No Evidence for an Influence of Grammatical Number
in Two-Digit Magnitude and Place-Value Processing in Adults

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Abstract

Numerous studies revealed effects of some linguistic properties like inversion or reading/writing direction on number processing. However, it remains more controversial, whether influences at a syntactic level, such as singular vs. plural form associated with certain numbers, can also influence magnitude and place-value processing and vice versa. In this study, we investigated for the first time in a classical two-digit number comparison task whether grammatical number also affects magnitude and place-value processing (and vice versa). To do so, we used a peculiarity of the Polish language, where the inflection of a verb depends on the unit digit of a number (singular for 25-29, 35-39, etc. and plural for 22-24, 32-34, etc.). This systematic pattern allows the manipulation of congruency between grammatical number and magnitude information, both on an item and a response level (i.e., the grammatical number is either compatible or incompatible to the magnitude information or the response side). We observed no significant interference effects, neither between grammatical number (i.e., associated singular/ plural inflection of the number) and magnitude information, nor between grammatical number and the response side. Model comparisons revealed that models without grammatical number, could explain our data best. Hence, grammatical number did not contribute to the explanation of the data beyond unit-decade compatibility, distance effect and SNARC effect and, thus, seems to be negligible in two-digit number comparison. Task characteristics, which might contribute to this finding are discussed.

Keywords: grammatical number, two-digit number comparison, unit-decade compatibility effect, SNARC effect, linguistic influences

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Numerous studies revealed effects of linguistic properties on number processing, ranging from number comparison to more complex abilities like calculation (Colomé, Laka, & Sebastian-Galles, 2010; Göbel, Moeller, Pixner, Kaufmann, & Nuerk, 2014; Nuerk, Weger, & Willmes, 2005; Pixner, Zuber, et al., 2011; for an overview see Dowker & Nuerk, 2016). However, the mechanisms behind those language influences are not fully understood and often not even considered.

Models on numerical cognition also vary regarding the role of language and its potential influences on numerical processing. For example, McCloskey (1992) proposed that irrespective of the notation format (Arabic digits or number words) the number is transcoded in an abstract representation, which is the basis for further numerical processing, such as calculation or magnitude comparison. Studies providing evidence for influences of linguistic properties challenge the assumption of an abstract, language-independent representation (Colomé et al., 2010; Göbel et al., 2014; Nuerk, Weger, et al., 2005; Pixner, Moeller, Hermanova, Nuerk, & Kaufmann, 2011). In contrast, the triple-code model by Dehaene (1992) assumes three categories of mental representation (i.e., the visual Arabic number form, the verbal word frame and analogue magnitude representation) depending on the task (i.e., the required mental operation) and the format in which the numbers are presented (e.g., Arabic digits or number words). According to this model, language effects are predicted only for the verbal system and related mental operations (like calculation or counting, Colomé et al., 2010). Previous studies also revealed language effects for tasks requiring the visual Arabic number form and the analogue magnitude representation, such as the two-digit number comparison task (Nuerk, Weger, et al., 2005). Moreover, numerical tasks, which involve general linguistic processes, may include additional levels of representation such as

phonemic, graphemic or lexical codes (Dehaene & Cohen, 1995). However, the relationship between those representations is not yet well specified.

Recently, Dowker and Nuerk (2016) distinguished seven linguistic levels at which language influences on number processing occur (i.e., conceptual, semantic, syntactic, lexical, visuo-spatial-orthographic, phonological, and other levels). They concluded that future research is needed to investigate more precisely, at which level linguistic properties influence particular numerical tasks. The roles of these different linguistic properties are studied to different degrees. A new taxonomy by Bahnmueller, Nuerk and Moeller (2018) shows that while lexical influences (e.g., number word inversion or transparency) are widely studied, other linguistic properties received only little attention. For instance, we do not know whether or under which conditions syntactic language properties influence complex multi-digit number processing in adults. Moreover, the mechanisms behind the potential relation are unclear. There are some data for syntactic influences on infants' early number acquisition (see Sarnecka, 2014) and that grammatical number may be associated with spatial direction (e.g., Roettger & Domahs, 2015). Nevertheless, it has rarely been studied whether syntactic influences affect the common number use in adults, which usually includes multi-digit numbers.

In order to contribute to this open research question, we investigated the influence of grammatical number (i.e., linguistic influences at a syntactic level: singular vs. plural) on two-digit number comparison.

Two-digit number comparison

In a two-digit number comparison task, participants are asked to select the larger of two presented two-digit numbers. The two-digit number comparison task is well suited to study number processing, as robust and often shown hallmark effects in two-digit number comparison allow conclusions regarding the cognitive processes involved in the solution

process of the task: i.e., magnitude processing, place-value understanding and syntactic processes. Specific effects haven been discussed as operationalizations of these processes: the distance effect and the SNARC effect for the magnitude processing, unit-decade compatibility effect for the place-value understanding and the grammatical number effects for syntactic processes. Hereinafter, we will discuss these effects in more detail.

The distance effect. The *distance effect* refers to the finding that number comparison is faster for larger distances (e.g., 41 and 65) than for smaller distances (e.g., 53 and 65, Dehaene, Dupoux, & Mehler, 1990; Hinrichs, Yurko, & Hu, 1981; see Moyer & Landauer, 1967 for distance effect in single-digit number comparison).

The SNARC effect. The *Spatial-Numerical Association of Response Codes* (SNARC) refers to the spontaneous association of numbers and space. Concretely, it describes the observation that responses to small numbers are faster when responses are made on the left side than on the right side. In contrast, responses to larger numbers are faster when responses are made on the right side than on the left side (Dehaene, Bossini, & Giraux, 1993; Dehaene et al., 1990; Toomarian & Hubbard, 2018; see Wood, Willmes, Nuerk, & Fischer, 2008, for a meta-analysis, see Zhou, Chen, Chen, & Dong, 2008 for SNARC in two-digit numbers).

The unit-decade compatibility effect. The *unit-decade compatibility effect* describes performance differences in a two-digit number comparison task depending on the compatibility of the magnitude information of tens and units digits (Nuerk, Weger, & Willmes, 2001). A pair of numbers is defined as *unit-decade-compatible* if both comparisons between tens and units lead to the same decision. For example the number pair 31 and 58 is compatible, as both the comparison of the tens ($3 < 5$) and the comparison of the units ($1 < 8$) lead to the same decision. In contrast, a pair of numbers is defined as *unit-decade-incompatible* if the comparisons for tens and units lead to opposite results (e.g., 38 vs. 61, $3 < 6$, but $8 > 1$). Participants responded more slowly and less accurately to incompatible number pairs than to compatible number pairs (i.e., the compatibility effect, see also Ganor-Stern,

Tzelgov, & Ellenbogen, 2007; Macizo & Herrera, 2008; Van Rinsveld, Schiltz, Landerl, Brunner, & Ugen, 2016). Compatibility was not only found to influence number comparison with symbolic Arabic numbers, but also number comparison in a verbal notation (i.e., when using number words; Nuerk, Weger, & Willmes, 2002; Nuerk, Weger, et al., 2005).

Interaction between distance and unit-decade compatibility effect. The compatibility effect is influenced by the distance between the digits, especially by unit distance in RT data (Ganor-Stern et al., 2007; Nuerk et al., 2001; Van Rinsveld et al., 2016). The compatibility effect for Arabic digits (i.e., RT for incompatible items minus RT for compatible items) was larger for large unit distances than for small unit distances, which can be explained by the larger interference in trials with large unit distance (Huber, Nuerk, Willmes, & Moeller, 2016). Moreover, compatibility effects were larger for difficult comparisons, i.e., for small decade distances in the accuracy data (Nuerk et al., 2001).

For German number words, task performance was worse in incompatible than in compatible trials for large unit distances (as it was found for Arabic numbers). In contrast, for small unit distances, there was a reversed effect: compatible magnitude comparisons were slower than incompatible ones, which can be explained by matching overall distance between compatible and incompatible items (see Nuerk, Weger, & Willmes, 2005).

Language effects in the unit-decade compatibility effect. Studies investigating language differences regarding the compatibility effect focused primarily on lexical aspects, like the transparency of number word structure (e.g., the inversion property) and orthographic properties (i.e., the writing/reading direction) of a language (see Moeller, Shaki, Göbel, & Nuerk, 2015). For non-inverted languages - like Italian, Spanish, Polish and English - number words (for numbers > 20) correspond to the Arabic notation (e.g., 25 corresponds to twenty-five). Other languages - like Arabic, Dutch and German - are inverted regarding the order, i.e., number words invert the order of tens and units, which is called inversion (e.g., in German 25 corresponds to the number word „fünfundzwanzig“, i.e., „five and twenty“).

Nuerk, Weger, and Willmes (2005) found that the compatibility effect for Arabic numbers is not language-specific, i.e., can be found both for German and English native-speakers. However, language modulated the size of the compatibility effect, which was larger for German native-speakers than for English native-speakers. The finding got later replicated with children (Pixner, Moeller, et al., 2011) and with adolescents (Van Rinsveld et al., 2016), but not in an internet setting (Huber, Nuerk, Reips, & Soltanlou, 2019), where, however, language context cannot be thoroughly controlled.

Several studies found no compatibility effect for number words in languages with non-inverted number words, like English (Nuerk et al., 2005), Spanish (Macizo & Herrera, 2010) and Italian (Macizo, Herrera, Paolieri, & Romn, 2010). In contrast, for German participants compatibility interacted with unit-distance. Nuerk et al. (2005) concluded that the verbal representation is co-activated during Arabic magnitude comparison. Therefore, linguistic differences of two-digit number words (like the inversion property) influence two-digit magnitude comparison with Arabic numbers as well.

