent in English and were instructed in English at school. The children were equally divided across sex both within and across grade, and represented all socioeconomic status levels as determined by parental occupational data and scores on the Blishen, Carroll, and Moore (1987) socioeconomic status index. Participants did not have any speech or language difficulties, or experience any extreme learning disabilities as reported by their teachers. Furthermore, none of the children had failed or skipped a grade level and thus, children's grade levels were consistent with their chronological ages. Four children were replaced because they did not meet at least one of the above criteria.

Materials

The same number word lists and presentation orders from Study 1 were used in Study 2 on the basic number knowledge and forward/backward naming and counting tasks. Consistent with the number presentation conventions of the Imperial system, all numerals were presented with commas. However, to measure children's number naming and counting times, numerals were presented on the monochrome screen of a 486 lap top computer. A computer program was designed to record a naming time and a counting time in milliseconds for each number presented. The number naming time referred to the time children took to name a number and included the time from which the numeral first appeared on the computer screen to the end of the child's naming response. The counting time referred to the time children took to count in a forward or backward direction from a number and included the time between the end of the child's naming response and the end of his or her counting response. The timer on the lap top was activated when the experimenter pressed keys on the computer keyboard.

For the number naming reaction time task, seven basic numerals (i.e., 60, 70, 80, 100, 1000, 1,000,000, 1,000,000,000), seven randomly selected non-basic numeral comparisons (i.e., 61, 77, 83, 400, 5000, 6,000,000, 3,000,000,000), and an additional 14 numerals that served as fillers were presented in a differing random order for each participant on a monochrome computer screen. Where possible, the randomly selected non-basic numerals were selected such that they would share the same number of digits in the numeral and syllables in the resulting number word as the basic numbers to which they would be compared. Selecting number words with the same number of syllables was limited at the decade level, since there is only one basic decade word (i.e., seventy) that contains the same number of syllables as most other non-basic decade words. Nevertheless, two additional basic decade words (i.e., sixty and eighty) containing fewer syllables than all the non-basic comparisons were used to increase the number of observations, and improve the validity of the timing data. A computer program was designed to record both the children's reaction time to name a number. and the total time taken to name the number. The number reaction time included the time from which the number appeared on the computer screen to the time when the child first started to say the number. The total number naming time included the time from which children started naming a number to the time that they finished naming the number. The timer was activated when the experimenter pressed keys on the keyboard.

To obtain a comprehensive evaluation of mathematical knowledge, two subtests on the Woodcock-Johnson (Revised) Tests of Achievement were used to obtain a comprehensive evaluation of mathematical knowledge. The Quantitative Concepts subtest provides an assessment of math concepts and vocabulary, while the Calculation subtest requires students to solve written math problems in addition, subtraction, multiplication, division, geometry, trigonometry and calculus. Questions on these tests are organized in order of relative difficulty and children begin the test at a starting point that is acceptable for their grade level. If they receive credit for a certain number of items at the established starting point, they are given credit for all preceding items. In the event that children do not receive credit for one of the first six questions administered, the experimenter is required to administer previously ordered questions until six consecutive correct answers are obtained. Testing then continues from the original starting point and is terminated once a child makes an error on six consecutive questions. Thus, children are not evaluated on all test items, and children of different ages are not typically exposed to all of the same test items.

Finally, as in Study 1, teachers rated the mathematics and reading abilities of the children in their classes on five-point scales to obtain a measure of their math and linguistic abilities.

Procedure

All children were interviewed individually by a female experimenter in two sessions and the sessions were tape recorded. The first session lasted approximately one hour and the second session lasted about 20 minutes. In three cases, due to very slow performance on the naming/counting tasks or unforeseen time constraints, testing was completed in three sessions. The children were asked to complete several number naming and counting tasks to determine how high they could name and count numbers. During the first session, children completed the basic number knowledge task, forward/backward number naming and counting tasks, the numerical problem solving task, and the cardinality task, in that order. In the second session, children completed the number naming reaction time task, and the Quantitative Concepts and the Calculation subtests of the Woodcock Johnson (Revised) Tests of Achievement. The tasks used in Study 2 are described in detail below.

Basic Number Knowledge and Forward/Backward Naming/Counting Tasks

The procedures for the basic number knowledge task and forward/backward naming and counting tasks were identical to procedures described in Study 1, except that the numbers were presented to children on a laptop computer screen.

Numerical Problem Solving Task

For the numerical problem solving task, a procedure similar to that described in Study 1 was followed. However, for half of the participants at each grade, the pseudo number word was changed from <u>one guggle</u> to <u>one gillion</u> in Study 2 for the reasons described above. Children were randomly assigned to either the <u>one guggle</u> or <u>one gillion</u> number wording, with the restriction that half of the grade level were exposed to one pseudo number word, while the other half were exposed to the other pseudo number word. Furthermore, in addition to counting forward from one guggle (or one gillion) as described in Study 1, two extra trials were added in Study 2. These trials were added to provide more data in support of the hypothesis that when provided with appropriate vocabulary words, children are able to generate additional numbers in the series. Specifically, children were asked to count forward for three numbers from one guggle (gillion) and sixty-six and backward for three numbers from one guggle (gillion) and eighty-three. These extra trials were also counterbalanced such that half of the children at each grade counted forward from one guggle (gillion) and sixty-six (and backward from one guggle (gillion) and eighty-three), while the other half counted forward from one guggle (gillion) and eighty-three (and backward from one guggle (gillion) and sixty-six).

Cardinality Task

Following the numerical problem solving task, children completed the cardinality task. The goal of this task was to ensure that children understood the principle of cardinality (Gelman & Gallistel, 1978) and could apply the principle to any situation. For the first part of the task, children were presented with the following abstract scenario, to ease them into the questioning procedure, and to expose them to a scenario involving counting imaginary objects:

> I want you to watch and listen carefully to what I am doing and then I am going to ask you a question. I am going to count some things. They are all on the table here (experimenter points to space on the table) and when I am done, I am going to ask you how many things there are. Ready? Here we go: "one, two, three, four, five" (while saying the number words, the experimenter points to five places on the table). Okay. How many things are there in total?

It was expected that all children would give the correct answer of five. Once the first question was completed, children were then asked to listen and respond to the following scenario:

> Suppose there was an alien from outer space named Zephron, who had a bag full of things and he wanted to know how many things were in his bag. What do you think would be the best way to figure out how many things are in his bag? Let's pretend that Zephron asked you to watch him count the things to make sure he did not make any mistakes. He began pulling the things out of the bag one at a time. But since Zephron could not speak English very well, he counted in his own alien language. He counted them as <u>mok</u>, <u>ouk</u>, <u>tula</u>, <u>shpet</u>, <u>rud</u> and so on. However, the bag of things was very large, and he kept counting and counting for hours to reach the bottom of the bag. Finally, he labelled the last things as <u>veta-fingt</u>, <u>veta-va</u>, <u>veta-juke</u>, and <u>veta-hoopa</u>.
>
> Assuming that he did not make any mistakes, how many things were in the bag?

Provided that children have mastered the cardinality principle, they should state the name of the last pseudo number word produced as <u>veta-hoopa</u> to refer to the total number of objects.

If children produced a correct response for one or both of the above questions, it was assumed that they had knowledge of the principle of cardinality and testing on this task was terminated. However, two grade one girls who did not produce a correct response for either the first or second scenario were asked to demonstrate knowledge of the cardinality principle using a more standard version of the task (Gelman & Gallistel, 1978). The two girls were given a box containing six small dolls and they were asked to determine how many dolls were in the box.

Number Naming Reaction Time Task

In the second session of Study 2, children completed the number naming reaction time task. On this task, children were asked to name numbers presented on a computer screen as soon as possible. They were told to work as quickly as possible without making mistakes as they were being timed while naming the numbers. All children were assigned to one of five number naming levels for this task based on their performance during the number naming tasks in the first session. Specifically, children were placed into a level provided that they had received credit for at least one of the numbers at that level during the number naming tasks. Children placed in the first level were only exposed to the decade numerals on the reaction time task since performance on the number naming task revealed they could not name numbers any higher than the decades. Each successive level included the addition of extra numerals. Levels two, three, four, and five included all numbers up to and including numbers in the hundreds, thousands, millions, and billions, respectively.

Woodcock-Johnson Revised Test of Achievement

Following the number naming reaction time task, children completed the two mathematical subtests on the Woodcock-Johnson Revised Tests of Achievement. For the Quantitative Concepts subtest, children were shown pictures and orally answered questions relating to their knowledge of mathematical concepts. For the Calculation subtest, children completed some mathematical problems in an answer booklet.

Scoring

Number Naming, Counting, Problem Solving, Cardinality and Achievement Test Data

The experimenter scored the correctness of children's responses on the basic number knowledge task, forward/backward number naming and counting tasks, and reaction time tasks during testing by unobtrusively pressing buttons on the computer. All children's scores on the basic number naming task, forward and backward number naming and counting tasks were then calculated consistent with the procedure described in Study 1. Thus, the same estimation procedures were used to calculate vocabulary differences and the same categorical scale was used to describe individual differences in children's number naming and counting skills.

Three scores were calculated for the numerical problem solving test. Children received a score for their performance on numbers following one guggle (gillion) which could range from one to five. Children also received a score from one to three on each of the trials where they were required to count forward and backward from a number. Mean scores were then determined for children at each grade, sex, and pseudo number word condition (guggle versus gillion).

On the cardinality task, children received a point for each correctly answered question, and thus, children's scores could range from zero to three. If children demonstrated knowledge of the principle of cardinality in either the first or second question, they were automatically given credit for the third (easiest) question involving the counting of a box of dolls. There were no scores of zero, indicating that all children had some knowledge of the cardinality principle, and the two grade one girls who did not answer the first two questions correctly were the only two students to receive scores of one.

Data from the Woodcock-Johnson Revised Tests of Achievement were scored according to the standard procedures described in the testing manual. Grade equivalent norms were used to calculate the children's standard scores, and these standard scores were then converted into percentiles. A percentile score of 45 would indicate that a child performed equal to or better than 45% of the children tested when norms were established.

Number Production Time and Reaction Time Data

Children's times to correctly name and count the random forward and backward number naming and counting tasks were summed independently at each of the decades, hundreds, thousands, millions, and billions series for each participant. Any times that were affected by a child's waning attention or unforeseen distractions, or times that were not valid because a child was asked to repeat a response were excluded. These summed times were then divided by the total number of random number words answered correctly at each number series, to produce a mean number naming, and a mean counting time on the forward and backward tasks for each participant at each of the five number levels.

Mean naming times were also calculated for numbers at the decade level on the number naming reaction time task. Specifically, since preliminary analyses revealed that syllable length had no effect on children's naming and reaction times for basic and non-basic decade words, the times children took to start naming, and complete naming the basic decade numbers, 60, 70 and 80 were averaged for each participant. Likewise, the times children took to begin naming and finish naming the non-basic number word comparisons, 61, 77, and 83 were also averaged for each student. These averages included only the times of numbers where children produced a correct response, and any times that were spoiled due to unforseen circumstances were excluded. Since there was only one basic number and one non-basic comparison at each of the hundreds, thousands, millions, and billions number series, these times were simply averaged across children at each grade and sex level. Although some researchers may have difficulty with the interpretation of one data point for basic number words (e.g., the reaction time for naming 100), it was anticipated that the noise in the data was minimized by removing any data spoiled due to waning attention span, and other noticeable environmental distractions. Again, grade averages included only the times of numbers where children produced a correct response, and any times that were spoiled were excluded. Finally, it should be noted that children were only included in analyses comparing basic and non-basic words, provided that they had correctly produced both the basic and the non-basic number word correctly at a particular number series (or at least one word from each category correctly in the case of the decade words).

Results

The results section in Study 2 is divided into five main parts. Consistent with Study 1, the first section contains the outcomes of several repeated measures ANOVAs and dependent t-tests on children's number naming and counting scores as a function of grade and sex. In the second section, scores from the total number naming and counting tasks are used to obtain estimates of children's basic, problem solved, and total number word vocabularies. Next, individual differences in children's number naming and counting performance are reported as a function of grade. The fourth section contains the outcomes of several repeated measures ANOVAs and dependent t-tests on children's total number naming and counting times, and their reaction times to name numbers. Finally, correlation coefficients are used to examine the relation between teacher ratings of children's academic abilities, children's scores on the mathematical subtests of the Woodcock Johnson achievement tests, and children's performance on the number naming and counting tasks in the fifth section. Since preliminary analyses did not reveal any significant effects as a function of school, socioeconomic status, word list or task order, these conditions were collapsed and all analyses were conducted across them.

Analyses on Children's Number Naming, Counting, Problem Solving and Cardinality Knowledge Data

Table 12 demonstrates children's mean scores on the basic number knowledge task, total number naming and counting tasks, numerical problem solving task, and cardinality task as a function of grade and sex. A grade by sex ANOVA conducted on children's mean basic number knowledge scores revealed a significant main effect of grade, $F(3, 88) = 28.79$, $p < .001$, a significant main effect of sex, $F(1, 88) = 6.62$, $p < .012$, and a significant grade by sex interaction $F(3, 88) = 3.409$, $p < .021$. With respect to the grade effect, Tukey post hoc procedures revealed that only the grade one mean differed significantly from the grade three, five and seven means ($p < .05$). Consistent with the data from Study 1, most children in grades one, three, five, and seven could identify all of the basic number words up to eighty, one thousand, one million, and one billion respectively. Although there was a significant sex effect in favor of boys, this result is complicated by the significant grade by sex interaction. Close examination of the mean performance of both sexes at each grade revealed that boys and girls at each of the grade three, five and seven levels were quite evenly matched. Only the male and female means in grade one differed significantly ($p < .05$).

