**Processing multi-digit numbers – A translingual eye tracking study**

Running head: Processing strategies in three-digit number processing

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**Abstract**

The present study aimed at investigating the underlying cognitive processes and language specificities of three-digit number processing. More specifically, it was intended to clarify whether the single digits of three-digit numbers are processed in parallel and/or sequentially and whether processing strategies are influenced by the inversion of number words with respect to the Arabic digits [e.g., 43: dreiundvierzig (“three and forty”)] and/or by differences in reading behavior of the respective first language.

Therefore, English- and German-speaking adults had to complete a three-digit number comparison task while their eye fixation behavior was recorded. Replicating previous results, reliable hundred-decade-compatibility effects (e.g., 742\_896: hundred-decade compatible because 7<8 and4<9; 362\_517: hundred-decade incompatible because 3<5 but6>1) for English- as well as hundred-unit-compatibility effects for English- and German-speaking participants were observed, indicating parallel processing strategies. While no indices of partial sequential processing were found for the English-speaking group, about half of the German-speaking participants showed an inverse hundred-decade-compatibility effect accompanied by longer inspection time on the hundred digit indicating additional sequential processes.

Thereby, the present data revealed that in transition from two- to higher multi-digit numbers the homogeneity of underlying processing strategies varies between language groups. The regular German orthography (allowing for letter-by-letter reading) and its associated more sequential reading behavior may have promoted sequential processing strategies in multi-digit number processing. Furthermore, these results indicated that the inversion of number words alone is not sufficient to explain all observed language differences in three-digit number processing.

Word count:

Abstract: 241 words

8272 words in text body including references

**Keywords:**

Multi-digit numbers, language influences, inversion, reading behavior, eye tracking

**Introduction**

For two-digit numbers, there is accumulating evidence suggesting that tens and units are processed in a parallel decomposed manner (e.g., Nuerk, Weger, & Willmes, 2001; see Nuerk, Moeller, Klein, Willmes, & Fischer, 2011 for a review). However, for the processing of numbers beyond the two-digit range such as three-, four- and six-digit numbers, it was argued that there is an additional sequential processing component because numbers become too wide to be processed entirely in parallel (Korvorst & Damian, 2008; Meyerhoff, Moeller, Debus, & Nuerk, 2012; Poltrock & Schwartz, 1984). However, so far it is not clear whether the additional sequential processing component is a general phenomenon observed when numbers get larger or whether sequential processing characteristics are influenced by language as well.

Generally, a growing body of research indicates that language specificities influence multi-digit number processing (e.g., Nuerk et al., 2011 for a review). For example, number word inversion describes the fact that in some languages (e.g., German, Arabic, Danish) the order of tens and units in number words is inverted compared to symbolic Arabic notation (e.g., in German 37 spoken as *siebenunddreißig* literally: *seven and thirty*). Inversion has been shown to influence Arabic digit processing (e.g., Göbel et al., 2014; Helmreich et al. 2011; Nuerk et al., 2005; Zuber, Pixner, Moeller, & Nuerk; 2009, but see Brysbaert, Fias, & Noël, 1998 and Noël, Fias, & Brysbaert, 1997). On the other hand, several studies investigated the influence of reading and writing direction on numerical processing (e.g., Shaki & Fischer, 2008; Shaki, Fischer, & Petrusic, 2009). In addition to reading and writing direction, orthographies also differ in their consistency between the spelling and pronunciation of words which was found to influence reading development but also the reading of skilled readers for different languages (for a review see Ziegler & Goswami, 2005). For instance, Rau, Moll, Snowling, and Landerl (2015) observed in an eye-tracking study that children and even adult readers of the less consistent English orthography showed more parallel reading behavior on the word level than readers of the highly consistent German orthography, who exhibited more sequential reading behavior. Transferred to the case of multi-digit numbers beyond the two-digit number range, it seems possible that the way words are read also influences the way multi-digit numbers are processed. However, in contrast to influences of inversion and reading direction, the relation between reading behavior (i.e., more sequential or parallel reading as influenced by orthographic consistency) and number processing has not been investigated yet.

Considering inversion as well as influences of differences in orthographic consistency on reading behavior, the current study set out to investigate processing characteristics and possible language influences on three-digit number processing in German- and English-speaking participants using eye-tracking. In the following, we will first give a brief introduction into specific aspects of multi-digit number processing before discussing how these might be influenced by differences in inversion and reading behavior.

*Multi-digit numbers: parallel and sequential decomposed processing*

Magnitude processing of numbers is often investigated using number magnitude comparison tasks. The most important aspect influencing participants’ responses is numerical distance. Responses get faster and less error prone with increasing numerical distance (e.g., 1\_9 vs 4\_5; cf. Moyer & Landauer, 1967). However, when comparing multi-digit numbers, another effect needs to be considered. For two-digit numbers, separate comparisons of tens and units can either be compatible or incompatible. A number pair is considered decade-unit-compatible when separate comparisons of decades and units lead to the same decision (e.g., 42\_57, 4<5 **and** 2<7). When separate comparisons of decades and units lead to opposing decisions, the number pair is termed decade-unit-incompatible (e.g., 47\_62, 4 < 6 **but** 7 > 2). Usually, decade-unit-compatible number pairs are responded to faster and with fewer errors than decade-unit incompatible pairs (i.e., the decade-unit-compatibility effect: Nuerk et al., 2001; Nuerk et al., 2011).