Syntactical influences on number processing.

The influence of syntactic factors, like grammatical number, has not received a lot attention in research on numerical cognition, although grammatical number contributes to the development of number concepts (Dowker & Nuerk, 2016; Sarnecka, 2014). The syntactic level, including the grammatical structure of languages, is a higher processing level and not as closely linked to the processed numbers as the often-studied lexical or orthographic level (including inversion or reading/ writing direction). Grammatical number expresses the meaning of number through grammar. The quantity can be encoded by nouns (singular or plural form) and verbs, which can be inflected depending on whether they refer to a singular or plural noun. Languages differ how they encode quantity in their grammar (Corbett, 2000; Overmann, 2015). Many languages (including English and German) mark the difference

between singular (a set of one) and plural (a set of two and more) by adding a suffix. For example, in English nouns are inflected by adding the suffix –s to the noun (singular: cat; plural: cats). Furthermore, singular/ plural is marked by the conjugation of the verb (singular: is; plural: are). The distinction between singular and plural is the most frequent grammatical number system. However, other languages also employ a singular/ dual/ plural system (e.g., Slovenian and Saudi Arabic) or even use a marker for paucal referring to small sets (Corbett, 2000; Overmann, 2015; Sarnecka, 2014). Moreover, there are languages (like Mandarin or Japanese) with very little singular/ plural marking (Sarnecka, 2014).

Several studies revealed a link between grammatical number and magnitude. For example, cross-linguistic studies revealed that the grammatical number system affects children's acquisition of number word meaning. Concretely, the distinction, between singular, dual and plural seems to facilitate number word learning (Almoammer et al., 2013; Sarnecka, Kamenskaya, Yamana, Ogura, & Yudovina, 2007). Moreover, results of neuroimaging studies suggest that the processing of singular and plural nouns (i.e., grammatical number) involves areas known to be relevant also for the processing of quantity (Carreiras, Carr, Barber, & Hernandez, 2011; Domahs et al., 2012).

Furthermore, Berent, Pinker, Tzelgov, Bibi, and Goldfarb (2005) suggest that semantic number is extracted automatically from morphological information despite being task-irrelevant. In a Stroop-like task, participants were asked to determine the number of visually presented words (one or two) while ignoring their contents (e.g., dogs dogs). Participants were slower when the number of words was incongruent with their morphological number (examples for incongruent trials: „dogs“ - one word but plural marking –s or „dog dog“ - two singular words). Similarly, Roettger and Domahs (2015) concluded that quantity representations are accessed when processing grammatical number. In a two-alternative forced-choice task, they asked participants to decide whether the presented German nouns

denoted one entity or more than one. They found a grammatical SNARC effect, i.e., a relative left-hand advantage for singular words and a right-hand advantage for plural words.

To sum up, previous studies revealed evidence not only for a link between magnitude and grammatical number, but also for an automatic processing of semantic number when processing grammatical number. Thus, grammatical number might also influence magnitude processing in Arabic digits/ number words.

The present study

In the present study, we investigated the influence of grammatical number (i.e., linguistic influences at a syntactic level: singular vs. plural) on the processing of two-digit numbers (Arabic digits/ number words). To realize this, we used a peculiarity of the Polish language. In Polish, the inflection of verbs and nouns depends on the unit digit of the number (see Table 1 for an overview). Verbs or nouns, which refer to the number „one“, are both used in the singular form. For the numbers „two“, „three“ and „four“ the verb inflection is plural and for nouns the (nominative) plural form is used (note: in English the nominative plural form is used for all numbers larger than one). However, for the numbers „five“ to „nine“ in Polish the verb is used in the singular form, but the noun in genitive plural. This pattern repeats for two-digit numbers larger than 21 (see Table 1; Plural verb form for 22-24, 32-34, etc. and singular verb form for 25-29, 35-39, etc.). Thus, within each decade smaller units are associated with plural verb forms and larger units with singular verb forms.

Table 1

Mapping between cardinal number and the corresponding inflection for verbs and nouns (i.e., grammatical number) in the Polish language (see Cipora et al., 2019)

Number	Verb	Noun	Example and English translation
1	Singular	nominative, singular	Tam jest jedno jabłko. (There is one apple)
2-4	Plural	nominative, plural	Tam są dwa jabłka. (There are two apples)
5-9	Singular	genitive, plural	Tam jest pięć jabłek. (There is five of apples)
10-21	Singular	genitive, plural	Tam jest dziesięć jabłek (There is ten of apples)
X2 - X4	Plural	nominative, plural	Tam są dwadzieścia trzy jabłka. (There are twenty-three apples)
X1 and X5 - X9	Singular	genitive, plural	Tam jest czterdzieści siedem jabłek. (There is forty-seven of apples.)

Note. X is the variable for the tens digit, ranging between 2 and 9

This grammatical number system allows for a systematic investigation of effects of grammatical number on two-digit number comparison as it enables the manipulation of congruency between grammatical number and magnitude. To do so, we were able to study the influence of grammatical number directly in a within-subject design, avoiding problems of quasi-experimental cross-linguistic study designs. The main disadvantage of cross-linguistic designs is, that if differences are found between two language groups, it is difficult to attribute the difference to language, as the groups differ also with regard to other aspects (e.g. the

educational system). Therefore, we investigated the effect of grammatical number in a within-subject design, by manipulating the congruency between grammatical number and the magnitude information or the response side. In the following section we describe this complex manipulation in great detail.

For better readability numbers with a singular verb inflection (25-29, 35-39, etc.) hereinafter are called *Singular Numbers*, analogous numbers with a plural verb inflection (22-24, 32-34, etc.) are called *Plural Numbers*. If grammatical number is activated during two-digit number comparison, the grammatical number information might interact with the magnitude information of the number. The unit-decade compatibility effect results from conflicting or corresponding magnitude information of the tens and the unit digit (i.e., on an item level). Similarly, grammatical number might either correspond or conflict with the magnitude information (i.e., resulting in either compatible or incompatible stimuli). The number is *grammatical compatible* when the grammatical information is compatible to the magnitude information (i.e., when a Plural Number is also the larger numerical number or when a Singular Number is the smaller numerical number). In contrast, a trial is *grammatical incompatible* when a Plural Number is the smaller number or when a Singular Number is the larger number. In the present study, we constructed stimuli, which were both grammatical compatible/ incompatible and unit-decade compatible/ incompatible (see Table 2 for examples of stimuli).

Table 2

Examples of number pairs being both unit-decade (in)compatible and grammatical (in)compatible

		Grammatical number compatibility					
		Compatible			Incompatible		
Unit-decade compatibility	Compatible	4	1	Sg.	2	3	Pl.
		^	^	^	^	^	v
		9	3	Pl.	8	5	Sg.
	Incompatible	3	5	Sg.	3	2	Pl.
		^	v	^	^	v	v
		8	3	Pl.	9	1	Sg.

Note. Green color indicates compatibility, red color incompatibility

When participants rely on both grammatical number and the magnitude information of tens and unit digits, it might create congruencies and interferences, resulting in an interaction between grammatical number (i.e., Singular/ Plural number) and the unit-decade compatibility effect. Assuming an additive influence of both factors, items being both grammatical and unit-decade incompatible should be most difficult resulting in the longest response times and highest error rates. In contrast items being both grammatical and unit-decade compatible, should be easiest to solve.

The results of Roettger and Domahs (2015) indicate that grammatical number (i.e., singular and plural nouns) has a spatial association with singular being associated with left and plural being associated with right. Thus, a trial is *grammatical congruent* when a number has a singular verb inflection and a left-hand response is required (or when the number has a plural verb inflection and a right-hand response is required). In contrast, a trial is *grammatical incongruent* when a number has a singular verb inflection, but is responded to with the right hand; and vice versa. The response association of the grammatical number might correspond

or contradict the famous spatial-numerical associations of the SNARC effect, where smaller numbers are associated with the left-hand side and larger numbers are associated with the right-hand side (i.e., *SNARC congruent* trials). Consequently, larger numbers being responded with left-hand side or smaller numbers being responded with right-hand side are considered as *SNARC incongruent*. The present study includes stimuli being both grammatical congruent/ incongruent and SNARC congruent/ incongruent (see Table 3 for examples).

Table 3
Examples of number pairs being both SNARC (in)congruent and grammatical (in)congruent

		Grammatical number congruity			
		Congruent		Incongruent	
SNARC	Congruent	4 1 Sg. ^ ^		4 3 Pl. ^ v	
		9 3 Pl.		9 1 Sg.
		Incongruent			
	Incongruent	9 1 Sg. v ^		9 3 Pl. v v	
		4 3 Pl.		4 1 Sg.

Note: In these examples response assignment in SNARC congruent examples is: larger number – right hand-side and response assignment in SNARC incongruent examples is smaller number – right hand-side. Green arrows indicate that the spatial association fits response assignment. Red arrows indicate that the spatial associations contradict are opposite to the response required in the experiment.

When both spatial associations (i.e., grammatical and numerical) are activated in two-digit number comparison and bias different responses, performance should be slower and more erroneously. This would indicate that the spatial association with singular/ plural interferes with the spatial association of the magnitude information. We analyzed theses hypotheses using the usual frequentist approach (i.e., null hypothesis testing).