Results of a repeated measures ANOVA with grade and sex as between subject factors and task direction (i.e., forward versus backward) as the within subjects factor on children's

Table 12

Children's Mean Basic Number Knowledge, Total Naming and Counting, Numerical Problem Solving and Cardinality Scores in Study 2 as a Function of Grade and Sex

	Grade				
Basic Number Knowledge Task	1	3	5	7	Overall
(out of 38)					
Boys	27.42	29.83	29.67	31.00	29.48
Girls	24.25	28.92	29.92	30.67	28.44
Overall	25.83	29.38	29.79	30.83	28.96
Naming Task					
1) OVERALL NAMING					
(out of 156)					
Boys	50.92	80.42	105.67	147.50	96.13
Girls	33.25	76.08	114.83	124.75	87.23
Overall	42.08	78.25	110.25	136.13	91.68
2) FORWARD NAMING					
(out of 78)					
Boys	25.33	40.83	53.17	74.17	48.38
Girls	17.42	38.75	58.08	62.50	44.19
Overall	21.38	39.79	55.63	68.33	46.28

Table 12 (continued)

3) BACKWARD NAMING					
(out of 78)					
Boys	25.58	39.58	51.91	73.25	46.04
Girls	15.83	37.33	56.83	62.33	40.23
Overall	18.33	35.21	52.71	66.29	43.14
Counting Task					
1) OVERALL COUNTING					
(out of 156)					
Boys	48.17	76.17	102.67	146.75	93.44
Girls	30.25	68.25	110.33	120.08	82.23
Overall	39.21	72.21	106.50	133.42	87.83
2) FORWARD COUNTING					
(out of 78)					
Boys	25.17	38.83	52.08	73.50	47.33
Girls	16.58	35.08	55.33	61.08	42.02
Overall	20.88	36.83	53.71	67.29	44.68
3) BACKWARD COUNTING					
(out of 78)					
Boys	23.00	37.25	50.42	73.50	46.04
Girls	13.67	33.17	55.00	59.08	40.23
Overall	18.33	35.25	52.71	66.21	43.14

Table 12 (continued)

Numerical Problem Solving Task (out of 5)

1) GUGGLE CONDITION					
Boys	0.00	0.00	1.38	1.67	0.81
Girls	0.00	0.83	0.00	0.00	0.23
Overall	0.00	0.42	0.92	0.83	0.54
2) GILLION CONDITION					
Boys	2.33	3.67	3.75	2.67	3.05
Girls	1.83	2.50	3.88	3.33	2.96
Overall	2.08	3.08	3.83	3.00	3.00

Forward/Backward Questions on

Problem Solving Task

FORWARD TRIALS (out of 3)

1) GUGGLE CONDITION					
Boys	0.00	0.50	1.50	2.00	1.04
Girls	0.33	1.50	1.50	1.00	1.05
Overall	0.17	1.00	1.50	1.50	1.04
2) GILLION CONDITION					
Boys	2.00	2.17	3.00	2.50	2.36
Girls	0.00	2.50	2.38	2.50	1.89
Overall	1.00	2.33	2.58	2.50	2.10

Table 12 (continued)

BACKWARD TRIALS					
1) GUGGLE CONDITION	0.00	0.50	1.63	2.00	1.08
Boys	0.50	1.50	1.50	1.00	1.09
Girls	0.25	1.00	1.58	1.50	1.08
Overall					
2) GILLION CONDITION					
Boys	1.17	2.17	2.25	2.50	2.00
Girls	0.00	3.00	2.63	2.50	2.08
Overall	0.58	2.58	2.50	2.50	2.04
Cardinality Task					
(out of 3)					
Boys	1.92	2.17	2.50	2.58	2.29
Girls	2.17	2.25	2.58	2.50	2.38
Overall	2.04	2.21	2.54	2.54	2.33

total number naming ability replicated the significant grade effect observed in Study 1, $F(3, 88) = 73.54$, $p < .001$. The average grade one naming score fell in the hundreds series, with 33% of grade one students receiving credit for at least one of the numbers in this series. The average grade three number naming score fell in the ten thousands, with 58% of the students at this grade level being able to name at least one number correctly at this level. At the grade five level, children's number naming score was in the ten millions, and 58% of grade five students were able to name a minimum of one number correctly at this level. Finally, children's mean number naming score at the grade seven level fell within the ten billions series, and 67% of grade seven students were able to name at least one number at this level correctly. Tukey post hoc tests revealed that the means at all grade levels differed significantly ($p < .05$).

However, results of the repeated measures ANOVA also revealed that children's number naming scores were influenced by the direction of the counting task, $F(1, 88) = 4.06$, $p < .047$. Although children's mean naming performance fell within the same number series for each grade on the forward and backward tasks, children generally had more difficulty naming numbers on trials where they were required to count backward than on trials where they were required to count forward. This significant finding may represent a carry-over effect of the difficulty of counting backward. However, paired difference t-tests did not reveal any significant differences in naming performance on the forward and backward tasks within each grade. It should also be noted that this significant directional effect was not simply influenced by children's naming scores on the special case number words, as the direction effect was still significant when only random numbers were considered, $F(1, 88) = 4.59$, $p < .035$.

With respect to counting performance, a repeated measures ANOVA with grade and sex as between subjects measures and counting direction as the within subject factor revealed a significant grade effect, $F(3, 92) = 67.39$, $p < .001$, a significant sex effect in favor of boys, $F(1, 88) = 5.51$, $p < .021$, and counting direction effect, $F(1, 92)$, $p < .007$. As shown in Table 12, children were more proficient at counting forward than backward, but paired difference t-tests at each grade level revealed that the advantage for forward counting was only significant for grade one students, $t(23) = 3.18$, $p < .004$.

Consistent with the naming data, children's counting scores increased with grade in the predicted pattern, and Tukey post hoc procedures revealed that all means differed significantly ($p < .05$). In grade one, 100% and 96% of the children could count forward and backward from at least one number in the decades respectively, and the average grade one scores fell in the seventies. By grade three, 46% of the students could count forward and backward from numbers in the ten thousands. At the grade five level, both the forward and backward counting means fell in the ten millions, and 63% of grade five students were able to count forward from at least one number in the ten millions series. Finally, at the grade seven level, 67% of children could count forward and backward from a number in the ten billions, respectively, placing the grade seven means for these counting tasks in the ten billions.[8]

The consistency of children's stopping points on the basic number knowledge and number production tasks is presented as a function of grade in Table 13. Consistent with the data from Study 1, approximately half of the children produced number words correctly from the same number series on both kinds of tasks. However, 19 percent of the children (especially those in grades one and three) obtained higher scores on the basic number knowledge than the number production tasks.

Table 13

Percentage of Children who Produced Consistent Scores on Both the Basic Number Knowledge Task and the Number Production Tasks in Study 2

Grade	Consistent	Inconsistent #1 (Basic score greater)	Inconsistent #2 (Number Production Score Greater)
1	63	25	13
3	46	33	21
5	33	8	58
7	75	8	16
Total	54	19	27

Conversely, 27 percent of students (especially children in grades five and seven) received higher scores on the number production than the basic number knowledge tasks.

The frequency of children's numerical problem solving scores as a function of grade and number word condition are presented in Table 14. Similar to the data obtained in Study 1, children did not obtain any scores of 2 or 3 (out of a possible score of 5), showing that children were again consistent in their responding and received credit for almost all or none of the questions on this task. A grade by sex by number word condition (i.e., "guggle" versus "gillion") ANOVA performed on children's problem solving scores revealed a significant number word effect, $F(1, 80) = 147.30$, $p < .001$, but no grade effect, $F(3,95) = 1.83$, $p < .149$. Children made more correct problem solving attempts when asked to count forward from "one gillion" than from "one guggle" and post hoc analyses revealed that the mean performance differential between the "guggle" versus "gillion" wordings was significant at all grade levels ($p < .05$). Children's strong performance on the "gillion" number wording likely contributed to the non-significant grade effect observed on this task in Study 2. Across grade, 56 children did not receive credit for any of the items on the numerical problem solving task. Relative to the data from Study 1, children in the "guggle" number word condition obtained very low scores on the numerical problem solving task; specifically, 88% of children in the "guggle" condition did not receive credit for any of the questions. Nevertheless, close analysis of children's incorrect problem solving attempts revealed a similar breakdown of error types as reported in Study 1.

Children's performance to count forward and backward by three numbers from the pseudo number word was also analysed using a repeated measures ANOVA, with grade, sex, and number word condition (i.e., guggle versus gillion) as the between subject factors and task

Table 14

Frequency of Children's Numerical Problem Solving Scores as a Function of Grade and Number Word Condition in Study 2

	Numerical Problem Solving Score					
	0	1	2	3	4	5
Grade 1						
1) GUGGLE	12	0	0	0	0	0
2) GILLION	6	1	0	0	1	4
Grade 3						
1) GUGGLE	11	0	0	0	0	1
2) GILLION	2	3	0	0	1	6
Grade 5						
1) GUGGLE	9	1	0	0	0	2
2) GILLION	2	1	0	0	0	9
Grade 7						
1) GUGGLE	10	0	0	0	0	2
2) GILLION	4	1	0	0	0	7
Overall						
1) GUGGLE	42	1	0	0	0	5
2) GILLION	14	6	0	0	2	26

direction (i.e., forward versus backward) as the within subject measure. Results indicated a significant grade effect, $F(3, 80) = 8.26$, $p < .001$, a significant number word condition effect, $F(1, 80) = 16.02$, $p < .001$, a significant sex by task direction interaction, $F(1, 80) = 5.80$, $p < .018$, and a significant sex by number word condition by task direction interaction, $F(1, 80) = 5.40$, $p < .023$. With respect to the grade effect, Tukey post hoc tests revealed that children in grades three, five, and seven produced more correct problem solved attempts to continue the series than grade one children. Furthermore, children exposed to the "gillion" instruction wording once again, produced more correct problem solved attempts than children exposed to the "guggle" wording.

The significant sex by task direction effect likely resulted from boys outperforming girls on average on the forward trials, and girls outperforming boys, on average, on the backward trials. However, this significant interaction was influenced by the pseudo number word to which children were exposed. Close examination of the data at each specific sex by number word by task direction level indicated that all children in these conditions were quite evenly matched, except for the high performance of boys' exposed to the gillion wording on the forward trials.

Results of a grade by sex ANOVA on children's cardinality scores revealed a significant grade effect, $F(3, 88) = 5.01$, $p < .003$. Although children's scores on the cardinality task increased from grade one, to grade three, to grades five and seven, Tukey post hoc procedures revealed that only the grade one mean differed significantly from the grade five and seven means ($p < .05$).

Estimates of Children's Number Naming and Counting Knowledge

Children's median number naming and total counting estimates as a function of grade are presented in Table 15. Given aforementioned differences in children's performance on the forward and backward naming and counting tasks, median estimates are also reported as a function of these tasks in Table 16. Since there were 24 children per grade, the median score is the average of the twelfth and thirteenth ranked children's estimates. It should be noted that the total naming and counting estimates are based on children's knowledge of all numbers from 1 through 1,000,000,000,000. Furthermore, as reported in Study 1, the median naming and median counting scores do not necessarily contain data from the same children. Medians were reported instead of means and ANOVAs were not calculated due to the extreme variability in scores.

From these estimates, the median number of cardinal number words that could at a maximum be constructed through problem solving was determined for children at each grade. As in Study 1, these scores were computed by subtracting the mean number of words known on the basic number knowledge task from the total median number word naming and counting estimates and are presented in Table 17. Once again, means and ANOVAs were not computed on the estimates of words generated through problem solving due to variability in the scores.

Table 15

Median Estimated Number (and Range) of Cardinal Number Words Nameable and Countable at Each Grade in Study 2

Grade	Naming Estimate	Counting Estimate
1	100	95
	(12 - 11,650,376)	(15 - 198,998)
3	41,461	9961
	(99 - 500,499,999,993)	(95 - 500,499,999,993)
5	126,994,375	75,924,999
	(1000 - 1×10^{12})	(1000 - 999,999,999,995)
7	999,886,206,250	999,880,586,246
	(387,999 - 1×10^{12})	(387,995 - 1×10^{12})

Table 16

Median Estimated Number (and Range) of Cardinal Number Words and Range of Estimated Scores Nameable and Countable on the Forward and Backward Tasks at Each Grade Level in Study 2

Grade	Forward Naming Estimate	Backward Naming Estimate
1	100	100
	(15 - 298,002)	(9 - 23,002,751)
3	43,712	27,889
	(99 - 999,999,999,990)	(99 - 3,227,499,995)
5	113,500,001	124,063,755
	(1000 - 1,000,000,000,000)	(1000 - 1,000,000,000,000)
7	999,988,749,998	999,886,037,501
	(1002 - 1,000,000,000,000)	(3258 - 1,000,000,000,000)
Grade	Forward Counting Estimate	Backward Counting Estimate
1	100	91
	(15 - 225,992)	(14 - 322,747)
3	8873	9,923
	(98 - 999,752,483)	(92 - 3,227,499,995)
5	999,998	22,598,874
	(1000 - 999,999,999,996)	(1000 - 1,000,000,000,000)
7	999,987,624,995	999,885,924,999
	(998 - 1,000,000,000,000)	(1006 - 1,000,000,000,000)

Table 17

Median Estimated Number of Words Deducible Through Problem Solving at Each Grade in Study 2

Grade	Mean Basic Number Knowledge Score	Naming Estimate	Counting Estimate
1	25.83	74	69
3	29.38	41,432	9932
5	29.79	126,994,345	75,924,969
7	30.83	999,886,206,219	999,880,586,215

Individual Differences in Number Naming and Counting Abilities

The percentage of children who fell into each of the four categories of the Number Production Proficiency Scale are presented in Table 18 at each grade and each number series. The percentages of children who fell into the four levels are further subdivided into children's forward and backward naming and counting performance scores at more specific number levels (e.g., ten thousands, hundred thousands) in Tables 19, 20, 21 and 22.

Consistent with the data reported in Study 1, there were large variations in number naming and counting performance within each grade (but once again, please consult endnote 7). As demonstrated in Table 18, between one third and one half of the grade one children had mastered producing decade level numbers, depending on the nature of the task, and were beginning to produce numbers in the hundreds. However, four children (i.e., 16.7 percent) demonstrated limited knowledge on producing numbers at the decades level, while one grade one male student counted some numbers into the hundred thousands and named some numbers in the ten millions. In grade three, between 33 and 58 percent of the children had mastered producing numbers in the low thousands series. However, one student had no knowledge of how to name and count numbers into the hundreds, while another student was able to produce numbers in the hundred billions. Although more than half of the students in grade five were capable of naming and counting at least one number correctly in the millions, there was one grade five student who could not name or count any numbers correctly in the low thousands. Finally, in grade seven, over half of the students (i.e., 54.2 percent) had mastered naming and counting numbers into the hundred billions. However, there was one student who was still working on mastering naming and counting numbers in the hundred thousands (see Table 22).