The presence of a compatibility effect is usually interpreted to indicate componential processing of multi-digit numbers (Nuerk et al., 2001). In this vein, a regular unit decade compatibility effect has been argued to indicate that tens and units are processed in parallel because the irrelevant unit digit interferes with the processing of the decision-relevant decade digit. However, inverted compatibility effects - indicating that incompatible number pairs are processed faster than compatible number pairs - were also observed (e.g., children: Mann, Moeller, Pixner, Kaufmann, & Nuerk, 2012; two-digit number words: Nuerk et al. 2005) and interpreted to indicate sequential processing of tens and units. This interpretation is based on the fact that the distance between the two decade digits is necessarily larger for decade-unit incompatible number pairs as compared to compatible pairs (e.g., compatible: 32\_47 with a decade distance of 4 – 3 = 1; incompatible: 37\_52 with a decade distance of 5 – 3 = 2, overall distance matched at 15; for a mathematical elaboration see Nuerk, Weger, & Willmes, 2002). Reflecting a numerical distance effect with faster responses for the comparison of more distant numbers (e.g., Moyer & Landauer, 1967), faster reaction times for incompatible number pairs are to be expected when only the leftmost digit (e.g., the decade digit) is considered for the comparison process.

Importantly, sequential and parallel processing of multi-digit numbers can also be differentiated by participants’ eye-fixation behavior. Eye tracking is a useful technique providing additional information about underlying processing strategies that lead to specific behavioral outcomes (e.g., reaction time or error rate differences). Following the *eye-mind* *assumption*, a fixation location is a reliable indicator of the particular part of a stimulus from which visual information is currently being extracted (e.g., Rayner & Pollatsek, 1989). Additionally, the duration of fixations is seen as a reliable index of the time it takes to process the respective piece of information (for a review see Rayner, 1998). Against this background, considering participants’ eye-fixation behavior in multi-digit number comparison may be highly informative because it is possible to evaluate which digits (i.e., units, tens, hundreds) are processed at a particular time and how long this processing takes (see Hartmann (2015) and Mock et al. (under review) for reviews on eye movements and number processing).

Differentiating between sequential and parallel processing strategies using participants’ eye-fixation data, Moeller, Fischer, Nuerk, & Willmes (2009) and Meyerhoff et al. (2012) argued that sequential processing is reflected by digits being primarily scanned from left to right and only very few or even no fixations are observed on digits that are irrelevant for a correct decision – such as tens and units in the case of our critical number pairs (e.g., 365\_ 721). However, such a fixation pattern, where fixations fall only on the leftmost digits is rather unlikely, especially when filler pairs are included that increase the relevance of digits further to the right (i.e., tens and units). On the other hand, parallel processing was associated with fixations more or less distributed equally across all digits with a potential bias towards an optimal viewing position at the center of the digit string (see also Huber, Cornelsen, Moeller, & Nuerk, 2014). Additionally, interference relating to compatibility effects should be mirrored in fixation patterns so that comparably higher fixation durations or more fixations should be observed for digits that influence the comparison process negatively (i.e., unit digits in decade-unit incompatible trials, cf. Moeller et al., 2009).

*Three-digit numbers and beyond*

In contrast to studies on two-digit numbers, studies investigating the magnitude processing of multi-digit numbers beyond the two-digit number range are scarce (e.g., Huber, Moeller, Nuerk, & Willmes, 2013; Korvorst & Damian, 2008; Meyerhoff et al., 2012; Poltrock & Schwartz, 1984). Importantly, all of these studies reported the presence of both sequential as well as parallel processing strategies. For instance, Korvorst and Damian (2008) investigated the processing of three-digit numbers in an English-speaking sample. Following the logic of the decade-unit-compatibility effect for two-digit numbers, two further compatibility effects can be defined for three-digit numbers: Hundred-decade-compatibility and hundred-unit-compatibility (e.g., 327\_465: hundred-decade compatible because 3 < 4 **and** 2 < 6, but hundred-unit-incompatible because 3 < 4 **but** 7 > 5). Korvorst and Damian (2008) observed reliable hundred-decade (HDC) as well as hundred-unit-compatibility (HUC) effects indicating parallel componential processing of three-digit numbers. However, the HUC effect was less pronounced as compared to the HDC effect leading Korvorst and Damian (2008) to suggest that differences in the sizes of the HDC and HUC effect indicate partial sequential processing with a left-to-right processing gradient.[[1]](#footnote-1)

Considering even higher multi-digit numbers, Meyerhoff et al. (2012) found that six-digit numbers are too long to be processed entirely in parallel. Instead, they suggest that a combination of sequential and parallel processes (in a chunking-like fashion, e.g., of two to four neighboring digits each) is the most efficient strategy. Additionally, they observed interindividual differences regarding the processing of four-digit numbers with approximately half of the participants showing a regular compatibility effect (indicating parallel processing) and the other half showing an inverse compatibility effect (indicating sequential processing). This result indicates that German-speaking participants do not seem to adhere to a homogeneous processing pattern when processing four-digit numbers. In sum, previous studies investigating processing strategies in multi-digit number processing beyond the two-digit number range were conducted separately on participants with different first languages differing in orthographic consistency and used multi-digit numbers of differing lengths. Therefore, it remains open whether parallel and sequential processing strategies in multi-digit number processing simply vary for different digit lengths or whether they are also influenced by certain characteristics of a language such as orthographic consistency and its impact on reading behavior.