As this is the first study investigating the influence of grammatical number on two-digit number comparison, there are various hypotheses conceivable, which we also investigated using an information-theoretic approach to determine the best fitting model (i.e., model comparison). To do so, we specified the following increasingly complex models, by systematically adding the factor grammatical number:

1. the *main effect model* is a replication of standard effects from the literature, included as main effects in the model (i.e., the effect of notation format + the distance effect + the unit-decade compatibility effect + SNARC effect). According to this model number comparison is influenced by the notation format, distance effect, unit-decade compatibility effect and the SNARC effect. There is no influence of grammatical number on two-digit number comparison in this model.
2. the *baseline interaction model* is a replication of standard effects from the literature considering already known interaction between these effects (i.e., the unit-decade

compatibility effect interacting with distance and notation format + the SNARC effect).

We did not include an interaction between notation format and the SNARC effect, as Nuerk, Wood, and Willmes (2005) found the SNARC effect was comparable in different notations (Arabic digits, number words). Again, there is no influence of grammatical number on two-digit number comparison.

3. The following models assume an influence of grammatical number on two-digit number comparison and therefore add grammatical number to *the baseline interaction model*.

3a) *Grammatical compatibility model*: If grammatical number is active during two-digit number comparison and affects the processing of the stimuli, it might interact with the magnitude information of the number (i.e., the unit-decade compatibility effect interacting with distance and notation format + the SNARC effect + grammatical number interacting with magnitude of the tens digit). Items should be responded faster and more accurately, when both magnitude information and grammatical number bias the same decision, which facilitates the response (and vice versa).

3b) *Grammatical congruity model*: Grammatical number might also affect the response of a two-digit number comparison task by interacting with response side (i.e., the unit-decade compatibility effect interacting with distance and notation format + the SNARC effect + grammatical number interacting with response side). In line with the grammatical SNARC effect, grammatical congruent items should be responded faster and more accurately than grammatical incongruent items, as the spatial association of singular/plural might bias the response.

4. the *grammatical number interaction models* consider interactions between grammatical number and standard effects from the literature. We differentiate three models:

4a) the baseline interaction model complemented by an *interaction between grammatical number and the unit-decade compatibility effect* (i.e., the unit-decade compatibility effect interacting with distance and notation format + the SNARC effect + grammatical number

interacting with the unit-decade compatibility effect). As derived above, items being both grammatical and unit-decade incompatible should be most difficult, while items being both grammatical and unit-decade compatible, should be easiest to solve.

4b) the baseline interaction model complemented by an *interaction between grammatical number and the SNARC effect* (i.e., the unit-decade compatibility effect interacting with distance and notation format + the SNARC effect + grammatical number interacting with the SNARC effect). When both spatial associations (i.e., grammatical and numerical) correspond, responses should be faster, whereas when the spatial associations bias different responses, performance should be slower and more erroneously.

4c) complemented by *both* an interaction between grammatical number and the unit-decade compatibility effect and the interaction between grammatical number and SNARC effect (i.e., the unit-decade compatibility effect interacting with distance and notation format + the SNARC effect interacting with the grammatical number + unit-decade compatibility effect interacting with grammatical number).

Method

Participants

The sample consisted of a total of 28 native Polish-speaking adults (10 male; M_{age} : 23.07 years, $SD = 4.21$ years; age range: 19-36 years). All participants provided written informed consent prior to their participation. The ethics committee of Warsaw University approved the study.

Apparatus and Stimuli

The experiment was implemented using the Presentation[®] software (Neurobehavioral Systems, 2016). Participants performed the magnitude comparison task on a LENOVO YOGA 700 sitting approximately 60 cm in front of a 14'' screen (resolution 1920×1080).

The stimuli consisted of 320 two-digit number pairs ranging between 21 and 96, among them 160 within-decade filler items including 80 within- and 80 between-grammatical numbers items [i.e., number pairs with same grammatical number, e.g., 41 (Singular) vs. 45 (Singular) or 32 (Plural) vs 34 (Plural)]. The 50% filler items, in which the unit digit is decisive for the magnitude decision, ensure that the attention (as indexed by eye movements) is directed both, at units and at decades (Huber, Mann, Nuerk, & Moeller, 2014; Macizo & Herrera, 2011). The 50% (N =160) between-decade experimental trials consisted of 20 items per condition. We manipulated unit-decade compatibility (compatible vs. incompatible), decade distance (small: 1-3 vs. large: 4-7), and grammatical number compatibility (compatible vs. incompatible; i.e., 2 unit-decade compatibility $\times$ 2 decade distances $\times$ 2 grammatical number compatibility $\times$ 20 repetitions = 160 items). Decade distance is the absolute difference between the tens digits. Numbers with whole tens (e.g., 30) or numbers with same ten and unit (e.g., 33) were not employed in the experiment.

Stimuli were matched for overall distance (absolutely and logarithmically) and problem size between the respective conditions. Moreover, the items were matched for syllable number between conditions, as we employed not only Arabic digits but also number words (see Table 1 in the Appendix). The two notation formats were presented in different blocks. Participants completed a total of four blocks, which differ regarding the notation of the numbers (Arabic digits vs. Polish number words) and the response assignments (left response key indicating smaller vs. larger number). Thus, the 320 items were presented four times, resulting a total of 1280 experimental trials (640 between- and 640 within-decade items). The response assignment was kept constant for two blocks (one block with Arabic digits and one block with number words) and, thus, changed only once during the experiment to avoid confusion of the participants through repeated stimulus-response-assignment change. The order of the four conditions was counterbalanced between participants, resulting in 8 different orders of the conditions (see Table 2 Appendix).

The two to-be-compared numbers were presented one above the other. To prevent automatic column-wise comparison of the digits, the position of the two numbers were jittered, i.e., varied slightly to the left or right. All items were presented in black against light grey background (RGB: 210 210 210) in the “Times New Roman” font (font size 60). Responses were given by pressing the “A” key (i.e., left response key; marked with a blue sticker) or the “L” key (i.e., right response key; marked with a purple sticker) on a standard QWERTY keyboard with the left and the right index finger.

Procedure

The experiment was administered as individual test. Before starting the experiment, the participants provided demographic information. Each trial started with a fixation square (height: 25 pixels; width: 25 pixels), being presented for a randomized duration varying between 175ms and 250ms in steps of 25ms. Afterwards, the two to-be-compared stimuli appeared and remained visible until response or for a maximum of 3000ms. A 200ms long presented mask followed the stimuli. The participants completed 28 practice trials, before the experiment started. If a participant did not reach the accuracy threshold of 80%, the practice session was repeated. They were instructed to indicate via key press whether the lower number is smaller (one key) or larger (other key) than the upper number. The response assignment changed in the course of the experiment. In two consecutive blocks, participants were instructed to press the left key when the lower number (i.e., the target number) was smaller (and the right key when the lower number was larger) than the upper number (reference number). In the other half of the experiment participants were instructed to press the left key when the lower number was larger (and the right key when the lower number was smaller) than the upper number. An obligatory break of 30sec followed each block, which was extended when required. Before changing response assignment, there was an obligatory break of 60sec, which could also be extended when required.

Analysis

We analyzed both reaction times (RTs) and accuracy rates of the between-decade items (i.e., the experimental trials). In a first step, we excluded 8 participants from further analysis, who committed more than 30% errors (e.g., Camos, Lagner, & Barrouillet, 2009) in one of the four experimental blocks (notation format $\times$ response assignments). Usually, participants are quite accurate in a two-digit number comparison task. Previous studies revealed accuracy rates better than 94% for both digits and number words (Nuerk et al., 2002; Nuerk et al., 2001, 2005). Thus, we included 20 participants in the final analysis.

In a second step, we removed very fast RTs (<150 ms; e.g., Whelan, 2008), which reduced the data set by 1.3 %. Moreover, we excluded erroneous trials when analyzing RTs (i.e., 14.4%). RTs were analyzed using linear mixed effects models (LME). To satisfy the assumption of normal distribution, we applied a log transformation to reaction times (logRTs). Please note that in the results section, we report back-transformed RT in ms for better readability. Moreover, we conducted a model-based outlier analysis (e.g., Baayen & Milin, 2010), excluding all data points with z -standardized residuals of the model larger than 3 SD . This outlier analysis reduced the data set by 0.7 %. Following the recommendations of Barr, Levy, Scheepers, and Tily (2013) we employed the maximum random effects structure for RT analysis using LME.

Thus, fixed effects in our analysis (LME) were response hand (left vs. right), location of larger tens digit (lower vs. upper), location of larger unit digit (lower vs. upper), location of plural number (lower vs. upper), decade distance (small vs. large), and notation format (Arabic digit vs. number words) as well as their interactions. This procedure was necessary to avoid including the same factor multiple times. The unit-decade compatibility effect is the interaction between the factors location of the larger tens digit (LoL Tens) and the location of the larger unit digit (LoL Units). The grammatical number compatibility effect is the interaction between the location of the larger tens digit and the location of the plural number

(Pl. Num). Thus, there would be overlapping factors (namely the location of the larger tens digit) when including the grammatical compatibility effect and the unit-decade compatibility effect in the same model. Moreover, this analysis allows the simultaneous investigation of the grammatical compatibility effect and the grammatical congruity effect. The latter is the interaction between the location of the plural number and the response hand (Resp.). The SNARC effect is the interaction between the location of the larger tens digit and the response hand. Table 4 gives an overview of these investigated effects in two-digit number comparison and the corresponding factors in our analysis.