Table 18

Percentage of Children Falling in the Four Categories of the Number Production Proficiency Scale for Overall Naming and Counting at the Five Number Series in Study 2

Grade 1

Series	Naming 1*	2	3	4	Counting 1	2	3	4
Decades	0.0**	16.7	37.5	45.8	0.0	20.8	50.0	29.2
Hundreds	66.7	8.3	12.5	12.5	66.7	12.5	8.3	12.5
Thousands	87.5	12.5	0.0	0.0	87.5	12.5	0.0	0.0
Millions	95.8	4.2	0.0	0.0	100.0	0.0	0.0	0.0
Billions	100.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0

Grade 3

Series	Naming 1	2	3	4	Counting 1	2	3	4
Decades	0.0	0.0	0.0	100.0	0.0	0.0	4.2	95.8
Hundreds	4.2	0.0	29.2	66.7	4.2	8.3	33.3	54.2
Thousands	33.3	50.0	12.5	4.2	41.7	50.0	8.3	0.0
Millions	79.2	16.7	0.0	4.2	79.2	16.7	16.7	0.0
Billions	91.7	8.3	0.0	0.0	91.7	8.3	0.0	0.0

*1 = No Knowledge (0% Correct), 2 = Some Knowledge (1% - 74% Correct), 3 = Still Learning (75% - 99% Correct), 4 = Mastery (100% Correct)

**Please note that approximately 4.2 percent = one child

Table 18 (continued)

Grade 5	Naming				Counting			
Series	1*	2	3	4	1	2	3	4
Decades	0.0**	0.0	0.0	100.0	0.0	0.0	0.0	100.0
Hundreds	0.0	0.0	4.2	95.8	0.0	0.0	4.2	95.8
Thousands	4.2	33.3	33.3	29.2	4.2	41.7	33.3	20.8
Millions	29.2	29.2	25.0	16.7	37.5	20.8	20.8	20.8
Billions	70.8	0.0	4.2	25.0	70.8	0.0	0.0	29.2

Grade 7	Naming				Counting			
Series	1	2	3	4	1	2	3	4
Decades	0.0	0.0	4.2	95.8	0.0	0.0	4.2	95.8
Hundreds	0.0	0.0	0.0	100.0	0.0	0.0	0.0	100.0
Thousands	0.0	8.3	25.0	66.7	0.0	12.5	29.2	58.3
Millions	8.3	16.3	20.8	54.2	8.3	20.8	16.7	54.2
Billions	29.2	8.3	8.3	54.2	33.3	4.2	8.3	54.2

*1 = No Knowledge (0% Correct), 2 = Some Knowledge (1% - 74% Correct), 3 = Still Learning (75% - 99% Correct), 4 = Mastery (100% Correct)

**Please note that approximately 4.2 percent = one child

Table 19

Percentage of Grade One Students Falling in the Categories of the Number Production Proficiency Scale in Study 2 as a Function of Forward and Backward Naming and Counting

	Forward Naming Data				Backward Naming Data			
Number Series	Rtg= 1	Rtg= 2	Rtg= 3	Rtg= 4	Rtg= 1	Rtg= 2	Rtg= 3	Rtg= 4
Decades	0.0*	8.3	37.5	54.2	4.2	12.5	29.2	54.2
Hundreds	66.7	8.3	8.3	16.7	70.8	4.2	8.3	16.7
Low Thousands	91.7	4.2	0.0	4.2	91.7	0.0	8.3	0.0
Ten Thousands	91.7	0.0	4.2	4.2	91.7	4.2	0.0	4.2
Hundred Thousands	91.7	8.3	0.0	0.0	95.8	4.2	0.0	0.0
Low Millions	100.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0
Ten Millions	100.0	0.0	0.0	0.0	95.8	4.2	0.0	0.0
Hundred Millions	100.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0
Low Billions	100.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0
Ten Billions	100.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0
Hundred Billions	100.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0

*Please note that approximately 4.2% = One Child

Table 19 (continued)

Number Series	Forward Counting Data Rtg= 1	Rtg= 2	Rtg= 3	Rtg= 4	Backward Counting Data Rtg= 1	Rtg= 2	Rtg= 3	Rtg= 4
Decades	0.0	12.5	37.5	50.0	4.2	16.7	37.5	41.7
Hundreds	66.7	8.3	8.3	16.7	70.8	8.3	8.3	12.5
Low Thousands	91.7	0.0	4.2	4.2	91.7	0.0	8.3	0.0
Ten Thousands	91.7	0.0	8.3	0.0	91.7	0.0	0.0	8.3
Hundred Thousands	95.8	4.2	0.0	0.0	95.8	4.2	0.0	0.0
Low Millions	100.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0
Ten Millions	100.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0
Hundred Millions	100.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0
Low Billions	100.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0
Ten Billions	100.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0
Hundred Billions	100.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0

*Please note that approximately 4.2% = One Child

Table 20

Percentage of Grade Three Students Falling in the Categories of the Number Production Proficiency Scale in Study 2 as a Function of Forward and Backward Naming and Counting

	Forward Naming Data				Backward Naming Data			
Number Series	Rtg= 1	Rtg= 2	Rtg= 3	Rtg= 4	Rtg= 1	Rtg= 2	Rtg= 3	Rtg= 4
Decades	0.0*	0.0	0.0	100.0	0.0	0.0	0.0	100.0
Hundreds	4.2	0.0	4.2	91.7	4.2	0.0	29.2	66.7
Low Thousands	37.5	0.0	4.2	58.3	37.5	4.2	12.5	45.8
Ten Thousands	50.0	0.0	16.7	33.3	41.2	20.8	12.5	25.0
Hundred Thousands	79.2	4.2	8.3	8.3	87.5	4.2	0.0	8.3
Low Millions	91.7	4.2	0.0	4.2	91.7	0.0	0.0	8.3
Ten Millions	83.3	8.3	4.2	4.2	91.7	0.0	4.2	4.2
Hundred Millions	91.7	4.2	0.0	4.2	91.7	0.0	0.0	8.3
Low Billions	95.8	0.0	0.0	4.2	95.8	4.2	0.0	0.0
Ten Billions	95.8	0.0	0.0	4.2	100.0	0.0	0.0	0.0
Hundred Billions	95.8	0.0	0.0	4.2	100.0	0.0	0.0	0.0

*Please note that approximately 4.2% = One Child

Table 20 (continued)

Number Series	Forward Counting Data				Backward Counting Data			
	Rtg= 1	Rtg= 2	Rtg= 3	Rtg= 4	Rtg= 1	Rtg= 2	Rtg= 3	Rtg= 4
Decades	0.0	0.0	0.0	100.0	0.0	0.0	4.2	95.8
Hundreds	8.3	4.2	8.3	79.2	4.2	12.5	25.0	58.3
Low Thousands	45.8	0.0	16.7	37.5	45.8	8.3	12.5	33.3
Ten Thousands	58.3	0.0	12.5	29.2	54.2	16.7	8.3	20.8
Hundred Thousands	79.2	8.3	4.2	8.3	87.5	4.2	0.0	8.3
Low Millions	95.8	0.0	0.0	4.2	91.7	0.0	0.0	8.3
Ten Millions	83.3	4.2	8.3	4.2	91.7	0.0	4.2	4.2
Hundred Millions	95.8	0.0	0.0	4.2	91.7	0.0	0.0	8.3
Low Billions	95.8	0.0	0.0	4.2	95.8	4.2	0.0	0.0
Ten Billions	95.8	0.0	0.0	4.2	100.0	0.0	0.0	0.0
Hundred Billions	95.8	0.0	0.0	4.2	100.0	0.0	0.0	0.0

*Please note that approximately 4.2% = One Child

Table 21

Percentage of Grade Five Students Falling in the Categories of the Number Production Proficiency Scale in Study 2 as a Function of Forward and Backward Naming and Counting

	Forward Naming Data				Backward Naming Data			
Number Series	Rtg= 1	Rtg= 2	Rtg= 3	Rtg= 4	Rtg= 1	Rtg= 2	Rtg= 3	Rtg= 4
Decades	0.0*	0.0	0.0	100.0	0.0	0.0	0.0	100.0
Hundreds	0.0	0.0	4.2	100.0	0.0	0.0	0.0	100.0
Low Thousands	4.2	4.2	4.2	87.5	8.3	4.2	4.2	83.3
Ten Thousands	8.3	0.0	0.0	91.7	8.3	8.3	8.3	75.0
Hundred Thousands	29.2	12.5	4.2	54.2	37.5	20.8	0.0	41.7
Low Millions	54.2	0.0	0.0	45.8	54.2	4.2	16.7	25.0
Ten Millions	54.2	8.3	4.2	33.3	45.8	16.7	4.2	33.3
Hundred Millions	50.0	12.5	4.2	33.3	50.0	4.2	4.2	41.7
Low Billions	70.8	0.0	0.0	29.2	70.8	0.0	0.0	29.2
Ten Billions	70.8	0.0	0.0	29.2	70.8	0.0	4.2	25.0
Hundred Billions	70.8	0.0	0.0	29.2	70.8	0.0	0.0	29.2

*Please note that approximately 4.2% = One Child

Table 21 (continued)

	Forward Counting Data				Backward Counting Data			
Number Series	Rtg= 1	Rtg= 2	Rtg= 3	Rtg= 4	Rtg= 1	Rtg= 2	Rtg= 3	Rtg= 4
Decades	0.0	0.0	0.0	100.0	0.0	0.0	0.0	100.0
Hundreds	0.0	0.0	4.2	95.8	0.0	0.0	0.0	100.0
Low Thousands	4.2	4.2	16.7	75.0	12.5	0.0	12.5	75.0
Ten Thousands	8.3	0.0	4.2	87.5	8.3	12.5	8.3	70.8
Hundred Thousands	37.5	8.3	4.2	50.0	33.3	20.8	8.3	37.5
Low Millions	54.2	0.0	0.0	45.8	58.3	0.0	8.3	33.3
Ten Millions	54.2	8.3	4.2	33.3	41.7	16.7	4.2	37.5
Hundred Millions	54.2	8.3	8.3	29.2	54.2	0.0	4.2	41.7
Low Billions	70.8	0.0	0.0	29.2	70.8	0.0	0.0	29.2
Ten Billions	70.8	0.0	0.0	29.2	70.8	0.0	0.0	29.2
Hundred Billions	70.8	0.0	0.0	29.2	70.8	0.0	0.0	29.2

*Please note that approximately 4.2% = One Child

Table 22

Percentage of Grade Seven Students Falling in the Categories of the Number Production Proficiency Scale in Study 2 as a Function of Forward and Backward Naming and Counting

	Forward Naming Data				Backward Naming Data			
Number Series	Rtg= 1	Rtg= 2	Rtg= 3	Rtg= 4	Rtg= 1	Rtg= 2	Rtg= 3	Rtg= 4
Decades	0.0*	0.0	4.2	95.8	0.0	0.0	0.0	100.0
Hundreds	0.0	0.0	0.0	100.0	0.0	0.0	0.0	100.0
Low Thousands	0.0	0.0	4.2	95.8	4.2	0.0	4.2	91.7
Ten Thousands	0.0	0.0	4.2	95.8	4.2	4.2	4.2	87.5
Hundred Thousands	4.2	4.2	4.2	87.5	4.2	8.3	12.5	75.0
Low Millions	16.7	4.2	4.2	75.0	12.5	8.3	8.3	70.8
Ten Millions	12.5	12.5	4.2	70.8	12.5	8.3	0.0	79.2
Hundred Millions	20.8	4.2	4.2	70.8	20.8	4.2	8.3	66.7
Low Billions	29.2	4.2	4.2	62.5	37.5	4.2	0.0	58.3
Ten Billions	33.3	4.2	0.0	62.5	37.5	0.0	0.0	62.5
Hundred Billions	33.3	0.0	8.3	58.3	37.5	0.0	0.0	62.5

*Please note that approximately 4.2% = One Child

Table 22 (continued)

Number Series	Forward Counting Data Rtg= 1	Rtg= 2	Rtg= 3	Rtg= 4	Backward Counting Data Rtg= 1	Rtg= 2	Rtg= 3	Rtg= 4
Decades	0.0	0.0	4.2	95.8	0.0	0.0	0.0	100.0
Hundreds	0.0	0.0	0.0	100.0	0.0	0.0	0.0	100.0
Low Thousands	0.0	0.0	4.2	95.8	0.0	0.0	4.2	95.8
Ten Thousands	4.2	0.0	4.2	91.7	4.2	4.2	0.0	91.7
Hundred Thousands	8.3	0.0	12.5	79.2	4.2	8.3	12.5	75.0
Low Millions	16.7	4.2	8.3	70.8	12.5	8.3	4.2	75.0
Ten Millions	12.5	8.3	12.5	66.7	12.5	8.3	4.2	75.0
Hundred Millions	16.7	8.3	4.2	70.8	20.8	4.2	8.3	66.7
Low Billions	37.5	0.0	0.0	62.5	37.5	0.0	4.2	58.3
Ten Billions	33.3	0.0	4.2	62.5	37.5	0.0	4.2	58.3
Hundred Billions	33.3	0.0	4.2	62.5	37.5	0.0	0.0	62.5

*Please note that approximately 4.2% = One Child

Analyses on the Number Naming and Counting Time Data

Repeated measures ANOVAs were used to examine developmental differences in the times children took to name and count numbers at each number level. Once again, naming times included the time from which the number first appeared on the screen to the end of the child's correct named response. Counting times included the time between the end of a named response and the end of the correct counted response. Analyses were conducted separately at each number level since preliminary analyses revealed that number production times increased as children produced larger numbers, $F(4, 84) = 140.94$, $p < .001$. For the repeated measures ANOVAs, grade was treated as a between subject factor provided that there were at least five participants per cell, and given the aforementioned differences in number production performance as a function of the forward and backward naming and counting tasks, type of task was considered a within subject factor. All pairwise comparisons reported in this section were set at the .008 alpha level to protect against alpha slippage, and were tested using one-tailed tests. It should be noted that the use of this conservative alpha level may increase the prevalence of committing type two errors; nonetheless, post hocs were chosen to test the significance of several unanticipated differences in responding across tasks. Children were included in the analyses provided that they correctly identified at least one of the numbers within the particular number series analysed on each of the four number production tasks. The analyses included times of only the numbers children produced correctly. Children's mean number production times on the forward naming, forward counting, backward naming, and backward counting tasks as a function of grade are illustrated in Figures 1 and 2, and they are also listed in Table 23. Please note that the children's number production times are presented in

Figure 1: Times Taken to Name Numbers in Seconds as a function of Grade and Number Series in Study 2.