*Language influences on three-digit number processing*

*Influences of inversion*

Multi-digit number processing is influenced by the inversion property of number words (e.g., Nuerk et al., 2005; Helmreich et al. 2011; Göbel et al., 2014; Macizo, Herrera, Roman, & Martin, 2011a,b; see Klein et al. 2013 for a review on developmental aspects). With respect to number comparison tasks, there are only few studies that directly investigated language influences on the decade-unit-compatibility effect in two-digit Arabic numbers (e.g., Nuerk et al., 2005; Pixner, Moeller, Hermanova, Nuerk, & Kaufmann, 2011). These studies found that the decade-unit-compatibility effect was more pronounced for languages with inversion indicating that the unit digit plays a more interfering role for inverted as compared to non-inverted languages.

As for two-digit numbers, only tens and units are inverted in German three-digit numbers (e.g., in German 452 is spoken *vierhundertzweiundfünfzig* literally *four hundred two and fifty*). When similar effects of inversion are present in three-digit number processing, a specific pattern of results is expected for languages with and without inversion in three-digit number comparison. For participants speaking a language without inversion, the interference due to the decade digit was argued to be more pronounced than the interference due to the unit-digit (Korvorst & Damian, 2008). However, hundred distance and HDC in the stimulus set of Korvorst and Damian (2008) were confounded. Considering this confound in Korvorst and Damian (2008), one might also expect comparable interference of decade and unit digits. In contrast, for languages with an inversion of tens and units, one might assume that because the units directly follow the hundreds in, for instance, German number words (e.g., **2**7**4** 🡪 **zwei**hundert**vier**undsiebzig 🡪 literally: **two** hundred **four** and seventy) the interfering influence of the units should be specifically pronounced. In turn, this increased interference due to the unit digit should lead to a higher HUC effect in a language with inversion such as German as compared to a language without inversion. Considering compatibility effects in three-digit number comparison, it is thus possible to specifically investigate the use of parallel and sequential processing strategies as well as potential inversion-induced differences in multi-digit number processing.

*Influences of reading behavior*

The orthographic consistency of a language influences the way reading skills in a specific language are acquired (e.g., Frith, Wimmer, & Landerl, 1998; Seymour, Aro, & Erskine, 2003). Furthermore, it has been argued that these differences in reading acquisition leave “developmental footprints” in adult readers, since differences in reading behavior can still be observed in adults (Rau et al., 2015, Ziegler & Goswami, 2005; Ziegler, Perry, Jacobs, & Braun, 2001). Therefore, irrespective of differences due to number word inversion, differences in reading behavior might also lead to language differences in three-digit number processing.

Considering the close connection between spelling and pronunciation, the German orthography is more consistent than the English one. As a result it is possible to start reading a German word letter by letter (grapheme by grapheme) from the beginning of the word without running the risk of wrongly pronouncing it since the same letter is almost always pronounced in the same way. On the contrary, the English orthography is fairly inconsistent and the pronunciation of a word does not necessarily correspond to its spelling (e.g., ’thought’ vs. ’though’ vs. ’tough’). Therefore, letter-by-letter reading does not seem to be the most efficient strategy. Rather, the whole word has to be considered since the correct pronunciation of the word might only become clear when all letters are taken into consideration. This seems to lead to differences in reading strategies, even between skilled English and German readers. For instance, Ziegler and colleagues (2001) showed that German readers preferred to process a word in small units (e.g., one letter), whereas, for English readers, a preference for processing a word in large units (e.g., the whole word) was found. In line with this, Rau et al. (2015) investigated English- and German-speaking participants in an eye tracking study and demonstrated that for non-words, the word length effect in gaze duration was larger for English-speaking participants as compared to German-speaking participants. The authors argue that the most plausible explanation for this difference is that English-speaking participants are not as experienced in small unit processing (letter-by-letter reading) as are German-speaking participants and, therefore, need more time to read long and unfamiliar words. Due to these differences between languages, it is possible that the way words are read influences the way multi-digit numbers are processed. In particular, the tendency to process a number sequentially and in smaller units starting at the leftmost digit should be more pronounced for German-speaking participants. In contrast, more pronounced parallel processing of all the digits of a number can be assumed for English-speaking participants.

The current study set off to investigate the processing strategies and possible language differences in three-digit number processing. To do so, German- and English-speaking participants were asked to solve a three-digit number comparison task. In addition to response latencies, eye fixation patterns were recorded to specifically identify parallel and sequential processing components during online processing.

For both language groups, we expected the digits of three-digit numbers to be processed componentially, indexed by reliable HDC and HUC effects.