Table 4

Investigated effects and their operationalization in the models

Investigated effects	Factors in our analysis
unit-decade compatibility effect	LoL Tens $\times$ LoL Units
SNARC effect	LoL Tens $\times$ Resp.
grammatical number compatibility effect	LoL Tens $\times$ Pl. Num.
grammatical congruity effect	Pl. Num. $\times$ Resp.

Note: LoL Tens = location of the larger tens digit, LoL Units = location of the larger unit digit, Resp = response hand, Pl. Num. = location of the plural number

Moreover, we included the following random effects: random intercepts for participants and items, random slopes for response hand, location of larger tens digit, location of larger unit digit, location of plural number, decade distance, and notation format as well as their interactions for participants and random slope presentation condition for items (i.e., 43_61 vs. 61_43). All fixed and random effects were effect-coded. We ran the analysis using the programming language R for statistical computing (R Development Core Team, 2015) and

calculated p -values of fixed effects by running likelihood ratio tests using the R package *afex* (Singmann, Bolker, Westfall, & Aust, 2019).

Accuracy was analyzed running generalized linear mixed effects models (GLME) with a binomial error distribution and the logit as link function (Jaeger, 2008). In the GLME, we included the same fixed effects as in the LME: response hand (left vs. right), location of larger tens digit (lower vs. upper), location of larger unit digit (lower vs. upper), location of plural number (lower vs. upper), decade distance (small vs. large), and notation format (Arabic digit vs. number words) as well as their interactions. All fixed effects were effect-coded. Moreover, we included random intercepts for participants and items as random effects. The GLME was conducted using the R package *lme4* for the (G)LME (Bates, Mächler, Bolker, & Walker, 2015). The p -values for GLME were derived via likelihood ratio tests using the R package *afex* (Singmann et al., 2019).

Besides this frequentist approach, we also ran a model comparison to investigate which of several potential models can explain the present data best. We proposed different models regarding the influence of grammatical number on two-digit number comparison, differing not only regarding the potential influence of grammatical number, but also regarding potential interacting effects with the unit-decade-compatibility effect and the SNARC effect. The different models are given in Table 5. The models were compared by calculating the Akaike information criterion corrected for small sample sizes (AICc; Hurvich & Tsai, 1989; Sugiura, 1978) using the R package *AICcmodavg* (Mazerolle, 2019). We used the upwards method for testing whether a fixed effect contributes to the explanation of the data (i.e., we included a random intercept for participants and for items as random effects in the analyses). Based on the AICc, we then calculated model probabilities (Burnham, Anderson, & Huyvaert, 2011).

Results

Mean RTs and SDs for all conditions are given in the Appendix (Table 3). The respective descriptive statistics for accuracy in all conditions are given in Table 4 in the Appendix.

RTs

First, we investigated whether grammatical number influences RTs in two-digit number comparison. The influence of grammatical number would be indicated by a main effect of the fixed effect location of plural number or interaction with the fixed effect location of plural number (Pl. Num.). The complete results of the LME for RT data are given in Table 5 of the Appendix showing the statistics of the fixed effects, estimates of the fixed effects as well as the respective standard errors and confidence intervals.

We did not find a main effect of grammatical number. Moreover, we did not find a grammatical compatibility effect (i.e., grammatical number did not interact with the magnitude of the number, see Figure 1). Furthermore, there was no significant grammatical congruency effect (i.e., the interaction between grammatical number and the response hand side was not significant, see Figure 2).

Figure 1. Reaction times and accuracy rates as a function of grammatical compatibility, separately for the two notation formats Arabic digits and number words. Compatible means that the grammatical information is compatible to the magnitude information (i.e., Plural number is also the larger number or Singular number is also the smaller number). In contrast, incompatible refers to items where the grammatical information is incompatible to the magnitude of the number (i.e., Plural number is the smaller number or Singular number is the larger number).

Figure 2. Reaction times and accuracy rates as a function of grammatical congruity, separately for the two notation formats Arabic digits and number words. Congruent means that Plural numbers are responded with the right-hand side and Singular numbers responded with the left-hand side. Incongruent means that Plural numbers are responded with the left-hand side and Singular numbers with the right-hand side.

In addition, grammatical number did not interact with standard effects in two-digit number comparison (i.e., the unit-decade compatibility effect or the SNARC effect). However, we observed a significant interaction between the notation format (Not.), the location of larger tens digit (LoL Tens) and the location of larger unit digit (LoL Units), which indicates that the unit-decade compatibility depended on notation format (see Figure 3). In line with previous studies (Nuerk et al., 2001), for Arabic digits, participants compared incompatible items slower (back-transformed estimated $M = 784$ ms, $SE = 25.6$ ms) than compatible items (back-transformed estimated $M = 768$ ms, $SE = 25.1$ ms; $z = 2.20$, $p = .028$). In contrast, for number words, participants compared incompatible items faster (back-

transformed estimated $M = 1234$ ms, $SE = 40.4$ ms) than compatible items (back-transformed estimated $M = 1274$ ms, $SE = 41.7$ ms; $z = -3.26$, $p = .001$) largely consistent with similar data in other languages without inversion such as English (Nuerk, Weger, et al., 2005) due to the necessary greater decade distance in incompatible trials (Nuerk et al., 2002, for a mathematical elaboration).

Figure 3. Reaction times and accuracy rates as a function of unit-decade compatibility, separately for the two notation formats numbers and number words.

Furthermore, we found a significant SNARC effect for tens digits as indicated by the interaction between response side and location of larger tens digit (LoL Tens). Participants responded to congruent trials (back-transformed estimated $M = 986$ ms, $SE = 29.4$ ms) faster than to incongruent trials (back-transformed estimated $M = 1045$ ms, $SE = 31.1$ ms). Finally, there was a significant decade distance effect (Dec. Dist.) with faster responses for items with

large decade distances (back-transformed estimated $M = 976$ ms, $SE = 29.4$ ms) than for items with small decade distances (back-transformed estimated $M = 1055$ ms, $SE = 31.7$ ms).

Accuracy

Second, we investigated whether grammatical number influences the accuracy of participants in a two-digit number comparison task. Again, the influence of grammatical number would be indicated by either a significant main effect of the location of plural number (Pl. num) or a significant interaction with the location of plural number (Pl. num). The statistics of the results for accuracy data are summarized in Table 6 of the Appendix showing the estimates of the fixed effects with the corresponding standard errors and confidence intervals.

Also for accuracy data, we did not find a main effect of location of plural number or an interaction with location of plural number (Pl. num). There was neither a significant grammatical compatibility effect (see Figure 1) nor a significant grammatical congruity effect (see Figure 2). Similar to the results for RT, we did not find interactions between grammatical number and the unit-decade compatibility effect or the SNARC effect. However, we observed a significant unit-decade compatibility effect (i.e., interaction between location of larger tens digit [LoL Tens] and location of larger unit digit [LoL Units]), which was independent of notation format (see Figure 3). Participants were more accurate when responding to compatible (back-transformed from log odds: estimated $M = 93.3\%$, $SE = 1.04\%$) than to incompatible items (back-transformed estimated $M = 91.0\%$, $SE = 1.34\%$). Moreover, the decade distance effect depended on notation format, as there was a significant interaction between decade distance (Dec. Dist.) and notation format (Not.). The decade distance effect was larger for Arabic digits (large decade distances: back-transformed estimated $M = 97.0\%$, $SE = 0.5\%$, small decade distances: back-transformed estimated $M = 93.7\%$, $SE = 1.0\%$; decade distance effect: back-transformed estimated $M = 3.4\%$, $SE = 0.7\%$, $p < .001$) than for

number words (large decade distances: back-transformed estimated $M = 89.6\%$, $SE = 1.6\%$, small decade distances: back-transformed estimated $M = 88.3\%$, $SE = 1.7\%$; decade distance effect: back-transformed estimated $M = 1.3\%$, $SE = 0.8\%$, $p = .102$).

Model comparison

Finally, we investigated the potential influence of grammatical number on two-digit number comparison as well as potential interacting effects with a model comparison approach. Concretely, we investigated which model describes the data best. The models derived in the introduction vary regarding the influence of grammatical number. Table 5 gives a summary of the proposed influence factors and interactions of the investigated models described in the introduction. The *Main effect model* and the *Baseline interaction model* do not include location of plural number (i.e., grammatical number). Moreover, the Baseline interaction model served as a baseline model for the other models, which differ only regarding the influence of grammatical number on two-digit number comparison. Model probabilities for hypothesized models are given in Table 5. For log RT, the main effect model (which includes notation format, decade distance, the unit-decade compatibility effect and the SNARC effect) explained the data best as indicated by largest model probability. For accuracy data the *Baseline interaction model*, which includes a unit-decade compatibility effect modulated by notation format and decade distance as well as a SNARC effect for tens digit, explained the data best (as indicated by largest model probability). Models including grammatical number as additional factor received lower model probabilities.

Table 5

AICc, $\Delta AICc$ (Δ), and model probabilities (w) for log RT and accuracy data.