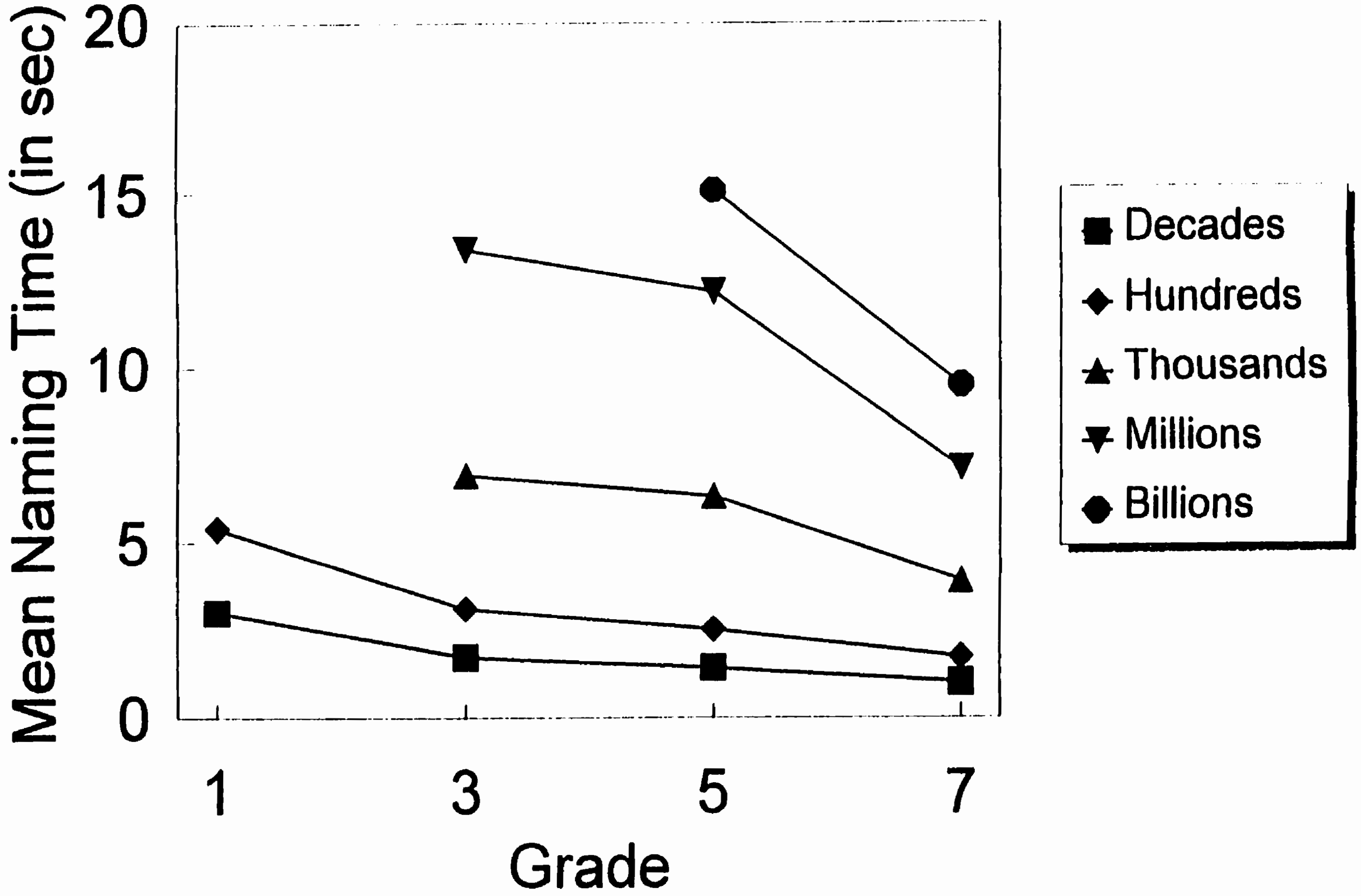

Figure 2: Times Taken to Count Numbers in Seconds as a function of Grade and Number Series in Study 2.

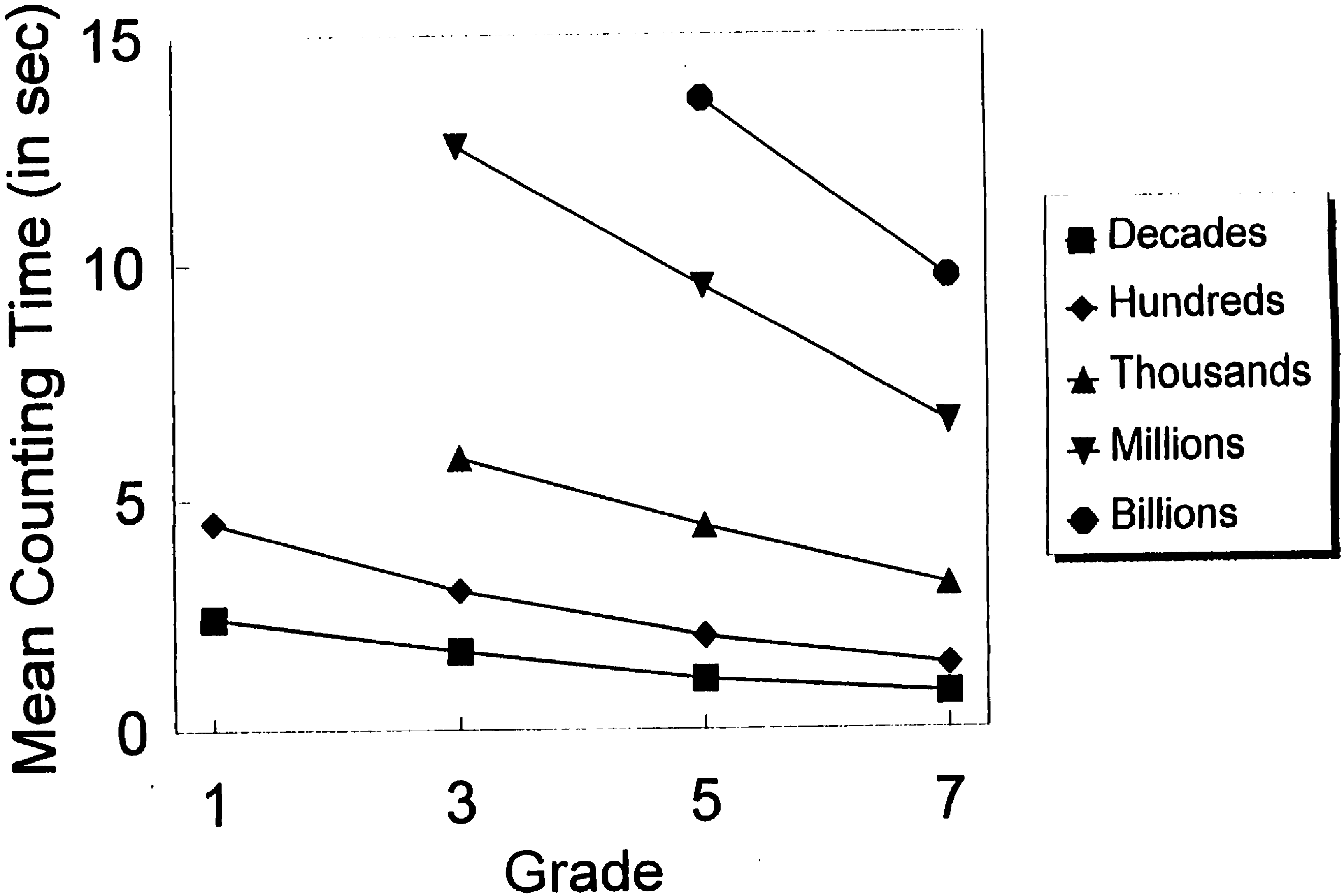

Table 23

Times Taken to Produce Numbers in milliseconds as a function of Grade in Study 2.

FORWARD NAMING	Decades		Hundreds		Thousands		Millions		Billions	
	Mean	N	Mean	N	Mean	N	Mean	N	Mean	N
Grade 1	2665	21	4814	7	N/A	< 5	N/A	< 5	N/A	< 5
Grade 3	1635	24	2964	22	6878	13	N/A	< 5	N/A	< 5
Grade 5	1355	24	2433	24	6462	22	9868	10	15397	7
Grade 7	948	24	1664	24	3671	22	6956	19	9227	15
Overall	1618	93	2562	77	5479	57	7960	29	11190	22

FORWARD COUNTING	Decades		Hundreds		Thousands		Millions		Billions	
	Mean	N	Mean	N	Mean	N	Mean	N	Mean	N
Grade 1	1942	21	4114	7	N/A	< 5	N/A	< 5	N/A	< 5
Grade 3	1496	24	2604	22	5737	13	N/A	< 5	N/A	< 5
Grade 5	1073	24	1878	24	4392	22	9407	10	14746	7
Grade 7	736	24	1340	24	3000	22	6496	19	9768	15
Overall	1291	93	2121	77	4161	57	7500	29	11298	22

Table 23 (continued)

BACKWARD NAMING	Decades		Hundreds		Thousands		Millions		Billions	
	Mean	N	Mean	N	Mean	N	Mean	N	Mean	N
Grade 1	3410	21	5823	7	N/A	< 5	N/A	< 5	N/A	< 5
Grade 3	1784	24	3256	22	6661	13	N/A	< 5	N/A	< 5
Grade 5	1484	24	2477	24	6497	22	11212	10	14822	7
Grade 7	1039	24	1848	24	3953	22	6993	19	9875	15
Overall	1881	93	2808	77	5651	57	8448	29	11449	22

BACKWARD COUNTING	Decades		Hundreds		Thousands		Millions		Billions	
	Mean	N	Mean	N	Mean	N	Mean	N	Mean	N
Grade 1	3000	21	5001	7	N/A	< 5	N/A	< 5	N/A	< 5
Grade 3	1826	24	3074	22	6130	13	N/A	< 5	N/A	< 5
Grade 5	1139	24	2084	24	4689	22	9902	10	13041	7
Grade 7	848	24	1493	24	3135	22	6736	19	9740	15
Overall	1661	93	2448	77	4418	57	7827	29	10790	22

seconds in the Figures (to improve the graphic layout), but they are presented in milliseconds (to maintain the precise quality of the data) in Table 23.

Results of the repeated measures ANOVA on decade numbers revealed a statistically significant grade effect, $F(3, 85) = 44.16$, $p < .001$, and a significant task effect, $F(3, 255) = 20.33$, $p < .001$, but these main effects were complicated by a significant grade by task interaction, $F(9, 255) = 4.65$, $p < .001$, and by a significant grade by sex by task interaction, $F(9, 255) = 2.55$, $p < .008$. With respect to the grade effect, children's times to produce numbers decreased with grade and Tukey HSD procedures revealed that all means differed significantly ($p < .05$). Surprisingly, even though the same naming task was paired with counting forward and backward, there were significant timing differences found between most tasks. More specifically, children were fastest at producing numbers correctly on the forward counting task, followed by the forward naming task, the backward counting task, and were slowest at producing numbers on the backward naming task. Paired difference t-tests revealed that all task means differed significantly (with the exception of the difference between backward naming and backward counting, and forward naming versus backward counting): $t(92) = 3.76$, $p < .001$ for forward versus backward naming; $t(92) = 3.71$, $p < .001$ for forward versus backward counting; $t(92) = 6.66$, $p < .001$ for forward counting versus backward naming; $t(92) = 5.63$, $p < .001$ for forward naming versus forward counting.

For the most part, the aforementioned task effects were replicated within each grade for both sexes. However, the significant grade by task interaction was likely due to non-significant differences between means for all tasks in grade three (with the exception of the significant difference between forward counting and backward naming in grade three, $t(23) = 2.81$, p

$<.005$). Likewise, although pairwise comparisons at the grade by sex by task level generally supported the pattern of results described above, only differences between means were significant at certain grade levels, for certain sexes. For example, the forward counting and backward naming means only differed significantly at the grade one level for boys, $t(11) = 4.12$, $p < .001$, at the grade five level for girls, $t(11) = 4.18$, $p < .001$ and at the grade seven level for girls, $t(11) = 3.51$, $p < .003$. Likewise, the difference between forward counting and forward naming was only significant for grade one girls, $t(8) = 4.95$, $p < .001$, and grade five boys, $t(11) = 3.43$, $p < .003$ and girls, $t(11) = 4.18$, $p < .001$. Finally, the difference between backward counting and naming means was significant only for grade five boys, $t(11) = 3.53$, $p < .003$. All other pairwise comparisons at each grade by sex by task level were not significant.

For the hundreds series, a repeated measures ANOVA revealed a significant grade effect, $F(3,73) = 691.30$, $p < .001$, a significant task effect, $F(3, 219) = 27.04$, $p < .001$, and a significant grade by task interaction, $F(9, 219) = 2.41$, $p < .013$. Consistent with the number production times at the decade level, older children were faster at producing numbers in the hundreds than younger children, and Tukey HSD tests revealed that differences between means at all grade levels were significant ($p < .05$).

However, task effects depended on the grade of the child tested. Grade one and three students were generally slower at producing all numbers compared to their older agemates, regardless of the task involved. There were no significant differences in times as a function of the task at the grade one level, and only two of the same comparisons at the grade three level yielded significant results. Specifically, grade three children were faster at producing numbers on the forward counting compared to the backward naming task, $t(21) = 2.79$, $p < .006$ and on the forward compared to the backward task, $t(21) = 3.11$, $p < .003$. The task did influence the speed of performance for the grade five and seven students. Children in grades five and seven produced numbers in the hundreds fastest on the forward counting task, followed by the backward counting task, the forward naming task, and were slowest at producing numbers on the backward naming task. All means differed significantly for the grade five (t's$(23) > 2.63$, p's $< .005$) and seven students (t's$(23) > 2.45$, p's $< .005$) with the exception of mean differences between forward and backward naming for the grade five students, and forward and backward counting for the grade five and seven students.

A repeated measures ANOVA (excluding grade one students due to low sample sizes) for numbers in the thousands series revealed a statistically significant grade effect, $F(3, 54) = 17.10$, $p < .001$, and a statistically significant task effect, $F(3, 162) = 18.54$, $p < .001$, and a statistically significant grade by task interaction, $F(6, 162) = 2.39$, $p < .03$. Once again, there was a decrease in children's number production times with grade, and Tukey post hoc analyses revealed that all means differed significantly ($p < .05$). With respect to the task effect, children were faster at producing numbers on the forward counting task, followed by the backward counting task, the forward naming task, and were slowest at producing numbers on the backward naming task. Consistent with the hundred series all means differed significantly, t's > 4.41, p's $< .001$, with the exception of the non-significant differences between forward naming and backward naming, $t(59) = .70$, $p < .486$, and between forward counting and backward counting, $t(56) = 1.29$, $p < 2.01$.