Because English is a non-inverted language and – at least in fluent adults – is mainly read at the word level (considering all letters of a word in parallel), we expected the size of both the HDC and the HUC effect to be comparable.

To disentangle influences of inversion and reading behavior in the data pattern of German-speaking participants’, eye-fixation data are considered in addition to reaction times: When three-digit number processing is influenced by inversion, German-speaking participants are expected to show reliable effects of HDC and HUC. Furthermore, we hypothesized the effect of HUC to be more pronounced as compared to the HDC effect due to the higher interfering influence resulting from the verbal proximity of unit and hundred digits in German number words. In this case, we further expected that the HUC effect should be more pronounced in German- as compared to English-speaking participants. Importantly, this inversion hypothesis should also be reflected in participants’ eye-fixation behavior by longer inspection times (e.g., sum of the duration of all fixations) on the unit digit for German- as compared to English-speaking participants.

In contrast, if reading behavior influences the comparison process, a reduced or even reversed HDC effect and no effect of effect of HUC is expected for the German-speaking participants. This may be caused by a tendency towards more sequential reading behavior in German-speakers due to the regular German orthography.

Differences with respect to reading behavior between language groups should also result in a more pronounced HDC effect for English- as compared to German-speaking participants. With respect to participants’ eye-fixation behavior a more sequential processing in German-speaking participants should be associated with specifically longer inspection times on the hundred and shorter inspection times on the decade digit.

**Methods**

*Participants*

Twenty-four native German-speaking students from the University of Tuebingen (3 male; 1 left-handed; mean age: 21.58, *SD* = 5.37; range: 18-44 years) and 24 native English-speaking students from the University of York, U.K., (4 male; 4 left-handed, mean age: 20.25, *SD* = 1.23; range: 19-23 years) participated in the current study in exchange for course credits or monetary compensation. The two language groups did not differ with respect to their math computation skills assessed with the math computation subtest of the Wide Range Achievement Test (WRAT4, Wilkinson & Robertson, 2006; German: *M* = 42, *SD* = 4; English: *M* = 43, *SD* = 6; *t*(37) = 0.84, *p* = .404, corrected for inhomogeneity of variances). All participants reported normal or corrected-to-normal vision.

*Apparatus*

Stimuli were presented on a 21" monitor driven at a refresh rate of 120 Hz with a resolution of 1024 x 768 pixels. Viewing distance between the screen and the participants’ eyes was approximately 60 cm. Eye-fixation behavior and reaction times were recorded using an Eyelink 1000 eye-tracking device (SR-Research, Osgoodie, Canada). To ensure a spatial resolution of less than 0.5° of visual angle, a 9-point calibration cycle at the beginning of the experiment and drift corrections before each trial were employed.

*Stimuli and design*

The stimulus set included 320 critical number pairs (e.g., 263\_718). In a 2 × 2 × 2 × 2 × 2 within-subject design, these critical number pairs were manipulated according to the factors hundred-decade-compatibility (HDC), hundred-unit-compatibility (HUC; each compatible vs. incompatible), and distance (small (1-3) vs. large (4-8)) between the hundreds (HD), decades (DD), and units (UD)). Problem size, overall distance as well as hundred, decade, and unit distance were matched across the respective stimulus categories.

Additionally, 320 filler items were included in the stimulus set to prevent participants from focusing on the decisive hundred-digit only. Of these filler items, 160 had the same hundred digit (e.g., 327\_385) and 160 had the same hundred- and decade-digit (e.g., 354\_358).

Multiples of hundred (e.g., 200) and/or multiples of ten (e.g., 420) were not included in the stimulus set. Furthermore, all three digits within one of the to-be-compared numbers differed from each other (e.g., 545 was excluded).

Number pairs were presented in Arabic notation in white color against a black background (font: “Courier New”, font size: 56 pt., bold). Stimuli were presented above each other. To prevent column-wise processing, the two numbers were jittered horizontally by one character position to the right or left (i.e., the decade digit of the upper number was presented above either the hundred or unit digit of the lower number). Thus, in half of the trials the positions of the numbers were (x-coordinate: 466/ y-coordinate: 250) and (558/600), in the other half they were (558/250) and (466/600). The fixation point was positioned above the upper number in the center of the top third of the screen (512 / 150).

*Task and Procedure*

In total, the experiment took approximately 50 minutes. After signing an informed consent form, participants completed the math computation subtest of the WRAT4 (Wilkinson & Robertson, 2006). For the German-speaking sample, unfamiliar presentation formats of math problems were adapted.

Afterwards, the eye-tracking device was calibrated and participants were instructed to indicate the larger of the two three-digit numbers as quickly and accurately as possible. When the upper number was larger, participants were asked to press the upper button of the arrow cross of a game controller with the left thumb. When the lower number was larger this should be indicated by pressing the lower button with the right thumb. Stimuli were presented in eight blocks of 80 number pairs each. After each block, participants could take a short break. Trial order was randomized separately for each participant. Stimuli were presented simultaneously and immediately after drift correction. They remained visible until any of the response keys was pressed. Directly after responding, the fixation point for the drift correction of the next trial was presented. Participants did not receive feedback as to the correctness of their response. Stimuli, design and procedure of the experiment were identical for the English- and German-speaking participants.