Model	logRT			Accuracy		
	<i>AICc</i>	Δ	w	<i>AICc</i>	Δ	w
<i>0. Intercept only model:</i>	14370	7892	.00	10227	345	.00
<i>1. Main effect model:</i> notation + distance + unit-decade compatibility + SNARC	6478	0	1.00	9903	21	.00
<i>2. Baseline interaction model:</i> unit-decade compatibility $\times$ distance $\times$ notation + SNARC	6518	40	.00	9882	0	.58
<i>3a. Grammatical compatibility model:</i> unit-decade compatibility $\times$ distance $\times$ notation + SNARC + grammatical number $\times$ magnitude of tens digit	6536	58	.00	9884	2	.21
<i>3a. Grammatical congruity model:</i> unit-decade compatibility $\times$ distance $\times$ notation + SNARC + grammatical number $\times$ response side	6534	56	.00	9885	4	.10
<i>4a. Grammatical number interaction model</i> <i>(interaction with unit-decade compatibility):</i> unit-decade compatibility $\times$ distance $\times$ notation + SNARC + unit-decade compatibility $\times$ grammatical number	6548	70	.00	9886	4	.07
<i>4b. Grammatical number interaction model</i> <i>(interaction with SNARC):</i> unit-decade compatibility $\times$ distance $\times$ notation + SNARC $\times$ grammatical number	6549	72	.00	9887	5	.05
<i>4c. Grammatical number interaction model</i> <i>(interaction both with unit-decade compatibility</i> <i>and SNARC):</i> unit-decade compatibility $\times$ distance $\times$ notation + SNARC + unit-decade compatibility $\times$ grammatical number + SNARC $\times$ grammatical number	6561	83	.00	9889	7	.01

Note: The unit-decade compatibility is the interaction between the location of larger tens digit and the location of larger unit digit. The SNARC effect is the interaction of the location of larger tens digit and the response. The grammatical number is the location of plural number. The distance is the decade distance.

Discussion

In the present study, we investigated whether grammatical number influences two-digit number comparison. We have consistently replicated all non-linguistic effects like the unit-decade compatibility effect, the distance effect, the SNARC effect providing evidence for the general validity of this study: We found that the unit-decade-compatibility effect in reaction times depended on notation format (cf. Nuerk, Moeller, Klein, Willmes, & Fischer, 2011; Nuerk et al., 2002; Nuerk, Weger, et al., 2005). In Arabic digits participants compared incompatible items slower than compatible items (i.e., regular compatibility effect). In number words we observed an inverse unit-decade compatibility effect (i.e. participants responded faster to incompatible items than to compatible items), which is consistent with earlier studies in languages without number word inversion (Nuerk, Weger, et al., 2005). For accuracy, we found a significant unit-decade compatibility effect, which was independent of notation format. Participants were more accurate when responding to compatible than to incompatible items, both when comparing number words and when comparing Arabic digits. Moreover, we found a reliable SNARC effect for reaction times for the tens digits, but not for the unit digits. In addition, we observed a significant (decade) distance effect for both reaction times and accuracy. For accuracy, the (decade) distance effect was modulated by the notation format. The decade distance effect was larger for Arabic digits than for number words.

However, and most importantly, while all these standard effects and their interaction were replicated, we did not find any hint of a grammatical number effect in our task: Both for reaction times and accuracy, we found no main effect of grammatical number. Similarly, there was no significant grammatical compatibility effect and no significant grammatical congruity effect in both measures. Furthermore, the interactions between grammatical number and previously investigated effects in two-digit number comparison (i.e., the unit-decade-compatibility effect and the SNARC effect) were not significant.

The model comparisons were highly consistent with the results from the frequentist approach: Model comparisons revealed that a model, which included all basic numerical effects, but not grammatical number, explained the present data best. Models including grammatical number as an additional factor received lower model probabilities. For log RT, the *Main effect model* (including

notation format, decade distance, the unit-decade compatibility effect and the SNARC effect)

explained the data best. For accuracy data, the *Baseline interaction model* (including the unit-decade compatibility effect modulated by notation format and decade distance as well as the SNARC effect) explained the data best.

In sum, irrespective of the analysis and dependent variable employed, results revealed a similar pattern. The distance, the SNARC and the unit-decade compatibility effect were significant and also provided a good model fit. In contrast, the linguistic variable grammatical number was a non-significant predictor and its inclusion in various models provided a worse model fit. Because previous studies had obtained linguistic effects in two-digit magnitude comparison, these consistent linguistic null effects for grammatical number were unexpected. We will elaborate on possible reasons below.

Why did we not find influences of grammatical number on two-digit magnitude processing?

The question remains whether and under which conditions grammatical number is processed during a numerical task. There are several potential explanations for the missing grammatical number effects in the present study: (1) differences in the experimental design to previous studies inducing different processing mechanisms, (2) differences between linguistic aspects, and (3) diverging singular/ plural inflection in Polish.

1. W- vs. N-grammatical number differences. One possible explanation why we did not find influences of grammatical number, whereas other studies did, could be that the differences in study design induce different processing mechanisms. Early studies, which found links between magnitude and grammatical number, used nouns with a singular or plural inflection. Morphological markers for plural (e.g., the ending –s in dogs) allow recognizing at a glance whether the presented word is singular or plural. The grammatical number is inherent part of the word. Cipora et al. (2019) refer to this type of grammatical number as word-related grammatical number (abbreviated W-grammatical number). In contrast, in the present study we investigated the grammatical number being *associated* with the respective numbers (i.e. number-related grammatical number, abbreviated N-grammatical number, Cipora et al., 2019). Thus, characteristic for this type of grammatical number is that the singular/ plural information is not explicitly included in the numerical stimuli, but rather implicitly

related to the number by linguistic rules. To have an effect of the N-grammatical number on number comparison, participants have to process not only the magnitude of the number itself, but also the associated linguistic form, which typically follows the respective number (according to the linguistic rules of the respective language, i.e. the N-grammatical number). Thus, one possible explanation for the missing influence of grammatical number might be that in the present study, where we used Arabic digits and number words instead of nouns, the N-grammatical number was not activated/ processed by the participants. In contrast, in the experiments of Berent et al. (2005, Experiment 1) and Roettger and Domahs (2015), employing W-grammatical number, the morphological markers are automatically processed causing interference effects although being task-irrelevant. Thus, grammatical number effects might occur only for W-grammatical numbers, but not for N-grammatical numbers.

Contradicting this explanation, however, Berent et al. (2005) found an interaction which can be interpreted as a significant N- grammatical number effect. Berent et al. (2005) used the number words “one” and “two” as representative for singular and plural, showing interference effects with the numerosity of the visual input (one word vs. two words). However, in this experiment participants were asked to indicate the number of words presented on the screen by pressing one key for one word (e.g., “one” or “two”) and another key for two words (e.g., “one one” or “two two”). Thus, there was an overlap between the numerical values of the stimuli (“one” and “two”) and the task responding to the number of words being presented (either one word or two words). Consequently, the observed interference effect might not necessarily be due to the interference of the N-grammatical number, but could also be due to the (in-)congruity of the numerical meaning of the number word and the numerosity of words. Having this alternative explanation for the results of Berent et al. (2005) in mind and based on the results of the present study, there is no clear evidence for an influence N-grammatical number on the processing of number words.

Taken together, it might be the case that grammatical number effects occur only for W-grammatical numbers, but not for N-grammatical numbers.

2. N-grammatical number effects less obvious than lexical effects. Moreover, also for the processing of Arabic digits, we did not observe an influence of N-grammatical number. Following Le Corre and Carey (2007), it is conceivable that there is a rather direct path from Arabic numbers to

magnitude representation in magnitude comparison, so that grammatical number might not interfere. Nevertheless, this path cannot be entirely independent from linguistic aspects, because lexical influences of number word inversion were observed both for elementary school children, adolescents and adults in two-digit Arabic magnitude comparison (Nuerk, Weger, et al., 2005; Pixner, Moeller, et al., 2011; Van Rinsveld et al., 2016) as well as in other tasks (Nuerk et al., 2015; for a review). However, as the N-grammatical number is not as obvious as for instance the inversion property, its influences might not be as strong as lexical influences and therefore do not exert influences in a magnitude comparison task with symbolic Arabic numbers. This might explain the null effects for Arabic digits.

3. Diverging singular/ plural inflection in Polish. A further explanation for the missing grammatical number influences in our study might be related to the linguistic rule of singular/ plural inflection in Polish. In the present study, the grammatical number (singular/ plural) was defined according to the inflection of the verb and not the noun. Moreover, the grammatical number of the noun critically differed from the grammatical number of the verb, which might have nullified the effect. Note that after all, the grammatical construction for 5 to 9 (and all two-digit numbers ending from 5 to 9, like 45 and 49) is a combination of singular in the verb and (genitive) plural in the noun (for example, “There *is* five of apples”).

Taken together, the question remains whether and under which conditions N-grammatical number is processed during a numerical task. As mentioned above, number words or also Arabic digits without further context information might not be enough to activate the N-grammatical number. However, it is conceivable that Arabic digits or number words might activate the N-grammatical number, when they are embedded in the context of a sentence, where the linguistic rule of singular/ plural inflection is applied. In this case, the W-grammatical number is necessarily also present (i.e., the singular/ plural inflection). Further studies are needed to clarify whether grammatical number influences numerical processing in other tasks, which include the singular/ plural information directly via grammar. Nevertheless, it is important to note that the null findings in the present study are not due to a methodological problem, as we replicated robust effects in two-digit number comparison task.