However, results of the timing data at the thousands level were complicated by a significant grade by task interaction effect. Close analysis of this interaction revealed that at

Table 24

Children's Reaction Times (in milliseconds) on the Number Naming Reaction Time Task in Study 2 at Each Number Level as a Function of Grade and Word Type.

	Basic	Non-Basic	N
Grade One			
1) Decades	1195	1495	23
2) Hundreds	1216	1214	9
3) Thousands	N/A	N/A	<5
4) Millions	N/A	N/A	<5
5) Billions	N/A	N/A	<5
Grade Three			
1) Decades	715	960	24
2) Hundreds	891	793	24
3) Thousands	978	1273	12
4) Millions	N/A	N/A	<5
5) Billions	N/A	N/A	<5
Grade Five			
1) Decades	634	748	24
2) Hundreds	781	740	24
3) Thousands	1069	1371	23
4) Millions	1889	2050	12
5) Billions	2276	4614	5

Table 24 (continued)

	Basic	Non-Basic	N
Grade Seven			
1) Decades	572	583	24
2) Hundreds	619	707	24
3) Thousands	811	765	24
4) Millions	2303	1961	16
5) Billions	1172	1241	13
Overall			
1) Decades	774	941	95
2) Hundreds	814	799	81
3) Thousands	946	1104	59
4) Millions	2126	1999	28
5) Billions	1479	2178	18

Table 25

Children's Number Naming Production Times (in milliseconds) on the Number Naming Reaction Time Task in Study 2 at Each Number Level as a Function of Grade and Word Type.

	Basic	Non-Basic	N
Grade One			
1) Decades	1923	2421	23
2) Hundreds	1746	2020	9
3) Thousands	N/A	N/A	<5
4) Millions	N/A	N/A	<5
5) Billions	N/A	N/A	<5
Grade Three			
1) Decades	1220	1501	24
2) Hundreds	1368	1329	24
3) Thousands	1513	1954	12
4) Millions	N/A	N/A	<5
5) Billions	N/A	N/A	<5
Grade Five			
1) Decades	1064	1294	24
2) Hundreds	1238	1252	24
3) Thousands	1594	2238	23
4) Millions	2939	3222	12
5) Billions	3020	5548	5

Table 25 (continued)

	Basic	Non-Basic	N
Grade Seven			
1) Decades	995	1033	24
2) Hundreds	1065	1150	24
3) Thousands	1360	1299	24
4) Millions	3343	3041	16
5) Billions	1849	2140	13
Overall			
1) Decades	1294	1553	95
2) Hundreds	1281	1330	81
3) Thousands	1482	1798	59
4) Millions	3170	3119	28
5) Billions	2174	3087	18

again, individual children were only included in the analyses provided that they produced both the basic and non-basic number word correctly from a particular number series. Sex was not included as a variable in these analyses as preliminary analyses did not reveal any significant sex differences. Furthermore, the data were analyzed at each grade level, provided that there were at least five children at a particular grade who were able to name both the basic and non-basic number words at a number level correctly. For example, comparisons at the thousands level excluded grade one students, since there were only four grade one children who could correctly name both the basic and the non-basic number word correctly at this level. Likewise, grade one and three students were excluded from the analyses at the million and billion levels, since fewer than five children were exposed to and/or received credit for the basic and non-basic number words at these number levels.

Results of a repeated measures ANOVA on children's mean reaction times to name words at the decade level revealed a significant grade effect, $F(3, 91) = 19.21$, $p<.001$ and a significant number word type effect, $F(1, 91) = 10.76$, $p<.001$. A significant grade effect, $F(3, 91) = 19.71$, $p<.001$ and a significant number word effect, $F(1, 91) = 9.64$, $p<.003$ was also obtained in the repeated measures ANOVA on children's completed decade number naming times. Consistent with the earlier reported naming time data, younger children were slower at starting and completing correct verbalizations of decade numbers. However, Tukey post hoc analyses revealed that only the difference between grade one and the grade three, five and seven means differed significantly ($p <.05$). With respect to the significant number word effect, results of both analyses revealed that children's reaction times and total number naming times were faster for the basic decade words versus the randomly selected non-basic decade word comparisons.

Children's mean reaction times and total number naming times were highly consistent across number word type and grade at the hundreds, thousands and millions levels. Consequently, the results of several repeated measures ANOVAs only revealed a significant grade effect on children's reaction times to name numbers at the hundreds level, $\underline{F}(3, 77) = 7.82$, $\underline{p} < .001$; and a significant grade effect, $\underline{F}(2, 56) = 3.33$, $\underline{p} < .043$ and a significant number word effect, $\underline{F}(1, 56) = 6.03$, $\underline{p} < .017$ for total number production time at the thousands level. With respect to the significant grade effect at the hundreds level, older children reacted faster to naming numbers, but post hoc tests revealed that only the grade one mean differed significantly from the means at other grades. The same trend was observed at the thousands level with older children producing number words faster than younger students, but post hoc analyses revealed that only grade five and grade seven means differed significantly from the grade three mean. However, as predicted, children were faster to name the basic number word <u>one thousand</u> correctly than its non-basic comparison <u>five thousand</u>.

Finally, results of the repeated measures ANOVAs on children's reaction times and total naming times at the billions level revealed two significant grade effects ($\underline{F}(1, 16) = 13.44$, $\underline{p} < .002$ and $\underline{F}(1, 16) = 12.70$, $\underline{p} < .003$, respectively), two significant number word type effects ($\underline{F}(1, 16) = 5.10$, $\underline{p} < .038$ and $\underline{F}(1, 16) = 6.99$, $\underline{p} < .018$, respectively), and two significant grade by number word type interactions ($\underline{F}(1, 16) = 4.54$, $\underline{p} < .049$ and $\underline{F}(1, 16) = 4.40$, $\underline{p} < .05$, respectively). Grade five students were slower at reacting to and naming the numbers at the billions level on this task compared to their grade seven counterparts. Furthermore, although both grade levels were slower at reacting to and naming the non-basic number word <u>six billion</u>

compared to the basic number word one billion, the difference in reaction times and total naming times for these two words was more pronounced at the grade five level.

Relation Between Number Production Performance and Academic Abilities

Pearson product-moment correlation coefficients measuring the relation between children's performance on the two subtests of the Woodcock-Johnson, teachers' ratings of their students' mathematical and reading abilities, and children's scores on the basic number knowledge task, total naming task, total counting task, and numerical problem solving task are presented in Table 26 as a function of grade. Since the correlations between children's number production abilities and scores on the two individual Woodcock-Johnson subtests did not yield a consistent and explainable pattern at all grade levels, percentile scores from the two achievement measures were averaged to obtain an overall mathematics achievement score. Correlations were also calculated on this composite mathematical achievement score.

As demonstrated in Table 26, teacher ratings of their students' academic abilities did not correlate strongly with their children's performance on the number production tasks in Study 2. Of the 32 correlational analyses conducted, only two were statistically significant.[9] Specifically, teacher ratings of children's mathematics ability were positively correlated with children's basic number word vocabulary in grade one, and total counting ability in grade five.

The correlations between children's achievement scores and their number production performance were positive at all grades. However, given statistical conventions in psychology, only a subset are considered significant. Specifically, at the grade one and seven levels, the children's total mathematics composite score was positively related to their basic number word vocabularies, and total number naming and counting performance. Likewise, at the grade five

Table 26

Correlation Coefficients Illustrating the Relation Between Teacher Ratings of Children's Academic Achievement, Children's Scores on the Woodcock-Johnson Achievement Test, and Children's Performance on the Number Production Tasks at Each Grade in Study 2.

Grade One	Math Rating	Reading Rating	Concepts Score	Calculation Score	Total Math Score
Basic Vocabulary	.47*	.41	.19	.68**	.53*
Total Naming	.46	.40	.46	.63**	.64**
Total Counting	.46	.42	.51*	.67**	.70**
Problem Solving	.12	.13	.16	.15	.18
Math Rating	1.00	.60*	.30	.47*	.46
Reading Rating		1.00	.39	.57*	.57*
Concepts Score			1.00	.45	.87**
Calculation Score				1.00	.83**
Total Math Score					1.00

* -indicates significance at the .01 alpha level (one-tailed)

** -indicates significance at the .001 alpha level (one-tailed)

Table 26 (continued)

Grade Three	Math Rating	Reading Rating	Concepts Score	Calculation Score	Total Math Score
Basic Vocabulary	-.10	-.22	.12	.13	.14
Total Naming	.40	.25	.13	.42	.31
Total Counting	.40	.20	.09	.37	.26
Problem Solving	.27	.12	.20	.44	.37
Math Rating	1.00	.86**	.32	.53*	.49*
Reading Rating		1.00	.37	.41	.45
Concepts Score			1.00	.49*	.87**
Calculation Score				1.00	.85**
Total Math Score					1.00

* -indicates significance at the .01 alpha level (one-tailed)

** -indicates significance at the .001 alpha level (one-tailed)

Table 26 (continued)

Grade Five	Math Rating	Reading Rating	Concepts Score	Calculation Score	Total Math Score
Basic Vocabulary	.25	.21	.47*	.31	.46
Total Naming	.47	.42	.46	.37	.49*
Total Counting	.48*	.41	.49*	.37	.51*
Problem Solving	.38	.34	.47	.23	.42
Math Rating	1.00	.78**	.49*	.46	.55*
Reading Rating		1.00	.60**	.52*	.65**
Concepts Score			1.00	.50*	.89**
Calculation Score				1.00	.84**
Total Math Score					1.00

* -indicates significance at the .01 alpha level (one-tailed)

** -indicates significance at the .001 alpha level (one-tailed)

Table 26 (continued)

Grade Seven	Math Rating	Reading Rating	Concepts Score	Calculation Score	Total Math Score
Basic Vocabulary	.22	.26	.61**	.50*	.59*
Total Naming	.34	.44	.41	.51*	.48*
Total Counting	.34	.44	.43	55*	.52*
Problem Solving	.24	.18	.27	.43	.37
Math Rating	1.00	.73**	.51*	.48*	.52*
Reading Rating		1.00	.61**	.60*	.64**
Concepts Score			1.00	.78**	.95**
Calculation Score				1.0000	.94**
Total Math Score					1.00

* -indicates significance at the .01 alpha level (one-tailed)

** -indicates significance at the .001 alpha level (one-tailed)

level, children's total mathematics score was positively correlated with their performance on the number naming and counting tasks.

Pearson product correlation coefficients were also used to examine the relation between children's composite mathematical achievement scores at each grade level and their number naming and counting times at each of the five number series. Results of these correlational tests revealed significant findings for grade seven students only. Specifically, grade seven students with higher mathematical performance scores on the Woodcock Johnson tests tended to be faster at naming numbers at the decades [$r(22) = -0.61$, $p < .05$], hundreds [$r(22) = -0.70$, $p < .05$], thousands [$r(22) = -0.6675$, $p < .05$], and millions series [$r(22) = -0.72$, $p < .01$]. Higher achieving grade seven students also tended to be faster at counting numbers in the thousands [$r(22) = -0.63$, $p < .05$], millions [$r(22) = -0.70$, $p < .05$] and billions [$r(22) = -0.69$, $p < .05$].

Discussion

Study 2 replicated the large increase in children's number naming and counting skills with grade. These findings confirm the substantial increase in children's understanding of the cardinal number system, and the increase in children's basic and total cardinal number word vocabularies during the school years. Consistent with Study 1, children's basic number word vocabularies were compatible with children's stopping points on the number production tasks in about one half of all cases. This finding provides at least some support for the assumption that a basic vocabulary is required for producing compound number words correctly, and when children do not have a requisite number word in their vocabulary, they can only count as high as the series containing the largest stored basic number word. (The remaining cases do not necessarily violate the assumption, but could be interpreted as were similar findings from Study

1 on pp. 55-57).

Even though several researchers have noted the cardinal number sequence can be generated using a small set of vocabulary words (Anglin, 1993b; Baroody, 1987; Ginsburg, 1977), stopping pattern data for about one fifth of the children revealed that simply knowing vocabulary words was not enough for children to generate additional number words. Informal observations revealed several cases where children produced all of the appropriate basic vocabulary words correctly, but did not receive credit for a complex number because vocabulary words were not ordered correctly within the number word compound. This finding is consistent with some emerging research suggesting that in addition to vocabulary mistakes, people also make syntactic (or compound construction) errors while translating numerals into number words (Power & Dal Martello, 1990; Seron & Fayol, 1994).

Consistent with Study 1, results also demonstrated strong individual differences in children's number production scores within each grade. These individual differences were significantly related to the children's mathematical achievement test scores at the grade one, five, and seven levels. The data were also consistent with previous research demonstrating some individual differences in children's counting abilities (Hubbard, 1995; Fuson, Richards, & Briars, 1982). However, the current project extended the literature in that children's number naming counting abilities were related to their mathematical knowledge even as late as the grade five and seven levels.

Although the grade three correlations between mathematical performance and number production abilities were positive, and were in the same low to moderate range as the significant correlations for the other grades, they did not reach significance in both studies. It is possible that this grade three discrepancy could be due to differences in the focus of the curricular requirements at this grade. For example, the number sense portion of the grade three curriculum tends to focus on the ordering of arabic numerals and ordinal numbers (Ministry of Education, 1985), which may not be highly related to number production skills. However, further investigations involving larger sample sizes (and essentially greater experimental power) are needed before conclusions of this nature are made.

Close observation of the number production proficiency data in both studies may also provide insight into children's developing knowledge of the cardinal number sequence. As demonstrated in Tables 7 and 18, with the exception of the grade one data, and the data at the thousands series, children often seem to move from having no knowledge of the number words in a series to completely mastering the number words at a particular level. This statement is based on the observation that with the above two exceptions, there were relatively few scores of two and three on the number production proficiency scale, which represent partial knowledge of the cardinal number sequence. The two categories were still low despite the fact that they contain a large portion of the percentage data (i.e., between one and ninety-nine percent of number words mastered in a series). The findings are consistent with research by Baroody, Gannon, Brent, and Ginsburg (1984) indicating that children's acquisition of the cardinal number sequence is step-like, and they learn portions of the number sequence in series (i.e., decades first followed by hundreds, and so forth).

However, the grade one data did not follow the above pattern in that the scores were more evenly distributed across the four proficiency categories at least for the decades and hundreds series. This finding may have occurred because the grade one students are still learning the fundamentals of number production. Since 28 of the hypothesized basic vocabulary words are introduced in the decades, along with several compounding rules, it seems likely that these children may commit errors coordinating the requisite knowledge for number words.