**Results**

Only trials with correct response were considered for data analyses. Outliers were identified by first excluding RTs faster than 200ms and slower than 2000ms. Since the distribution of RT data was positively skewed, we used the inverse Gaussian transformation to reduce the impact of outliers resulting in *speed* as dependent variable (unit of speed: items per second; see e.g., Whelan, 2008, Ratcliff, 1993). To allow the reader for a better grip on the data, all results are also given in plain RT. Afterwards, we further excluded responses exceeding the range delimited by each participant’s mean speed +/- 3 standard deviations in an iterative procedure. The average loss of data using this trimming procedure was 0.6% (*SD* = 0.6%; German: *M* = 0.4%, *SD* = 0.4%, English: *M* = 0.7%, *SD* = 0.7%) of the 320 experimental trials. Errors were infrequent (*M* = 2.7%, *SD* = 1.7%; German: *M* = 2.2%, *SD* = 1.1%, English: *M* = 3.3%, *SD* = 1.9%) and will not be analyzed any further.

*Reaction times (RT) – Pattern of compatibility effects across language groups*

A 2 × 2 × 2 × 2 ANOVA was run on speed with the between-subject factor language (English vs. German) and the within-subject factors HDC (compatible vs. incompatible), HUC (compatible vs. incompatible), and HD (small vs. large). Since the focus of the present study was on language differences concerning compatibility effects, decade and unit distance were not considered in the analyses. Overall, the English- and the German-speaking group did not differ in speed [*F*(1, 46) <1.00, *p*=.846, *ηp²* <.01; German:*M*=1.32 (764 ms), *SD*=0.13 (74 ms); English: *M*=1.33 (767 ms), *SD*=0.18 (107 ms)]. A significant main effect of distance between the hundreds (HD) was found [*F*(1, 46)=516.67, *p*<.001, *ηp²*=.92]. Number pairs with a large HD were responded to on average 0.11 items per second (66 ms) faster than number pairs with a small HD [large: *M*=1.38 (734 ms), *SD*=0.16 (86 ms); small: *M*=1.27 (800 ms), *SD*=0.16 (98 ms)] indicating that number magnitude was processed. Moreover, the HD effect was significantly larger for German- than English-speaking participants [*F*(1, 46)=4.76, *p*=.034, *ηp²*=.09]. German speakers responded 0.12 items per second (72 ms) faster to number pairs with a large HD [large: *M*=1.38 (730 ms), *SD*=0.13 (70 ms); small: *M*=1.36 (802 ms), *SD*=0.13 (80 ms)], whereas English speakers responded 0.10 items per second (60 ms) faster [large: *M*=1.38 (738 ms), *SD*=0.19 (102 ms); small: *M*=1.28 (798 ms), *SD*=0.18 (115 ms)]. Furthermore, the main effect of HDC was significant [*F*(1, 46)=13.991, *p*=.001, *ηp²*=.23]. On average, hundred-decade compatible number pairs were responded to 0.02 items per second [11 ms] faster than hundred-decade incompatible number pairs [compatible: *M*=1.33 (760 ms), *SD*=0.16 (90 ms); incompatible: *M*=1.32 (771 ms), *SD*=0.16 (94 ms)]. The interaction of HDC and language was significant [*F*(1, 46)=4.193, *p*=.046, *ηp²*=.08] indicating that the effect of HDC was larger for the English- [0.03 items per second (17 ms); compatible: *M*=1.34 (758 ms), *SD*=0.19 (106 ms); incompatible: *M*=1.32 (775 ms), *SD*=0.18 (110 ms)] than the German-speaking group [0.01 items per second (5 ms); compatible: *M*=1.32 (762 ms), *SD*=0.13 (73 ms); incompatible: *M*=1.32 (767 ms), *SD*=0.13 (76 ms)]. Evaluating the simple effects by post-hoc *t*-tests (Bonferroni-corrected for multiple comparisons) revealed that the effect of HDC was significant for the English-speaking group [*t*(23)=3.99, *p*=.002] but not for the German-speaking group [*t*(23)=1.23, *p*=.462]. Additionally, a significant main effect of HUC [*F*(1, 46)=24.99, *p*<.001, *ηp²*=.36] was found indicating that hundred-unit-compatible number pairs were processed 0.02 items per second (12 ms) faster as compared to hundred-unit-incompatible number pairs [compatible: *M*=1.34 (758 ms), *SD*=0.16 (92 ms); incompatible: *M*=1.31 (770 ms), *SD*=0.15 (91 ms)]. No interaction of HUC and language [*F*(1, 46)=1.97, *p*=.167, *ηp²*=.04] was observed. Simple effects analyses showed that for both language groups a reliable effect of HUC was present [German: *t*(23)=2.98, *p*=.007; English: *t*(23)=4.36, *p*=.001]. See Figure 1 for an illustration of speed costs due to hundred-decade- and hundred-unit-incompatible number pairs for the two language groups. Additionally, the three-way interaction of HDC, HUC, and language was significant [*F*(1,46)=11.78, *p*=.001, *ηp²*=.20]. Breaking down this three-way interaction into its constituting two-way interactions revealed that the interaction of HUC and language was significant for hundred-decade-compatible [*F*(1, 46) = 13.54, *p* = .001, *ηp²* = .23] but not for hundred-decade-incompatible number pairs. The two-way interaction of HUC and language for hundred-decade-compatible number pairs shows that the effect of HUC was larger for English- as compared to German-speaking participants [English: *M*=-0.04 (19 ms), *SD*=0.03 (18 ms); German: *M*=0.00 (1 ms), *SD*=0.03 (19 ms)]. Two further interactions indicated that digit distances influenced the compatibility effects: Both the interaction of HD and HDC [*F*(1,46)=6.99, *p*=.011, *ηp²*=.12] and the interaction of HD and HUC reached significance [*F*(1,46)=18.67, *p*<.001, *ηp²*=.29]. The effect of HDC was larger for large HD [large: *M*=-0.03 (16 ms), *SD*=0.04 (21 ms); small: *M*=-0.01 (6 ms), *SD*=0.05 (31 ms)]. Contrarily, the effect of HUC was larger for small HD [large: *M*=0.00 (1 ms), *SD*=0.04 (18 ms); small: *M*=-0.04 (23 ms), *SD*=0.04 (25 ms)].