Replication of standard numerical effects

We found a significant unit-decade compatibility effect for reaction times, which was modulated by notation format. For Arabic digits, participants showed the typical compatibility effect responding slower for incompatible than for compatible items. The compatibility effect in this study was slightly smaller (estimated compatibility effect (incompatible – compatible) = 16ms) than in German participants (i.e., 36ms; Nuerk et al., 2001), but was still significant. This indicates that Polish participants did not totally ignore unit digits, despite being task-irrelevant in the analyzed trials. In contrast, for number words there was an inverse compatibility effect, participants were faster in incompatible trials than in compatible trials. This pattern of results is consistent with previous results for other non-inverted languages like English, Spanish or Italian (Macizo & Herrera, 2010; Macizo et al., 2010; Nuerk, Weger, et al., 2005). Previous research suggests that in non-inverted languages, participants focus on the tens digit and ignore the unit digit. As already mathematically has been shown by Nuerk et al. (2002), when matching for overall distance, incompatible trials have a larger decade distance than compatible trials. Thus, when processing only the tens digit, incompatible items should be processed faster (due to their larger decade distance) than compatible trials (i.e., inverse compatibility effect). Therefore, the inverse unit-decade compatibility effect can appear in verbal notation, for very small children, which may process more sequentially (Nuerk, Kaufmann, Zoppoth, & Willmes, 2004) or in SOA conditions, where the decade is presented first (Knops, 2006).

Moreover, we replicated the distance effect both for reaction times and accuracy (Dehaene et al., 1990; Hinrichs et al., 1981; Moyer & Landauer, 1967). Participants responded faster (and more accurate) to items with larger decade distance than to items with smaller decade distance. For accuracy data, we additionally found an interaction between decade distance and notation format. The decade distance effect was larger for Arabic digits than number words. The distance effect has long been interpreted as a result of differently overlapping representations (e.g., Dehaene, Dehaene-Lambertz, & Cohen, 1998), however, Verguts, Fias and Stevens (2005) obtained a distance effect by training a connectionist model with an error correction learning algorithm. Due to the training, larger numbers (e.g., 8) have a stronger connection to the larger response than smaller numbers (e.g., 7), as 8 is more often the larger number compared to 7, which is more often larger than 6, and so on. The stronger

connection to the larger response results in faster reaction times when the number pair 3 and 8 (larger distance: 5) is compared (than the number pair 3 and 7 is compared, smaller distance: 4; i.e., the distance effect). Applied to our data, the smaller decade distance effect for number words might occur, as written number words are infrequent in everyday life. As a result, number words might be less trained/ automatic than Arabic digits. This assumption is consistent with the descriptive statistics, showing higher error rates for number words than for Arabic digits. If number words are less trained, the connection with the larger response might be less automatic than the respective connections for Arabic digits, which can explain the smaller decade distance effect for number words.

Moreover, we replicated a SNARC effect in reaction times for the tens digit, although presenting the stimuli one above the other (vertical), but require a left-right response (horizontal). Participants responded faster to larger numbers, when responses are made on the right side than on the left side (Dehaene et al., 1993). We observed a SNARC effect for the tens digit, but not for the unit digit. This is in line with previous results revealing no SNARC effect for the task-irrelevant digit (Cipora, Soltanlou, Smaczny, Göbel, & Nuerk, 2019; Huber et al., 2014; Tan & Dixon, 2011). In the magnitude comparison task participants focus on the tens digit, inhibiting the properties of the units (Castronovo & Crollen, 2011; Huber et al., 2016). Recent evidence shows that SNARC effects for tens and units can be elicited simultaneously, if both, decades and units are attended, because they are task-relevant (due to secondary tasks). However, if only one of the digits is task-relevant and therefore the object of attention, the same stimuli do not elicits a SNARC effect for the irrelevant digit (cf. Weis, Nuerk, & Lachmann, 2018). The results of our study are in line with these findings. Because only the magnitude of the tens is relevant in between-decade trials and only its corresponding spatial association is activated, which results in a SNARC effect only for the tens digit.

Taken together, we replicated standard effects of two-digit number comparison suggesting that the not significant grammatical number effects in the present study are not due to a methodological problem.

Summary and Conclusions

In the present study, we did not find evidence for an influence of grammatical number on two-digit number comparison, neither for Arabic digits nor for number words. Concretely, we did not observe interference effects between grammatical number (i.e., associated singular/ plural inflection) and number magnitude. Moreover, we did not find an interference of grammatical number on a response level, like an interaction with the SNARC effect. These null effects are unlikely due to general attributes of the design, because all other effects of interest, numerical distance effect, unit-decade-compatibility effect, SNARC effect as well as previously reported interactions with notation were replicated.

Although lexical attributes of number words have repeatedly been shown to influence two-digit number magnitude comparison, the syntactic attributes (namely grammatical number) seem to be negligible in two-digit number comparison at least in adults, for which two-digit numbers are highly overlearned. While these findings do not preclude syntactic influences in other tasks than magnitude comparison and do not preclude syntactic influences in other age groups such as kindergarten children, they do suggest that the influence of language, especially syntax, on number processing is limited and may depend on the conditions of task, stimuli, paradigm, sample and other parameters.

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Appendix

Table 1

Absolute (Abs.) and Logarithmic (Log.) distances, problem size and syllable number for the different conditions

Unit-decade compatibility	Decade Distance	Grammatical number compatibility	Abs. distance	Log. distance	Problem size	Syllable number
Compatible	Large	Compatible	51,20	3,93	62,60	5,15
	Large	Incompatible	51,60	3,94	62,80	4,70
	Small	Compatible	18,50	2,88	62,25	5,05
	Small	Incompatible	19,70	2,93	65,05	4,70
Incompatible	Large	Compatible	51,50	3,93	62,55	4,80
	Large	Incompatible	51,70	3,92	62,15	5,20
	Small	Compatible	18,40	2,87	62,30	4,70
	Small	Incompatible	18,80	2,85	62,60	5,05

Table 2

Employed orders of the conditions response key assignment and notation format counterbalanced between participants

Version	Block 1	Block 2	Block 3	Block 4
1	Left key smaller + Number words	Left key smaller + Arabic digits	Left key larger + Number words	Left key larger + Arabic digits
2	Left key smaller + Number words	Left key smaller + Arabic digits	Left key larger + Arabic digits	Left key larger + Number words
3	Left key smaller + Arabic digits	Left key smaller + Number words	Left key larger + Number words	Left key larger + Arabic digits
4	Left key smaller + Arabic digits	Left key smaller + Number words	Left key larger + Arabic digits	Left key larger + Number words
5	Left key larger + Number words	Left key larger + Arabic digits	Left key smaller + Number words	Left key smaller + Arabic digits
6	Left key larger + Arabic digits	Left key larger + Number words	Left key smaller + Number words	Left key smaller + Arabic digits
7	Left key larger + Number words	Left key larger + Arabic digits	Left key smaller + Arabic digits	Left key smaller + Number words
8	Left key larger + Arabic digits	Left key larger + Number words	Left key smaller + Arabic digits	Left key smaller + Number words

Table 3

Mean RTs (ms) and standard deviation in all conditions.

Resp.	Dec. Dist.	LoL Tens	LoL Units	Pl. Num.	Number Words		Arabic Digits	
					<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Left	Large	Lower	Lower	Lower	1293	260	794	196
				Upper	1270	286	820	183
			Upper	Lower	1286	265	809	165
				Upper	1309	270	814	207
				Upper	1321	301	817	222
		Upper	Lower	Lower	1346	316	812	200
				Upper	1292	258	803	171
			Upper	Lower	1328	323	792	217
				Upper	1395	254	851	191
				Upper	1383	248	874	216
	Small	Lower	Lower	Lower	1328	251	947	222
				Upper	1308	245	877	194
			Upper	Lower	1347	269	848	189
				Upper	1365	262	899	233
				Upper	1440	273	883	214
		Upper	Lower	Lower	1398	268	816	156
				Upper	1247	320	727	170
			Upper	Lower	1248	323	730	170
				Lower	1178	306	739	179
				Upper	1249	300	754	205
Right	Large	Lower	Lower	Lower	1396	256	839	194
				Upper	1404	294	871	260
			Upper	Lower	1361	266	816	190
				Upper	1400	270	812	206
		Upper	Lower	Lower	1307	284	793	188
				Upper	1352	329	809	221
			Upper	Lower	1300	293	847	262
				Upper	1237	301	798	215
	Small	Lower	Lower	Lower	1388	264	868	182
				Upper	1446	270	930	216
			Upper	Lower	1535	304	922	252
				Upper	1512	309	893	220

Note. Resp. = Response, LoL Tens = Location of larger tens digit, LoL Units = Location of larger units digit, Pl. Num = Location of plural number, Dec. Dist. = Decade distance.

Table 4

Mean accuracy (in %) and standard deviations of in all conditions.

Resp.	Dec. Dist.	LoL Tens	LoL Units	Pl. Num.	Number Words		Arabic Digits	
					<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Left	Large	Lower	Lower	Lower	89	12	95	8
				Upper	91	12	96	9
			Upper	Lower	88	22	95	8
				Upper	84	25	96	8
		Upper	Lower	Lower	86	14	95	8
				Upper	86	21	97	5
			Upper	Lower	85	23	96	7
			Upper	Upper	84	26	97	8
	Small	Lower	Lower	Lower	86	20	93	11
				Upper	88	16	94	8
			Upper	Lower	83	23	91	11
				Upper	85	20	91	10
		Upper	Lower	Lower	84	21	91	11
				Upper	81	20	89	14
			Upper	Lower	91	15	95	6
			Upper	Upper	84	25	92	10
	Right	Lower	Lower	Lower	89	21	96	7
				Upper	89	23	96	6
			Upper	Lower	85	22	96	10
				Upper	84	23	96	9
		Upper	Lower	Lower	84	17	95	8
				Upper	87	16	95	8
			Upper	Lower	90	11	95	10
			Upper	Upper	89	11	96	9
	Small	Lower	Lower	Lower	85	24	93	10
				Upper	88	19	94	16
			Upper	Lower	86	19	91	16
				Upper	87	22	90	13
		Upper	Lower	Lower	85	20	88	11
				Upper	81	19	87	13
			Upper	Lower	87	15	94	10
			Upper	Upper	87	14	92	11

Note. Resp. = Response, LoL Tens = Location of larger tens digit, LoL Units = Location of larger units digit, Pl. Num = Location of plural number, Dec. Dist. = Decade distance.