Tables 7 and 18 also illustrate a more distributed pattern of number proficiency scores across the four categories for the thousands, compared to the distribution of scores at the other number series, for the grade three, grade five and, to a lesser extent, grade seven levels. This finding suggests that producing number words in the thousands is challenging for children even in the later elementary school years. The thousands series may be difficult for children because it is the first number series, where an increase in the number of arabic digits in the numeral is not associated with a new basic number word. Children must learn a new compounding rule to account for this discrepancy at both the ten thousand and hundred thousand levels. A closer breakdown of scores in Tables 8 to 11 of Study 1 and Tables 19 to 22 of Study 2 indicates that children's acquisition of the low thousands, ten thousands, and hundred thousands is step-like, in support of the argument that children must learn a new compounding rule at the ten thousands, and then again at the hundred thousands before they can continue the series.

Finally, data from the current project did not support the assumption made in previous research that the number system is completely generative following the hundreds. Close analysis of the mastery data in Tables 8 to 11 and in Tables 19 to 22 shows a gradual decline in perfect number production performance up to the low millions series, indicating that many children were unable to produce all number words correctly to that point. However, once children were able to produce numbers perfectly in the low millions, a large majority of these children continued to produce number words correctly into the hundred millions. Furthermore, despite a small decrease in mastery scores between the hundred millions and the low billions (possibly occurring because children did not know the basic word billion), most children who produced all the numbers in the low billions correctly continued to produce words correctly into the hundred billions. These data suggest that it is not until children master the numbers in the low millions at a minimum, and possibly even the billions, that they can extend the number sequence indefinitely (given requisite vocabulary words).

Consistent with the hypotheses, all children were able to demonstrate knowledge of the principle of cardinality on at least one of the cardinality tasks. Thus, it may be assumed that even though children were not asked to express their knowledge of the number words in Study 2, all children could theoretically demonstrate the meaning of these words by using objects and counting up to the required number word. However, results of the responding on the abstract cardinality task revealed significant increases in the number of correct responses with grade. These findings may be due to the fact that older children have better problem solving skills, and more advanced metacognitive abilities to interpret the abstract numerical quantities in the questions. Consequently, older children were more likely to produce the correct answer compared to their younger agemates.

The quality of children's responses on the numerical problem solving task was comparable to that for the responses discussed in Study 1, suggesting that most children in Study 2 also used some form of problem solving to answer the questions. However, analyses revealed that the children were highly sensitive to the sound pattern of the pseudo number words, and obtained higher scores when the pseudo number word was similar to other larger number words they may have encountered previously. This finding suggests that children have preconceived notions of the sound pattern of the large basic number words. Thus, children who were exposed to the "gillion" number word may have been more likely to relate the question to their own working model of the cardinal number system, retrieve the relevant compounding rules, and produce the correct answer compared to children in the more abstract "guggle" worded condition.

In addition to the substantial increase in children's cardinal number word vocabularies with grade, results of Study 2 revealed that there were substantial increases in children's abilities to produce numbers quickly with grade. In one extreme case, it took one grade three student two hours to complete the number production tasks into the billions with few errors, even though most grade seven students completed the same task in about 45 minutes. These findings add to the developmental hypothesis of children's number production capabilities. Specifically children do not simply learn to produce more number words with grade, but their entire cardinal number production capabilities become increasingly proficient during the school years. With formal schooling and other life experiences, children gain knowledge of additional basic number words, and likely practice producing these number words in combination with other number words. As a result of practice, the mental lexicon may become more organized, and older children who have had more practice, may be better able to retrieve number words and organize them more efficiently than their younger counterparts.

However, the speed at which children produced number words correctly depended on the nature of the number production task. In most cases, children were fastest at producing numbers on the forward counting task, followed by the backward counting task, the forward naming task, and were slowest on the backward naming task. These findings are concordant with the general performance differential between forward and backward counting obtained in both studies and in some other research (Steinberg, 1985; Thornton & Smith, 1988; Wright, 1994). Not only did children receive more credit for words on the forward number production tasks, but they also tended to produce numbers faster on the forward than backward tasks. However, the forward and backward counting effects were so strong in Study 2, that the counting effects surprisingly carried over into the naming trials. These results may have occurred because the forward counting sequence is typically practiced more often, is learned earlier (Ministry of Education, 1985), and thus it becomes more automatized than the backward number sequence. As a result, mental translations of numerals into number words are likely less taxing on short term storage and retrieval mechanisms when children are asked to complete the task in a forward as opposed to a backward directional context.

Contrary to expectations, children were faster at producing number words correctly on the counting trials compared to the naming trials. On first thought, it was expected that children would be slower at producing numbers correctly while counting than naming numbers, because they would need additional processing time to relate the previously named number word to the cardinal number sequence. However, the speeded performance on counting trials suggests that children did not always translate numerals into number words using problem solving on this trial. Children may have held the number words in short term memory, repeated the words on the counting trial, and in most cases made a one word adjustment to the last produced number word. This simple modification likely required less processing time than the time taken to use problem solving to construct words on naming trials.

Children's abilities to name and react to the three basic decade words, and two of the large multi-digit basic number words (i.e., thousand and billion) were faster than the children's abilities to produce the randomly selected non-basic comparisons at certain grades. This finding provides preliminary support for the hypothesis that individuals have a certain set of basic number words stored in semantic memory. Furthermore, children may be fast to react to and name the basic number words because they do not have to use problem solving skills to produce these words; the words are simply retrieved from semantic memory.

However, it should be noted that the number naming and reaction time differentials between basic number words and their non-basic number word comparisons were only significant at the grade levels where the majority of the children tested were still working on mastering the number series in question. For example, the difference between basic and non-basic decade words was only significant for grade one students. Likewise, the time differences in the billions series were only significant for grade five students. These findings may indicate that as children become proficient at producing number words for a particular series, the processing involved in compounding non-basic number words (at least of the type used in the number naming reaction time task) becomes so automatic, that the time taken to produce the basic versus the non-basic number words can no longer be detected. Alternatively, some non-basic number words may come to be used frequently in society (e.g., the decade numbers, famous historical dates) or by individuals (e.g., birth year, street number, lucky number) that they may become lexicalized entries.

grade is not likely solely due to children learning or becoming more proficient with problem solving skills with grade, but is likely also due to the repetitive nature of the cardinal number sequence. That is, as the cardinal number sequence increases, the potential number of cardinal number words that may be constructed through problem solving increases exponentially (see the multipliers in Appendix 5). Thus, problem solving estimates may be low for the young children because they have not yet learned or coordinated their number knowledge for words in the latter portions of the series (i.e., millions and billions) that are highly conducive to problem solving.

It should be noted that the vocabulary estimates obtained in the current investigation for both children's total cardinal number words and problem solved words strongly exceeded the estimates reported in Anglin (1993a) for the set of English words contained in an unabridged dictionary. Differences in estimates across the two investigations most certainly occurred because of the different characteristics inherent in the set of vocabulary words studied in each project. The set of English cardinal number words is heavily rule governed, and follow a repeating pattern that is generally consistent with the conventions of place value. As a result, very few basic vocabulary words and compounding rules are needed to construct additional words. The results of the current study demonstrated an extreme case of the importance of problem solving skills in vocabulary development.

Advancing the Research on Children's Cardinal Number Knowledge

Although research on children's counting has most often focused on preschoolers' acquisition of the number series into the decades and their developing knowledge of the five counting principles using a variety of counting tasks (e.g., object counting versus rote counting) (Baroody & Price, 1983; Becker, 1993; Brissiaud, 1992; Fuson, Pergament, Lyons & Hall, 1985; Fuson, Secada & Hall, 1983; Gelman & Gallistel, 1978; Ginsburg, 1977; Michie, 1984; Resnick, 1989; Saxe, Becker, Sadeghpour & Sicillian, 1989; Shannon, 1978; Shipley & Shepperson, 1990a, 1990b; Wagner & Walters, 1982), the current work has shown that children's counting abilities continue to develop throughout the school years. The current studies have replicated some research indicating that students up to grade three typically extend the number sequence into the hundreds and thousands (Bell & Burns, 1981; Kar & Dash, 1991; Fuson, 1988; Siegler & Richards, 1983). However, results of the testing have shown that it is not until the grade five and seven levels that children are able to continue the number sequence into the millions and billions series, respectively. Furthermore, even though children were not directly tested on numbers beyond one trillion, it is unlikely that most children at these grade levels would be able to count beyond the trillions, since only a handful of students knew the basic number words beyond trillion.

In addition to the large quantitative number production gains during the school years, results of the current investigation revealed some interesting qualitative accomplishments in the children's counting skills with grade. In previous research involving preschoolers, forward counting has often been used as an indication of children's counting knowledge, and objects or pictures of objects are used to solicit knowledge of the five basic counting principles (e.g., Fuson, 1988; Fuson, Pergament, Lyons & Hall, 1985; Shipley & Shepperson, 1990a, 1990b). However, informal observations revealed that all children in the current project could demonstrate their number production abilities at any arbitrary starting point in the number sequence, they could produce number words by translating numbers from their arabic form, and they could demonstrate their counting abilities in the absence of any objects. These observations suggest that with practice in school and other life experiences, the children in this project have likely developed a deep understanding of the cardinal number system, compared to the preschool participants tested in other research. Furthermore, with more advanced short term memory skills (Siegler, 1991), the children in this study may have developed flexible strategies enabling them to produce number words in conditions involving the more rigorous test demands of this research compared to methods used in other investigations.

The present results also demonstrated large individual differences in children's number production skills within grade, which in extreme cases, were larger than the differences observed between the mean number production scores of two consecutive grades tested. Although individual differences have been reported in other studies (Hubbard, 1995; Fuson, 1988; Fuson, Richards, & Briars, 1982), the current research demonstrated that these individual differences are important since they are related to children's mathematical achievement scores at most grades. It is possible that children with higher number production stopping points have developed a greater knowledge of place value and ultimately, a better understanding of the cardinal number system, which would enhance their scores on the mathematics tests, compared to their lower achieving same-aged peers. However, more research is clearly needed since the current experiments do not accurately discriminate between children's number production skills, place value knowledge, cardinal number knowledge, and their relation with conceptual and calculation skills in mathematics.

Sex Differences

Equal numbers of boys and girls were randomly assigned within each grade in the current investigation (with two slight exceptions in Study 1), such that conclusions about children's number word production skills could be generalized to both sexes. Even though the examination of sex differences was not of primary concern, equal numbers of boys and girls assigned within each grade permitted analyses of this type.

Results of the project further revealed some unanticipated sex differences in favor of boys on the number production tasks, especially at grades one and seven. These findings are relevant to some studies reporting that boys outperform girls on mathematical achievement tests (Felson & Trudeau, 1991; Friedman, 1989; Kimball, 1989; Maccoby & Jacklin, 1974), boys are better problem solvers than girls (Geary, 1996; Hyde, Fennema & Lamon, 1990), and even up to adulthood, males have more positive feelings and less anxiety toward mathematics than females (Kaiser-Messmer, 1993; LeFevre, Kulak, & Heymans, 1992). More importantly, the current findings are consistent with one study that found sex differences in counting up to 100 at the grade one level in favor of boys (Callahan & Clements, 1984). Although many explanations have been proposed to account for sex differences on mathematics related tasks, such as socialization practices, course selections, differential treatment of boys and girls by teachers (Fennema, 1990), more research is needed to determine the underlying factors responsible for these sex differences, especially since they occurred at such an early age. Furthermore, Callahan and Clements (1984) noted that caution should be used when interpreting sex differences in mathematics research, as they demonstrated that slight differences in task demands (specifically in counting experiments) reverse the direction of the effect.

Developing a Model for Children's Acquisition of the Cardinal Number Sequence

The current research findings extend cognitive developmental approaches attempting to understand children's acquisition of the cardinal number sequence, and the representation of number words in semantic memory. Consistent with previous work (Anglin, 1993b; Baroody, 1987; Ginsburg, 1977), children's stopping points, informal observations of their incorrect problem solved basic number word attempts, and data from the number naming and reaction time task support the notion that at a minimum, children (often by grade seven) seem to learn eventually a set of approximately 32 basic number vocabulary words, from which additional number words may be generated.

Results further indicated that school aged children used problem solving skills to generate at least some of the large multi-digit numerals studied in the project. Children's problem solved responses were most noticeable on the incorrectly attempted responses. For example, children showed evidence of problem solving in place of not knowing required basic number words (e.g., saying "one killion" for 100,000), when they did not seem to know relevant compound rules (e.g., producing "nine hundred thousand thirty-seven, six hundred seventy" for 937,670), or when they may have lacked knowledge of place value conventions (e.g., ignoring the meaning of the zero in 506, by stating "fifty-six"). Informal observations also revealed that children used their problem solving skills on the correct trials. For example, some children counted out sections of three digits separated by commas before responding, some students started to translate a numeral into words up to three times before producing a correct response, and some children used self-monitoring verbalizations while producing the words, indicating that they were not simply retrieving stored words from memory.

However, the observed effect of children failing to receive credit for a number word, despite knowing all relevant basic vocabulary words suggests there are other factors responsible for children's acquisition of the number sequence besides knowing the relevant basic number words. One such factor that has not been implicated in previous work is the implicit knowledge of the linguistic rules for translating numerals into words. That is, in addition to learning the compounding sequence for producing number words (as demonstrated in Appendix 1), children must also learn the difference between the digit and positional values of numerals and how this information translates linguistically (James & James, 1992; Karush, 1989, Shapiro, 1977). Although the current project has outlined the importance of these linguistic factors to the skill of counting, further research is needed to investigate the relative importance of each factor to children's numerical development.

The present results also provide further insight into the order in which children acquire the number sequence. Previous work has indicated that children learn a set of number vocabulary words, and problem solving skills first become relevant in the decade series when children realize the number words follow a repeating pattern (e.g., Fuson, 1988, Fuson, 1991; Fuson, 1992b; Fuson & Kwon, 1992b). However, the current work has demonstrated that children do not simply learn all basic number words at once, and are then capable of generating additional words in the series. The strong developmental increase in children's number production abilities with grade suggests that children learn the smaller, earlier appearing cardinal number words in the sequence before the larger, later appearing ones. Earlier appearing numbers are likely acquired first because they are usually not as morphemically complex as the later appearing numbers. Since the cardinal number system is generative, the smaller numbers may be used as building blocks and added to each other to produce larger numbers. Thus, it would be difficult to produce larger number words before knowing how to produce smaller numbers first.