*> Insert Fig. 1 about here <*

*Interindividual differences in processing patterns within the German-speaking sample*

Contradicting our hypotheses, the effect of HDC was not significant for the German-speaking sample. Since this pattern of results was unexpected, data for the German-speaking sample were inspected more closely at the participant level. To find out whether the null effect of HDC, in particular, was due to interindividual differences in processing styles, effects of HDC were considered for each participant separately. It became evident that roughly half of the German-speaking participants showed a regular (positive) effect of HDC [G+, n = 14; *M* = - 0.03 (19 ms), *SD* = 0.02 (13 ms); 95% CI [- 0.02 (11 ms), - 0.04 (26 ms)]], while the other half showed an inverse (negative) effect of HDC [G-, n = 10; *M* = 0.02 (-13 ms), *SD* = 0.02 (9 ms); 95% CI [0.04 (-19 ms), 0.01 (-6 ms)]], which in turn led to the zero effect when data of all participants was pooled (for a similar finding see Meyerhoff et al., 2012).

While clearly differing with respect to the HDC effect, the two German-speaking subgroups showed an effect of HUC [*F*(1,22) = 8.10, *p* = .009, *ηp²*=.27] that did not differ between groups [G+: *M* = - 0.01 (4 ms), *SD* = 0.02 (13 ms); G-: *M* = -0.03 (14 ms), *SD* = 0.03 (14 ms); *F*(1,22) = 2.08, *p* =.163]. Furthermore, the two groups did not differ in their overall speed [Speed: G+: *M* = 1.29 (783 ms), *SD* = 0.12 (72 ms); G-: *M* = 1.37 (738 ms), *SD* = 0.13 (72 ms); *t*(22) = 1.52, *p*=.144]. Finally, the two subgroups did not differ in their general math abilities (as indicated by the math computation subtest of the WRAT; *t*(22) = -0.21, *p* = .836).

In contrast, only five out of the 24 English-speaking participants showed an inverse hundred-decade-compatibility effect. Importantly, the largest inverse effect of hundred-decade-compatibility in the English-speaking sample was 0.02 items per second [-11 ms; *M* = 0.01 (-7 ms), *SD* = 0.01 (4 ms)] which is of comparable size to the mean inverse hundred-decade-compatibility of the German-speaking sample. This indicates that even if English-speaking participants showed an inverse hundred-decade-compatibility effect, it was comparably small.

*Eye-fixation behavior – Specificities of the underlying processing characteristics*

To further investigate whether the inversion of number words or influences of reading behavior drove differences between the two language groups but also within the German-speaking sample, non-overlapping interest areas (IA) were defined for each digit of both numbers. Each IA was 150 pixels high and 92 pixels wide. Fixations outside these IAs were not considered in further analyses. Additionally, the very first fixation (e.g., the fixation on the fixation point) of each trial was removed. For data analyses, total reading times (TRT; sum of durations of all fixations within one IA) for each IA were calculated and collapsed over digits at the same digit position resulting in a 3 level factor (e.g., hundred, decade and unit position).

The German sample was split into two groups based on the nature of the effect of HDC for further analyses (G+: regular effect of HDC; G-: inverse effect of HDC). The HDC effect was chosen, because differences in the direction of the effect are indicative of different processing strategies. An inverse HDC effect indicates that participants focused primarily (or at least more) on the hundred digit leading to faster RTs for hundred-decade-incompatible number pairs, since their hundred distance is necessarily larger as compared to hundred-decade compatible number pairs (see Nuerk et al., 2005 for a mathematical elaboration on this). Thus, an inverse HDC effect (actually reflecting a regular hundred distance effect) is indicative of a rather sequential processing strategy starting at leftmost digit (e.g., the hundred digit).

To correct for the overall difference in total reading times, relative total reading times were calculated (the percentage of TRT on a specific place-value position from TRT of all three place-value positions combined).