Table 5

Statistics and estimates of fixed effects for log transformed RTs.

Fixed effect	Interpretation	χ^2	p	p_{adj}	Effect	SE	95% CI
Intercept					6.892	0.0295	[6.834, 6.950]
Not.		71.54	<.001	<.001	0.4806	0.0263	[0.429, 0.532]
Resp.		11.88	<.001	.007	0.0164	0.0048	[0.007, 0.026]
LoL Tens		28.74	<.001	<.001	-0.0683	0.0096	[-0.087, -0.049]
LoL Units		2.11	.147	.637	0.0072	0.0049	[-0.002, 0.017]
Pl. Num.	Grammatical number	0.34	.562	.885	0.0029	0.0049	[-0.007, 0.013]
Dec. Dist.	Decade distance	47.51	<.001	<.001	-0.0805	0.0095	[-0.099, -0.062]
Not. × Resp.		4.27	.039	.350	-0.0097	0.0047	[-0.019, 0.000]
Not. × LoL Tens		3.27	.071	.424	-0.0085	0.0047	[-0.018, 0.001]
Resp. × LoL Tens	SNARC	147.43	<.001	<.001	0.0586	0.0048	[0.049, 0.068]
Not. × LoL Units		0.96	.327	.812	0.0046	0.0047	[-0.005, 0.014]
Resp. × LoL Units		0.09	.766	.955	-0.0014	0.0047	[-0.011, 0.008]
LoL Tens × LoL Units	Unit-decade compatibility effect	0.46	.497	.883	0.0057	0.0085	[-0.011, 0.022]
Not. × Pl. Num.		1.63	.202	.691	-0.0060	0.0047	[-0.015, 0.003]
Resp. × Pl. Num.	Grammatical congruity effect	3.99	.046	.384	0.0094	0.0047	[0.000, 0.019]
LoL Tens × Pl. Num.	Grammatical compatibility effect	0.57	.452	.877	0.0067	0.0089	[-0.011, 0.024]
LoL Units × Pl. Num.		3.48	.062	.411	-0.0171	0.0091	[-0.035, 0.001]
Not. × Dec. Dist.		2.84	.092	.504	0.0111	0.0065	[-0.002, 0.024]
Resp. × Dec. Dist.		0.95	.329	.812	0.0046	0.0047	[-0.005, 0.014]
LoL Tens × Dec. Dist.		0.91	.341	.812	-0.0047	0.0049	[-0.014, 0.005]
LoL Units × Dec. Dist.		2.89	.089	.504	0.0085	0.0049	[-0.001, 0.018]
Pl. Num. × Dec. Dist.		1.79	.181	.674	-0.0067	0.0049	[-0.016, 0.003]
Not. × Resp. × LoL Tens		0.01	.943	.972	-0.0002	0.0048	[-0.010, 0.009]
Not. × Resp. × LoL Units		0.03	.855	.955	0.0009	0.0047	[-0.008, 0.010]
Not. × LoL Tens × LoL Units	Notation × Unit-decade comp.	24.51	<.001	<.001	0.0262	0.0047	[0.017, 0.035]
Resp. × LoL Tens × LoL Units		2.00	.157	.659	-0.0066	0.0047	[-0.016, 0.003]
Not. × Resp. × Pl. Num.		0.00	1.000	1.000	0.0000	0.0047	[-0.009, 0.009]
Not. × LoL Tens × Pl. Num.		0.79	.374	.824	-0.0044	0.0048	[-0.014, 0.005]
Resp. × LoL Tens × Pl. Num.	SNARC × grammatical number	0.90	.341	.812	-0.0045	0.0047	[-0.014, 0.005]
Not. × LoL Units × Pl. Num.		5.20	.023	.258	0.0145	0.0059	[0.003, 0.026]
Resp. × LoL Units × Pl. Num.		1.17	.280	.785	-0.0051	0.0047	[-0.014, 0.004]
LoL Tens × LoL Units × Pl. Num.	Unit-decade comp. × grammatical number	0.94	.333	.812	0.0048	0.0049	[-0.005, 0.014]
Not. × Resp. × Dec. Dist.		2.75	.097	.511	0.0078	0.0047	[-0.001, 0.017]

Not. × LoL Tens × Dec. Dist.	0.29	.592	.894	-0.0030	0.0056	[-0.014, 0.008]
Resp. × LoL Tens × Dec. Dist.	0.06	.803	.955	0.0012	0.0047	[-0.008, 0.010]
Not. × LoL Units × Dec. Dist.	0.03	.856	.955	0.0008	0.0047	[-0.008, 0.010]
Resp. × LoL Units × Dec. Dist.	0.86	.354	.812	-0.0044	0.0047	[-0.014, 0.005]
LoL Tens × LoL Units × Dec. Dist.	1.19	.276	.785	-0.0098	0.0090	[-0.027, 0.008]
Not. × Pl. Num. × Dec. Dist.	0.09	.765	.955	-0.0014	0.0048	[-0.011, 0.008]
Resp. × Pl. Num. × Dec. Dist.	0.03	.868	.955	0.0002	0.0047	[-0.009, 0.009]
LoL Tens × Pl. Num. × Dec. Dist.	1.47	.225	.745	-0.0103	0.0084	[-0.027, 0.006]
LoL Units × Pl. Num. × Dec. Dist.	4.31	.038	.350	0.0179	0.0085	[0.001, 0.035]
Not. × Resp. × LoL Tens × LoL Units	1.13	.287	.786	-0.0050	0.0047	[-0.014, 0.004]
Not. × Resp. × LoL Tens × Pl. Num.	0.39	.532	.883	-0.0029	0.0047	[-0.012, 0.006]
Not. × Resp. × LoL Units × Pl. Num.	0.72	.396	.832	0.0040	0.0047	[-0.005, 0.013]
Not. × LoL Tens × LoL Units × Pl. Num.	0.01	.903	.964	-0.0006	0.0056	[-0.012, 0.010]
Resp. × LoL Tens × LoL Units × Pl. Num.	2.22	.137	.615	-0.0070	0.0047	[-0.016, 0.002]
Not. × Resp. × LoL Tens × Dec. Dist.	1.62	.203	.691	0.0060	0.0047	[-0.003, 0.015]
Not. × Resp. × LoL Units × Dec. Dist.	0.57	.449	.877	-0.0036	0.0047	[-0.013, 0.006]
Not. × LoL Tens × LoL Units × Dec. Dist.	4.52	.033	.350	-0.0117	0.0053	[-0.022, -0.001]
Resp. × LoL Tens × LoL Units × Dec. Dist.	0.41	.523	.883	0.0030	0.0047	[-0.006, 0.012]
Not. × Resp. × Pl. Num. × Dec. Dist.	1.62	.203	.691	0.0060	0.0047	[-0.003, 0.015]
Not. × LoL Tens × Pl. Num. × Dec. Dist.	0.28	.596	.894	0.0025	0.0047	[-0.007, 0.012]
Resp. × LoL Tens × Pl. Num. × Dec. Dist.	1.19	.275	.785	-0.0051	0.0047	[-0.014, 0.004]
Not. × LoL Units × Pl. Num. × Dec. Dist.	0.33	.566	.885	0.0027	0.0047	[-0.007, 0.012]
Resp. × LoL Units × Pl. Num. × Dec. Dist.	0.04	.832	.955	-0.0010	0.0047	[-0.010, 0.008]
LoL Tens × LoL Units × Pl. Num. × Dec. Dist.	0.04	.851	.955	-0.0001	0.0055	[-0.011, 0.011]
Not. × Resp. × LoL Tens × LoL Units × Pl. Num.	1.78	.182	.674	0.0063	0.0047	[-0.003, 0.016]
Not. × Resp. × LoL Tens × LoL Units × Dec. Dist.	2.26	.133	.615	-0.0071	0.0047	[-0.016, 0.002]
Not. × Resp. × LoL Tens × Pl. Num. × Dec. Dist.	0.02	.881	.955	0.0007	0.0047	[-0.009, 0.010]
Not. × Resp. × LoL Units × Pl. Num. × Dec. Dist.	0.43	.511	.883	-0.0031	0.0047	[-0.012, 0.006]
Not. × LoL Tens × LoL Units × Pl. Num. × Dec. Dist.	0.21	.647	.947	-0.0023	0.0051	[-0.012, 0.008]
Resp. × LoL Tens × LoL Units × Pl. Num. × Dec. Dist.	0.78	.379	.824	-0.0041	0.0047	[-0.013, 0.005]
Not. × Resp. × LoL Tens × LoL Units × Pl. Num. × Dec. Dist.	0.06	.799	.955	-0.0012	0.0047	[-0.010, 0.008]

Note. Not. = Notation, Resp. = Response, LoL Tens = Location of larger tens digit, LoL Units = Location of larger units digit, Pl. Num = Location

of plural number, Dec. Dist. = Decade distance. $df1 = 1$, $df2 = 98$. p_{adj} are p -values adjusted for multiple testing using the family wise error rate

(Benjamini & Hochberg, 1995). Significant fixed effects are written in bold font. Effects and CI = confidence intervals are given in log ms.