Furthermore, consistent with previous research (Baroody, Gannon, Berent & Ginsburg, 1984), the current work supported the argument that children acquire the cardinal number sequence in series. Data from the number production proficiency scale suggested that after children master the decade sequence, they begin to acquire number words in the hundreds, the low thousands, the ten thousands, the hundred thousands, and so forth. Children may learn specific portions of the cardinal number word system in this sequence because they have to coordinate knowledge of new compounding words with new basic number vocabulary words. For example, in the hundreds series, children have to learn a new basic word (i.e., "hundred"), and the convention for attaching this new basic number word to previously-mastered decade stems.

The current research also revealed that the thousands series is very difficult to master, and even some of the participants in the oldest age group produced thousands level words incorrectly. Once again, children may have had difficulty with the thousands sequence, because the thousands are the first series where the number of arabic digits in a numeral is no longer always associated with a new basic number word. Consequently, children may acquire specific portions of the thousands series separately because they have to learn and coordinate a new compounding rule each time the length of the numerals increases in digits (i.e., low thousands, ten thousands, hundred thousands).

Furthermore, the current work demonstrated that it is not until children produce number words in the millions at a minimum, that they are likely able to generate the sequence indefinitely (when supplied relevant vocabulary words). This statement is based on the observation that the millions is the first series where children have been exposed to basically all

Place value is a system of notation for understanding the meaning of a string of numerals. When children have mastered place value, they will either implicitly or explicitly learn that every digit in a number has a purpose and the inclusion and ordering of digits differentiate each number (James & James, 1992; Karush, 1989). Furthermore, every digit in a number has a digit value (i.e., the name of the digit when presented by itself, such as "1" is called "one"), and a positional value (i.e., the value of the digit in relation to where it is situated such as the "3" in 300 represents "three" of the hundreds series) (Shapiro, 1977). It is likely that children first learn about the concept of place value during their preschool counting experiences (where they are often asked to translate numbers into both spoken and written forms), yet parents and educators only make implicit reference to place value rules. Perhaps, if there was more emphasis aimed at bridging counting abilities with place value knowledge at an early age (e.g., by showing children the ones and tens columns and talking about how numbers are organized in the decades), the difficulties that children are reported to have in the literature with respect to acquiring place value during the school years (St. John Jesson, 1983; Jones, Thornton, Putt, 1994; Jones, et al., 1996; Kamii, 1986) may be overcome to some extent.

Furthermore, since children's number production abilities were significantly related to their mathematical abilities at most grades, likely because of the strong relation between counting and place value knowledge, it may be important to focus on the skill of counting at all grade levels. It could be argued that children should be taught all the basic number words in the cardinal number series. In addition to learning the basic number words, children might benefit by being explicitly taught the compound rules, especially in the thousands, for generating additional words. Children might also benefit by being taught the specific rules for translating numerals into spoken form and vice versa. Finally, given that the English cardinal number system is more irregular in structure compared to the number words in other languages (e.g., Bell, 1990; Fuson, Fraivillig & Burghardt, 1992; Fuson & Kwon, 1992c; Miura, Kim, Chang & Okamoto, 1988), it may be helpful for students to practice number words in other languages, before generating number words in English (Kliman & Janssen, 1996).

Questions for Further Research in Mathematics Education

Although the current research extends knowledge of children's acquisition of the cardinal number system, the project has uncovered some areas that deserve attention in future research. First, further investigations are needed to determine how children's number production abilities are affected by the linguistic aspects of number words (e.g., syllable length, magnitude, frequency, morphemic complexity) and other numeric factors (e.g., number of digits). Although some research has begun to tease apart the relation between some of these variables with adult participants and with numbers up to 99 (Brysbaert, 1995; Gielen, Brysbaert, & Dhondt, 1991; Pynte, 1974), the random sample of numbers in the current project did not permit analyses designed to determine the relative importance of the above factors with larger numbers and child participants.

However, children's performance on one of the randomly selected numbers, 11,000,204 deserves brief attention. When asked to produce this number, eight children received credit for identifying 11,000,204, despite making errors on all numerals in the hundred thousands, and all other numerals in the millions. In this example, the absence of non-zero digits in the thousands section eliminates the need for knowing the compound conventions for producing number words in the thousands. Thus, even though it is presumed that children generally learn smaller number words before larger ones, the example shows that children can produce large number words when the morphemic structure is simplified and/or the syllable length is reduced.

Relatedly, it would be beneficial to document the set of rules that children use to translate numerals into number words and determine the age at which children acquire these rules. For example, several studies including the current work have found that many school-aged children have difficulty grasping the convention that zeros in numerals hold places, even though the zeros are not translated or pronounced when the numeral is translated into words. Research in this area may have important implications for developing children's understanding of place value, and improving their mathematical achievement.

Finally, even though the current work provided support for the assumption made here, and by others that at least some of the basic number words are learned and stored in semantic memory, more controlled studies are needed to investigate the relation between basic and non-basic words. From both numerical developmental and semantic memory theoretical perspectives, it would be interesting to obtain more direct evidence that each of the 32 basic number words are stored in semantic memory and to establish whether some other (compound) number words might be as well. Some cross cultural research has begun to address the semantic storage of number words, and number retrieval processes. For example, Miller and Zhu (1991) found that due to the morphological complexity of the English teen words, English-speaking adults showed more difficulty reversing numbers containing ones (e.g., 15, 51) compared to numbers with no ones (e.g., 53, 84), but Chinese-speaking participants did not show this performance differential. As a result of the longer processing times for numbers in English, Miller and Zhu (1991) concluded that the English teen words may be lexicalized entries. However, more research using different experimental methods is needed to understand the semantic representation of numerals and their corresponding number words. The current project has demonstrated the potential usefulness of the developmental approach in studying number processing and the semantic organization of number words in English, and in other languages.

In conclusion, the current work has demonstrated strong, reliable increases in children's cardinal number word knowledge with grade. The studies have identified several factors that likely affect children's abilities to continue the cardinal number sequence indefinitely. Furthermore, the studies have emphasized the importance of learning number production skills, in that counting was related to children's mathematical abilities in most grades. Finally, the project contributes to other work aimed at bridging the gap between children's linguistic accomplishments and their mathematical achievement.

Appendix 1

This appendix describes one morphological compounding strategy that people may use to convert the cardinal numbers from 1 to 999,999,999,999 into words. However, since the rules for constructing the number words are highly repetitive, a few slight modifications to the procedure described below would enable numbers of an even larger magnitude to be converted into words. It should also be noted that the rules outlined in this appendix are very detailed, and even if people use something like this specific process to convert numerals into words, it may be used quite automatically and unconsciously by adults and even children to generate the number word series.

Before the compounding rules are presented, it is necessary to discuss some of the general strategies that people may use when interpreting the meaning of a number, and converting it into words. First, consistent with reading words and sentences in English, the digits in a numeral are read from left to right. Furthermore, (at least) four features of a numeral are attended to when it is being converted into either a written or spoken form, including: (1) the specific digits in the numeral (i.e., digits can range from 0 to 9, and each digit is associated with a different basic number word); (2) the position of a digit within the numeral (i.e., since numbers operate on a place value system, even though 210 and 120 contain the same digits, the ordering of the digits changes the meaning and written or spoken form of the numbers); (3) the size of the numeral (i.e., numbers having many digits may often require more modifiers to accurately describe them); and (4) zeros hold places within a numeral and are not pronounced. Finally, the English number words are created by considering digits in groups of three. This may explain why commas and spaces have been conventionally used to separate the digits of a numeral into groups of three in some number systems.

General Process for Converting Cardinal Numbers into Words

The process of converting the cardinal numbers into words begins by in a numeral into groups of three. This process is done by starting with the c[redacted] most position (e.g., 27608<u>8</u>) and counting along until the digit in the left mo[redacted] <u>2</u>76 088) is reached. Zeros are counted as digits. If the numbers are writte[redacted] commas or spaces, the commas and spaces mark the divisions. If a number i divisible by three, the left most group will not contain three digits (e.g., <u>17</u>,2 groups have been marked, the total number of groups should be counted.

The following general equation may, depending on the specific numb[redacted] part or in its entirety to convert the cardinal numbers less than 1,000,000,00[redacted]

$$X = \overset{(\#4)}{(CNW_4 + BILLION + A_4)} + \overset{(\#3)}{(CNW_3 + MILLION + A_3)} + \overset{(\#2)}{(CNW_2 + THOUSAND + A}$$ [redacted]

where,

"X" refers to the cardinal number word that is converted in either spoken or

CNW refers to a cardinal number word representing numbers from 0 to 999

"A" refers to the insertion of either the conjunction AND or a COMMA (or if the word is spoken), the choice depending on circumstances described bel

This equation is subdivided into four sections (identified by the four number above it), such that all number words in the billions, millions, thousands, hu[redacted]

For example, if the numeral is 22,890,111, there are eight digits and three digit groupings. According to Table 1A, the number is in the millions series and the starting point of the equation is at the number three position. In this case, the equation becomes: $X=(CNW_3+ MILLION+ A_3) + (CNW_2+ THOUSAND+ A_2) + (CNW_1)$, and all notation associated with the billions series in the equation (i.e., section four) is omitted.

Once the starting point of the equation has been established, the left most group of (maximum three) digits is translated into words first. Regardless of the starting point, the first step of all equation sections requires that this first group of digits be converted into a cardinal number word (CNW) less than one thousand. With the exception of CNW_1, these cardinal number words will later modify the large basic number words (e.g., million) that are associated with the same section of the equation. The digits can be converted into number words less than one thousand using the procedure that is described in this next section.

Procedure for Producing Cardinal Number Words Less Than "One Thousand"

Due to several irregularities in the production of the English cardinal number words below one hundred, the process of creating words for numbers less than 1000 is subdivided into four rules. One or more of these rules may be used where applicable to convert a numeral (or portion of a numeral) into words. To begin, examine the number of digits in the left most group, and identify the specific digits. Then read the four rules from A to D, and start at the first rule that accurately describes the digit group.

A) Follow this procedure IF there are three digits in the group, and the left most digit is NOT a zero (e.g., 611, 572, but not 071 or 003). If this rule is not applicable, go to Rule B.

$CNW_X = BNW + HUNDRED + AND + CNW_0$

where,

BNW refers to a basic number word from ONE to NINE, determined by the left most digit in the group.

HUNDRED refers to a large basic number word that is modified by the BNW

AND is the conjunction added to connect the word HUNDRED with any subsequent number words generated by CNW_0. However, in the event that CNW_0 is zero, the AND is omitted.

CNW_0 refers to either a decade cardinal number word, or a basic number word less than twenty. This number word is determined by looking at the last two digits in the group. If the last two digits are zero (e.g., 300), no further cardinal number words are necessary to describe the group of digits. Thus, one should skip to the end of these specific rules and follow further instructions. If the middle digit in the triad is a zero, but the last digit in the group is not (e.g., 301), one should consult Rule C. Otherwise, one should consult Rule B.

B) Follow this procedure IF the cardinal number word has two digits, and the first digit is NOT zero (e.g., 98, 16); OR IF there are three digits in the group and the left most digit is a zero (e.g., 069); OR IF one has been referred to rule B from rule A to convert the latter two digits into words (e.g., 980, 211). If this rule is not applicable, consult Rule C.

Examine the two digits (or the right most two digits in the group, if there are three digits) and determine whether they fall from 10 to 19 or from 20 to 99.

a) IF THEY FALL FROM 10 to 19, then CNW_X (or CNW_0 if referred here from A) consists of a basic teen word from TEN to NINETEEN.

b) IF THEY FALL FROM 20 to 99, then the CNW_X (or CNW_0) can be constructed according to the following procedure: CNW_X (or CNW_0)= BDW + a hyphen (-) + BNW where,

BDW refers to a basic decade word from TWENTY to NINETY, and

BNW refers to a basic word from ONE to NINE

If one of the procedures in Part B has been followed, the CNW_X (or CNW_0) has been created and one should skip to the end of this set of four rules to follow further instructions.

C) Follow this procedure IF the cardinal number word has only one digit (e.g., 4), OR IF the two left most digits are zeros (but not the right most digit in the triad) (e.g., 003), OR IF one has been referred to Rule C from Rule A (e.g., 90$\underline{3}$, 10$\underline{2}$).

In this situation, the CNW_X (or CNW_0 if referred here from A) refers to a basic number word from ONE to NINE. If this rule is followed, skip to the end of the set of four rules and follow further instructions.

D) IF all three digits in the group are zeros (e.g., 000), then a cardinal number word for this section of the general equation is not written or spoken. Furthermore, any number words, conjunctions or commas that would have been written in the same section of the general equation are also omitted. Essentially, the entire section (indicated by the brackets in the general equation) is skipped. Those following the procedure outlined by Rule D should go to the next (right most) group of digits in the numeral, and begin creating the next CNW (if one exists). If the group of zeros are the right most group of digits, the process is terminated and the number word is complete.

Once one or more of these specific rules has been followed, a cardinal number word should have been created. To this number word, one should add the appropriate large basic number word that is written in the same section of the general equation as the cardinal number word. Then, either AND or a comma is added according to the following provisions:

i) Add <u>AND</u> IF the <u>total</u> number of digits remaining on the right side of the digit group currently being considered, is less than 100 but not equal to zero.

ii) Add a comma (,) (or a SHORT PAUSE if the word is spoken) IF the digits remaining on the right side of the digit group currently being considered, is equal to or greater than 100.

iii) If the digits are equal to zero, then neither the conjunction nor a comma is added to the compound.

Once all notation in one section of the general equation has been attended to, one should consider the next right most group of three digits (if another group exists). Once again, the first step in generating a number word for this new group of numerals requires that a cardinal number word less than one thousand be created. One may consult the four specific rules discussed above when generating the number words for this new number triad. If there are no digit groups to the right of the digits already considered and one has completed the forth section of the equation, then the number word is complete and the number word production process is terminated.[3]

Thus, the arabic numeral 264,010 can be produced orthographically or phonetically according to the general equation and the four specific rules discussed above. Since there are two groups of three digits (i.e., 264 and 010) in this numeral, consulting Table 1A reveals that the number falls within the thousands series. The starting point of the equation is at the number two position, and the equation can be reduced to: $X = (CNW_2 + THOUSAND + A_2) + (CNW_1)$.

To produce CNW_2, the four specific rules are consulted. Since 264 has three digits (none of which are zeros), Rule A generates the words "TWO HUNDRED AND." Then rule B (part b) produces "SIXTY-FOUR." Now that all of the digits have been accounted for, it is necessary to return to the general equation and add the basic word "THOUSAND," and the conjunction AND (since the digit group following is less than 100). The same procedure is followed when the next right most group of digits is considered. Since CNW_1 begins with a zero, it is converted into TEN using rule B (part a). Finally, since all the digits have been accounted for the process is terminated and the final number word produced is: TWO HUNDRED AND SIXTY-FOUR THOUSAND AND TEN.