*Inversion influences*

To further evaluate whether the inversion property of German number words caused differential effects in the observed pattern of compatibility effects between but also within the German-speaking group, a univariate ANOVA was run on relative TRT on the unit digit. Contradicting an influence of inversion, results showed no main effect of group [*F*(2, 45) =1.24, *p*=.298, *ηp²*=.05; E: *M*=4%, *SD*=4%; G+: *M*=3%; *SD*=4%; G-: *M*=2%, *SD*=3%] indicating that the three participant groups fixated the unit digits about equally long.

*Influences of reading behavior*

To investigate language specific differences due to differential reading behavior, a 3 × 2 mixed model ANOVA was run on relative TRT with the between-subject factor group (English vs. G+ vs. G-) and the within-subject factor place-value position (hundred vs. decade), since primarily fixations on hundreds and decades are informative about possible differences in processing strategies. No main effect of group was observed [*F*(2, 45)=1.24, *p*=.298][[2]](#footnote-2). However, a significant main effect of place-value position was found [*F*(1, 45)=172.45, *p*<.001, *ηp²*=.79; hundreds: *M*=22%, *SD*=14%; decades: *M*=75%, *SD*=12%] which was further qualified by the interaction of place-value position and group [*F*(2, 45)=3.86, *p*=.028, *ηp²*=.15]. As can be seen in Figure 2, post hoc tests indicated that the G+ and the English group differed hardly at all [for both place-value positions p>.400]. To disentangle the interaction of place-value position and group, position effects (relative TRT on decade position – hundred position) were evaluated. Bonferroni-corrected post hoc tests showed that the position effect was more pronounced for the English as compared to the G- group [*p*=.024]. The effect did not differ between the G+ and the G- group [*p* = .180] nor between the G+ and the English-speaking group [*p*>.999]. Further univariate ANOVAs with the between subject factor group (English vs. G+ vs. G-) were run on the relative TRTs on the hundred and decade position separately indicating that TRT on both place-value positions differed between groups [*F*(2, 45) = 3.74, *p*=.031, *ηp²*=.14 and *F*(2, 45) = 3.89, *p*=.028, *ηp²*=.15, respectively]. Bonferroni-corrected post hoc tests indicated that the position effect was driven by significantly longer fixations on the hundred position [*MG-* = 32%, *SDG-* = 16%; *ME* = 18%, *SD*E = 13%; *p*=.027] and shorter fixations on the decades position [*MG-* = 66%, *SDG-* = 14%; *ME* = 78%, *SD*E = 11%; *p*=.024] for the G- group than for the English group reflecting the sequential processing component in the G- group. A similar result pattern was found for the comparison of the G- and the G+ group [hundred position: *MG+* = 21%, *SDG+* = 13%; *p*=.110; decade position *MG+* = 76%, *SDG+* = 11%]. However, between-group comparisons did not reach significance [hundred position: *p* = .220; decade position: *p* = .150].

*> Insert Figure 2 about here <*

**Discussion**

The present study investigated the underlying processing strategies and language differences in three-digit number processing. More specifically, we investigated the influence of two separate linguistic factors on three-digit number processing: number word inversion and differences in reading behavior (as influenced by orthographic consistency). The study aimed at clarifying to which degree number word characteristics (the inversion of number word structure) and differences in reading behavior (as influenced by orthographic consistency) between German and English speakers influence the proportion of parallel and sequential processing components during number processing. In line with Korvorst and Damian (2008), regular hundred-decade-compatibility effects for English- as well as hundred-unit-compatibility effects for English- and German-speaking participants indicated that both language groups processed three-digit numbers in a parallel decomposed manner. Inspection times further support the notion of parallel processing, since both language groups fixated the decade digit (the optimal viewing position) the longest (cf. Huber et al., 2015). Furthermore, the presence of compatibility effects contradicts the holistic model, which states that numbers are represented as holistic entities mapped onto an analogue magnitude representation (Brysbaert, 1995; Dehaene et al., 1990; Hinrichs, Yurko, & Hu, 1981). However, the homogeneity of parallel and sequential processing components varied between groups. More specifically, in contrast to results of Korvorst and Damian (2008), no difference was found between the sizes of the effects of HDC and HUC indicating that the proposed sequential left-to-right processing gradient for English-speaking participants was not corroborated by the present data. While, thus, no indices of partial sequential processing were found for the English-speaking group, about half of the German-speaking participants showed an inverse HDC effect accompanied by longer inspection time on the hundred digit indicating additional sequential processes. Importantly, these observed differences between the homogeneity of patterns of parallel and sequential processing characteristics within the two language groups are unlikely to result from differences due to the inverted number word structure of the German language, because the HUC effect and inspection times on the unit digit did not differ between groups. However, in line with an influence of reading behavior, a tendency to process a number in a partially sequential manner was found for the German-speaking sample. The present data thereby revealed that in transition from two- to higher multi-digit numbers the homogeneity of underlying processing strategies varies between language groups. We suggest that this is possibly related to differences in reading behavior.