Table 6

Statistics of fixed effects for accuracy and estimates of fixed effects for log odds.

Fixed effect	Interpretation	χ^2	<i>p</i>	<i>p_{adj}</i>	Effect	SE	95% CI
Intercept					2.6125	0.1647	[2.290, 2.935]
Not.		318.39	<.001	<.001	-1.0092	0.0594	[-1.126, -0.893]
Resp.		0.55	.459	.877	0.0436	0.0590	[-0.072, 0.159]
LoL Tens		0.88	.348	.812	0.0552	0.0590	[-0.060, 0.171]
LoL Units		0.45	.503	.883	-0.0395	0.0590	[-0.155, 0.076]
Pl. Num.	Grammatical number	0.01	.939	.972	-0.0046	0.0590	[-0.120, 0.111]
Dec. Dist.	Decade distance	31.72	<.001	<.001	0.4486	0.0744	[0.303, 0.594]
Not. × Resp.		1.17	.279	.785	-0.0637	0.0590	[-0.179, 0.052]
Not. × LoL Tens		0.04	.845	.955	0.0115	0.0590	[-0.104, 0.127]
Resp. × LoL Tens	SNARC	0.31	.576	.885	-0.0331	0.0590	[-0.149, 0.083]
Not. × LoL Units		0.39	.532	.883	0.0368	0.0590	[-0.079, 0.152]
Resp. × LoL Units		0.50	.479	.883	0.0416	0.0590	[-0.074, 0.157]
LoL Tens × LoL Units	Unit-decade compatibility	15.54	<.001	.001	0.3030	0.0743	[0.157, 0.449]
Not. × Pl. Num.		0.43	.511	.883	0.0388	0.0590	[-0.077, 0.154]
Resp. × Pl. Num.	Grammatical congruity effect	0.00	.999	1.000	-0.0001	0.0590	[-0.116, 0.116]
LoL Tens × Pl. Num.	Grammatical compatibility effect	1.23	.267	.785	-0.0822	0.0743	[-0.228, 0.063]
LoL Units × Pl. Num.		1.25	.263	.785	-0.0829	0.0743	[-0.229, 0.063]
Not. × Dec. Dist.	Notation × decade distance	28.70	<.001	<.001	-0.3128	0.0591	[-0.429, -0.197]
Resp. × Dec. Dist.		0.15	.697	.955	0.0230	0.0590	[-0.093, 0.139]
LoL Tens × Dec. Dist.		0.12	.729	.955	-0.0204	0.0590	[-0.136, 0.095]
LoL Units × Dec. Dist.		1.81	.179	.674	0.0791	0.0590	[-0.037, 0.195]
Pl. Num. × Dec. Dist.		3.70	.054	.403	-0.1132	0.0590	[-0.229, 0.002]
Not. × Resp. × LoL Tens		3.54	.060	.411	0.1109	0.0591	[-0.005, 0.227]
Not. × Resp. × LoL Units		0.31	.576	.885	0.0329	0.0590	[-0.083, 0.149]
Not. × LoL Tens × LoL Units		0.01	.922	.972	0.0056	0.0590	[-0.110, 0.121]
Resp. × LoL Tens × LoL Units		0.35	.557	.885	-0.0346	0.0590	[-0.150, 0.081]
Not. × Resp. × Pl. Num.		0.18	.671	.955	0.0250	0.0590	[-0.091, 0.141]
Not. × LoL Tens × Pl. Num.		0.12	.730	.955	-0.0203	0.0590	[-0.136, 0.095]
Resp. × LoL Tens × Pl. Num.	SNARC × grammatical number	0.56	.454	.877	-0.0441	0.0590	[-0.160, 0.072]
Not. × LoL Units × Pl. Num.		0.03	.874	.955	-0.0093	0.0590	[-0.125, 0.106]
Resp. × LoL Units × Pl. Num.		0.59	.442	.877	-0.0453	0.0590	[-0.161, 0.070]
LoL Tens × LoL Units × Pl. Num.	Unit-decade comp. × grammatical number	0.09	.761	.955	-0.0179	0.0590	[-0.134, 0.098]

Not. × Resp. × Dec. Dist.	0.00	.948	.972	-0.0039	0.0590	[-0.120, 0.112]
Not. × LoL Tens × Dec. Dist.	0.42	.519	.883	0.0380	0.0590	[-0.078, 0.154]
Resp. × LoL Tens × Dec. Dist.	0.17	.676	.955	0.0245	0.0590	[-0.091, 0.140]
Not. × LoL Units × Dec. Dist.	0.74	.391	.832	0.0505	0.0590	[-0.065, 0.166]
Resp. × LoL Units × Dec. Dist.	0.03	.868	.955	0.0098	0.0590	[-0.106, 0.125]
LoL Tens × LoL Units × Dec. Dist.	2.27	.132	.615	-0.1121	0.0743	[-0.258, 0.034]
Not. × Pl. Num. × Dec. Dist.	1.79	.180	.674	0.0789	0.0590	[-0.037, 0.195]
Resp. × Pl. Num. × Dec. Dist.	0.61	.436	.877	-0.0460	0.0590	[-0.162, 0.070]
LoL Tens × Pl. Num. × Dec. Dist.	3.37	.066	.418	0.1369	0.0743	[-0.009, 0.283]
LoL Units × Pl. Num. × Dec. Dist.	0.00	.945	.972	0.0053	0.0743	[-0.140, 0.151]
Not. × Resp. × LoL Tens × LoL Units	0.12	.729	.955	0.0204	0.0590	[-0.095, 0.136]
Not. × Resp. × LoL Tens × Pl. Num.	0.04	.845	.955	-0.0115	0.0590	[-0.127, 0.104]
Not. × Resp. × LoL Units × Pl. Num.	0.02	.887	.955	-0.0083	0.0590	[-0.124, 0.107]
Not. × LoL Tens × LoL Units × Pl. Num.	0.10	.747	.955	-0.0190	0.0590	[-0.135, 0.097]
Resp. × LoL Tens × LoL Units × Pl. Num.	0.00	.977	.993	0.0017	0.0590	[-0.114, 0.117]
Not. × Resp. × LoL Tens × Dec. Dist.	2.27	.132	.615	0.0887	0.0590	[-0.027, 0.204]
Not. × Resp. × LoL Units × Dec. Dist.	0.07	.790	.955	0.0157	0.0590	[-0.100, 0.131]
Not. × LoL Tens × LoL Units × Dec. Dist.	3.74	.053	.403	0.1138	0.0590	[-0.002, 0.230]
Resp. × LoL Tens × LoL Units × Dec. Dist.	0.35	.554	.885	-0.0348	0.0590	[-0.150, 0.081]
Not. × Resp. × Pl. Num. × Dec. Dist.	0.48	.490	.883	0.0407	0.0590	[-0.075, 0.156]
Not. × LoL Tens × Pl. Num. × Dec. Dist.	0.02	.881	.955	-0.0090	0.0590	[-0.125, 0.107]
Resp. × LoL Tens × Pl. Num. × Dec. Dist.	0.24	.622	.922	0.0291	0.0590	[-0.087, 0.145]
Not. × LoL Units × Pl. Num. × Dec. Dist.	0.87	.350	.812	-0.0550	0.0590	[-0.171, 0.061]
Resp. × LoL Units × Pl. Num. × Dec. Dist.	0.03	.872	.955	-0.0095	0.0590	[-0.125, 0.106]
LoL Tens × LoL Units × Pl. Num. × Dec. Dist.	0.04	.839	.955	-0.0120	0.0590	[-0.128, 0.104]
Not. × Resp. × LoL Tens × LoL Units × Pl. Num.	0.04	.844	.955	-0.0116	0.0590	[-0.127, 0.104]
Not. × Resp. × LoL Tens × LoL Units × Dec. Dist.	1.44	.231	.745	-0.0705	0.0590	[-0.186, 0.045]
Not. × Resp. × LoL Tens × Pl. Num. × Dec. Dist.	0.04	.846	.955	-0.0115	0.0590	[-0.127, 0.104]
Not. × Resp. × LoL Units × Pl. Num. × Dec. Dist.	0.20	.654	.947	0.0264	0.0590	[-0.089, 0.142]
Not. × LoL Tens × LoL Units × Pl. Num. × Dec. Dist.	0.02	.887	.955	-0.0084	0.0590	[-0.124, 0.107]
Resp. × LoL Tens × LoL Units × Pl. Num. × Dec. Dist.	0.91	.339	.812	-0.0563	0.0590	[-0.172, 0.059]
Not. × Resp. × LoL Tens × LoL Units × Pl. Num. × Dec. Dist.	0.77	.379	.824	-0.0517	0.0590	[-0.167, 0.064]

Note. Not. = Notation, Resp. = Response, LoL Tens = Location of larger tens digit, LoL Units = Location of larger units digit, Pl. Num = Location

of plural number, Dec. Dist. = Decade distance. $df1 = 1$, $df2 = 65$. p_{adj} are p -values adjusted for multiple testing using the family wise error rate

(Benjamini & Hochberg, 1995). Significant fixed effects are written in bold font. Effects and CI = confidence intervals are given in log odds.