Likewise, the above procedure can be used to convert a number containing many zeros such as 1,000,000,001 into words. Since this number contains four digit groups (or ten total digits), it is from the billions series and the entire equation is needed to generate the number word. To produce CNW_4, it is necessary to consider the left most group of digits (i.e.. 1 in this case) and consult the four specific rules for generating words for numbers less than 1000. Because there is only one digit in the "group," rule C is used to create the basic number word "ONE." Returning to the general equation, the words "BILLION AND" are added (since the digits to the right are less than 100, but not equal to zero). Next, according to rule D of the specific rules, the million and thousand sections are skipped since the next two right digit groups contain all zeros. Finally, the 1 in the right most group of digits is generated from part C of the four specific rules. Since there are no more digits to be considered, the final number word produced is: ONE BILLION AND ONE.

Appendix 2

Numbers with Names Considered Psychologically Basic and Used in the Basic Number Knowledge Task

Number	Name
1	one
2	two
3	three
4	four
5	five
6	six
7	seven
8	eight
9	nine
10	ten
11	eleven
12	twelve
13	thirteen
14	fourteen
15	fifteen
16	sixteen
17	seventeen
18	eighteen
19	nineteen

Continued...

Appendix 2 (Continued)

Number	Name
20	twenty
30	thirty
40	forty
50	fifty
60	sixty
70	seventy
80	eighty
90	ninety
100	hundred
1,000	thousand
1,000,000	million
1,000,000,000	billion
1,000,000,000,000	trillion
1,000,000,000,000,000	quadrillion
1,000,000,000,000,000,000	quintillion
1,000,000,000,000,000,000,000	sextillion
1,000,000,000,000,000,000,000,000	septillion
1,000,000,000,000,000,000,000,000,000	octillion
1,000,000,000,000,000,000,000,000,000,000	nonillion
1,000,000,000,000,000,000,000,000,000,000,000	decillion

Appendix 3

The Special Case Numbers Used on the Forward and Backward Counting Tasks

Forward List

29	999	99,999,999,999
39	9,999	999,999,999,999
49	99,999	
59	999,999	
69	9,999,999	
79	99,999,999	
89	999,999,999	
99	9,999,999,999	

Backward List

30*	100	1,000,000,000
40	1,000	10,000,000,000
50	10,000	100,000,000,000
60	100,000	1,000,000,000,000
70	1,000,000	
80	10,000,000	
90	100,000,000	

*The decade number word twenty was not considered a special case in this study because it is assumed to be part of the early number sequence that must be memorized. Thus, it would not have to be retrieved following a series of number words generated through problem solving.

Appendix 4

The 120 Random Numbers Used in the Forward/Backward Number Naming and Counting Tasks

List 1

10	264	2,178	3,529,647	1,390,022,867
12	288	6,499	6,507,584	1,981,506,549
23	354	8,331	7,727,080	7,379,252,410
37	387	9,640	9,808,277	9,476,072,464
42	471	27,469	42,256,851	13,331,059,914
45	563	34,410	51,574,795	15,941,362,851
54	575	56,550	62,522,914	62,813,100,300
65	680	63,970	84,792,768	99,792,028,855
76	831	205,165	405,188,139	327,881,757,056
81	837	407,276	527,079,953	358,472,869,519
84	931	652,013	689,809,354	739,596,131,101
91	991	937,670	789,754,387	810,723,821,940

List 2

11	133	6,234	4,905,686	1,758,753,794
15	138	6,606	6,288,980	2,825,395,270
31	254	6,893	7,468,509	5,427,268,428
35	274	8,007	7,517,649	6,188,108,513
46	452	11,344	11,000,204	16,136,226,950
51	480	27,429	65,053,448	68,342,990,168
53	506	79,290	69,403,685	76,772,626,962
56	543	89,524	74,027,721	85,424,278,513
71	717	489,474	320,889,837	130,329,270,288
75	765	532,547	524,633,824	171,911,711,716
86	839	557,182	645,747,774	253,524,170,697
96	932	964,509	734,408,721	764,885,261,343

Appendix 5

Ranges of Numbers From Which Numbers were Randomly Sampled in the Decades Series

Range	Number of Numerals	
10-20	11	
21-28	8	
31-38	8	
41-48	8	
51-58	8	
61-68	8	
71-78	8	
81-88	8	
91-98	8	Multiplier= 75

Ranges of Numbers From Which Numbers were Randomly Sampled in the Hundreds, Thousands, Millions and Billions Series

Range of Numbers	Corresponding Multiplier
101 - 998	898
1,001 - 9,998	8,998
10,001 - 99,998	89,998
100,001 - 999,998	899,998
1,000,001 - 9,999,998	8,999,998
10,000,001 - 99,999,998	89,999,998

Continued...

Appendix 5 (Continued)

100,000,001 - 999,999,998	899,999,998
1,000,000,001 - 9,999,999,998	8,999,999,998
10,000,000,001 - 99,999,999,998	89,999,999,998
100,000,000,001 - 999,999,999,998	899,999,999,998

Endnotes

[1] It should be noted that all statements regarding number words in this paper are based on the organization of the number series according to the American system. However, virtually identical conclusions could be drawn using the organization of numbers in the British system. For a description of the differences between the American and British number systems, consult Webster's dictionary (1981).

[2] It should be noted that under some mathematical conventions, the conjunction "and," is not included as a part of the compound number word. It is reserved for representing arabic numerals with decimals. However, informal pilot testing revealed that the vast majority of adults use "and" within the elements of a whole cardinal number word. Thus, use of the conjunction "and" was incorporated as a part of the compounding rules in this project.

[3] Readers may be quick to point out that some conventions for words in the hundred and thousands series are not consistent with these compounding rules. These approaches may be considered short forms of the compounding strategies described in this paper and in other compounding techniques described elsewhere (Hurford, 1987). For example, number words in the thousands can often be expressed as continuations of the hundreds series (e.g., twenty-three hundred for 2300). Furthermore, it is common to completely omit the basic words hundred and thousand, and label each arabic digit (or combination of digits) with basic number words (e.g., one fifty-two, for 152; nineteen, sixty-nine for 1969). Perhaps these short form conventions have been introduced with number words in the hundred and thousand series since these morphologically complex words are commonly used in society.

[4] Children were not tested on their knowledge of number words from one to nine on the

forward and backward number naming and counting tasks in Study 1. However, since all children were able to demonstrate knowledge of all of these number words on the basic number knowledge task, and previous research has shown that children the same age as the youngest participants are able to name and count from numbers well into the decade series (e.g., Baroody, 1986; Fuson, 1988; Siegler & Robinson, 1982) it was assumed that all children in the study could name and count from these number words. Thus, 9 was added to all vocabulary estimates. Children were directly tested on the number words less than 10 in Study 2 to ensure that this assumption is valid.

[5] Children's number naming scores were further subdivided into mean random and special case components, and repeated measures ANOVAs with grade and sex as between subject factors and task direction (i.e., forward versus backward) as the within subject factor were also conducted on these mean scores. Since the results were highly consistent with the total number naming data, they are only reported as an endnote. With respect to naming random number words, analyses indicated a significant grade effect ($F(3, 56) = 57.09$, $p < .001$), with Tukey (HSD) post hoc procedures revealing significant mean differences at all grades ($p < .05$). Specifically, on average grade one, three, five, and seven children named random number words up to the hundreds, ten thousands, ten millions, and ten billions respectively (M's increased with grade from 29.00, 59.69, 82.13, to 110.63 respectively out of a possible score of 120).

Similarly, the results of the analyses on children's special case number naming abilities revealed a main effect of grade, $F(3, 56) = 51.84$, $p < .001$, with children in grades one, three, five, and seven on average identifying all special case cardinal number words up to eighty, ten thousand, ten million, and ninety-nine billion, nine hundred and ninety-nine million, nine hundred and ninety-nine thousand, nine hundred and ninety-nine, respectively (M's increased with grade from 14.13, 20.44, 26.88, to 33.44 out of a possible score of 36). Tukey (HSD) post hoc tests indicated that all means differed significantly ($p < .05$). In addition to the grade effect, results of the repeated measures ANOVA also revealed a significant sex effect, $F(1, 56) = 7.96$, $p < .007$. More specifically, boys ($M = 24.94$) identified more special case number words than girls ($M = 22.50$), but the differences between means of boys and girls was only significant at grades one and seven ($p < .05$).

[6] Children's mean counting scores were also subdivided into mean random and special case counting scores and analyzed. Two repeated measures ANOVAs (with grade and sex as between subject measures and task direction as the within subject measure) conducted on children's mean random and special case counting scores revealed significant main effects of grade [$F(3, 56) = 61.42$, $p < .001$, and $F(3, 56) = 41.71$, $p < .001$, respectively] and sex [$F(1, 56) = 4.39$, $p < .041$ and $F(1, 56) = 11.89$, $p < .001$, respectively]. Tukey post hoc procedures indicated that all mean differences between grades in the random analysis were significant ($p < .05$); and all means in the special case counting analysis differed significantly except for the difference between the grade three and five means ($p < .05$). In grade one, most children counted into the low hundreds on the random trials ($M = 24.88$ out of 120) and into the seventies on the special case trials ($M = 10.50$ out of 36). In grade three, many children counted into the ten thousands on both the random ($M = 58.69$) and special case trials ($M = 18.81$). Many grade five children could count up to the ten millions on the random task ($M = 81.69$) and up to one million on the special case trials ($M = 23.63$). By grade seven, most children counted into the ten billions on the random trials ($M = 109.75$) and into the low billions on the special

case trials (M= 30.25). Finally, with respect to the significant sex differences, boys outperformed girls on both the random (i.e., M= 71.63 for boys versus M= 65.88 for girls) and special case trials (i.e., M= 22.50 for boys versus M= 19.09 for girls).

[7] It should be noted that the percentages reported in Tables 8 through 11 (and then again in Study 2 in Tables 19 through 22) for the specific number production tasks are sometimes different than the more general percentages reported in Table 7 (and Table 18). Specifically, percentages in categories one and four are sometimes lower in the general table than they are in the more specific tables, since children must receive credit for, or show no knowledge of all of the numbers within a particular number series to be included in category four or category one of the general table, respectively. In some cases, children received credit for mastering a particular number series, in a particular task (e.g., forward counting), and would be included in the mastery data for that specific task. However, they may have made errors on the other task (i.e., backward counting), which would prevent them from receiving credit for all numbers at a particular series, and would eliminate them from category four in the general table. For example, the category four percentage in the general table for grade seven students' counting performance in the millions is 56.3, whereas the same value ranges from 68.8 to 87.5 percent in the more specific table. These percentages suggest that only 56.3 percent of the children received credit for all of the numbers in the millions, even though some children mastered the million series numbers on some of the number production tasks.

In other cases, the general table scores were more inclusive than the percentages in the more specific tables. For example, some children did not demonstrate any knowledge of numbers within a particular number series on one task (e.g., backward counting), but then demonstrated knowledge of that series on another task (e.g., forward counting). These children would be included in the percentages of the general table for knowing at least part of a number series (i.e., category two), but they would not be included in the same percentages as knowing the numbers on the specific tasks. As a result of these tabular discrepancies, comparisons across the general and specific tables are not recommended.

[8] Four separate repeated measures ANOVAs on the children's naming and counting data with grade and sex as between subject measures and task type (i.e., forward versus backward) were also conducted on the random and special case numbers. Since these findings were highly consistent with the results of the main analyses reported in both studies, they are reported as an endnote.

For the random numbers, results of the analyses revealed significant grade effects for the naming and counting tasks, $F(3, 88) = 72.73$, $p < .001$ and $F(3, 88) = 72.33$, $p < .001$, respectively, and significant task direction effects, $F(1, 88) = 4.59$, $p < .035$ and $F(1, 88) = 4.76$, $p < .032$, respectively. Although children named and counted more numbers correctly on the forward than the backward tasks, children's mean naming and counting scores in grades one, three, five and seven fell in the low hundreds, low thousands, ten millions, and low billions respectively (M's increased with grade from 14.21, 29.79, 42.42, to 52.46 for naming, and 13.54, 28.38, 41.42 to 52.04 for counting out of a possible score of 60). Tukey post hoc tests revealed that all means differed significantly ($p < .05$).

Results of the analyses on the special case number words revealed significant grade effects for both naming $F(3, 88) = 60.16$, $p < .001$ and counting $F(3, 88) = 53.04$, $p < .001$. In addition to these grade effects, results indicated significant sex effects for naming $F(1, 88) =$

6.60, $p < .012$ and counting $F(1, 88) = 18.49$, $p < .001$, significant grade by sex interactions for naming, $F(3, 88) = 2.84$, $p < .043$ and counting, $F(3, 88) = 2.80$, $p < .044$, and a significant task direction effect for counting, $F(1, 88) = 6.61$, $p < .012$. Children's performance on naming the special case number words increased with grade and children in grades one, three, five, and seven named special case numbers on average up to ninety, ten thousand, ten million, and ten billion, respectively (M's increased with grade from 14.33, 20.08, 26.17 to 31.63 out of a possible score of 36). With respect to the significant sex effects, boys (M= 24.29) obtained higher number naming scores than girls (M= 21.81), and this difference was particularly pronounced at the grade one and seven levels.

On the special case counting trials, children produced the names of more special case numbers containing zeros correctly on the forward task (M= 10.63), compared to the names of numbers containing many nines on the backward task (M= 10.06). However, children's abilities to name special case numbers strongly increased with grade and children in grades one, three, five, and seven were able to name numbers on average in the high decades, low thousands, hundred thousands, and hundred millions respectively (M's increased with grade from 7.04, 8.75, 11.75, to 15.00 on the forward task, and from 5.91, 8.54, 11.33, to 14.46 on the backward task out of a possible score of 18). Consistent with previously reported sex differences, boys (M= 22.81) counted more special case numbers correctly than girls (M= 18.58), and these sex differences were most pronounced at the grade one and seven levels.

[9] It should be noted that although there was a substantial increase in participants from Study 1 (i.e., n = 16 per grade) to Study 2 (i.e., n = 24 per grade), and consequently an improvement in sample size, power calculations indicated that there was still only 48% chance

of obtaining significant moderate effects in Study 2, given that they exist.

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IMAGE EVALUATION TEST TARGET (QA-3)

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