*Reading behavior affects number processing*

The observed differences in the direction of the HDC effect within the German-speaking group indicate that there are differences in the nature of the decomposed processing which may be driven by characteristics of the German language. Since the HUC effect does not differ between groups (neither within the German group nor between language groups), it is highly unlikely that the inversion of German number words led to the observed results. When the inversion property of German number words would have influenced the comparison process, the interference due to the unit digit should have been more pronounced in German resulting in a larger compatibility effect. This is not what we found. Therefore, our findings are in line with recent results by Bahnmueller and colleagues (2015), who also did not observe inversion-related differences in three-digit number comparison. Thus, our results do not support the idea that the unit digit interferes with the comparison process due to its verbal proximity to the hundred digit in inverted German number words. In contrast to two-digit numbers, for which a more pronounced decade-unit-compatibility effect in German-speaking participants was observed, the decision relevant hundred digit is not part of the digits being inverted and, therefore, does not seem to lead to comparable response biases. Thus, our results indicate that previously found inversion related effects for two-digit numbers cannot be generalized to the effects present in the current study. The absence of inversion-related language differences has also been demonstrated for other numerical tasks (e.g., multiplication: Noël et al., 1997; addition: Brysbaert et al., 1998). Thereby, the present data corroborate the notion that inverted number words do not necessarily influence numerical processing whenever we are confronted with multi-digit numbers. Rather, the effect of inversion seems to be task-dependent and influenced by input and output formats.

However, our data fit nicely with the assumption that the way children learn to read influences three-digit number processing even in adult, skilled readers. Learning to read phonologically incongruent English words requires readers to consider the single letters of a word in parallel since the way a specific letter/or grapheme is pronounced is dependent of the context in which it occurs (i.e., neighboring letters in the word, e.g., in English the letter *a* is pronounced differently in the words ‘ball’, ‘park’, and ‘hand’; Ziegler et al., 2001). Similar to English words, results indicated that English-speaking participants processed three-digit numbers in a highly parallel manner with no indication of additional sequential processing components. In contrast, learning to read highly congruent German words allows for sequential, letter-by-letter reading (based on letter-sound conversion) of words from left to right as the pronunciation of single letters is highly consistent across words and does (mostly) not depend on neighboring letters (e.g., Wimmer & Goswami, 1994). In line with such a reading behavior, there were indications of at least partially sequential decomposed processing strategies in the German sample. Most prominently, half of the German speaking sample showed an inverse HDC effect evidently driven by a more pronounced focus on the decision relevant hundred digit. Taken together, these data corroborate the idea that the way children learn to read influences the way multi-digit numbers are processed.

It is important to note that these differences occurred in an adult sample and in a nonverbal task. Reading of skilled readers (irrespective of the degree of orthographic consistency) becomes highly parallel with age and experience and single letters are no longer scanned individually and combined afterwards. Therefore, we want to point out that we do not argue that adult German participants still read letter-by-letter from left to right. However, differences in the fixation pattern with parts of the German-speaking participants fixating more on the leftmost hundred digit corroborate the idea that characteristics of the respective language’s orthography seem to influence the way multi-digit numbers are processed as well – even far beyond the stage of reading acquisition (cf. Rau et al., 2015). Nevertheless, it is important to note that the eye fixation patterns of both language groups revealed most fixations to fall on the center of gravity (the decade digit) representing a perfect starting point to process the digits in parallel – corroborating the argument that it is only a tendency to process numbers more sequentially in German-speaking participants.

One possible explanation for the observed differences in the extent of parallel and sequential processing strategies within the German-speaking sample might be differences in the way participants were taught to read in school. While teaching English pupils to read focuses predominantly on whole word reading practices, there is a lot more variance in teaching methods in German. Teaching approaches range from the classical letter-by-letter reading, over syllable reading to the use of whole word reading practices (Scheerer-Neumann, 2006). The respective approach may vary considerably not only between schools but even across teachers. Therefore, it is possible that German participants whose reading instruction was not only based on initial letter-by-letter reading exhibited less sequential processing than did participants who were taught predominantly using letter-by-letter strategies. Another possible explanation for the observed variance within the German-speaking sample might be differences in second languages that the participants speak and, more importantly, read fluently. For instance, one might speculate that German participants, who are highly skilled in English reading, may adapt their general reading strategies leading to a pattern more similar to that observed for the native English speakers. However, all German-speaking participants were university students and should have learned English to a similar extent at school. Nonetheless, based on the available data both accounts are speculative and await further empirical evaluation in future studies.

*Interindividual differences are language-specific and digit-length dependent*

Interestingly, the observation that there are interindividual differences in a number comparison task for German-speaking participants has been made before. Meyerhoff et al. (2012) conducted a four-digit number comparison task, in which they also did not find reliable effects of compatibility. However, similar to the present study, approximately half of their German-speaking participants showed a regular compatibility effect while the other half showed an inverse compatibility effect in this four-digit number comparison task. To explain this result Meyerhoff and colleagues (2012) proposed that, while two-digit numbers can easily be processed in parallel, longer multi-digit numbers are rather processed in a combined parallel-sequential, chunking-like manner to ensure processing of numbers in the most economical way. While the results of Meyerhoff et al. (2012) indicate that such a chunking-like processing strategy is consistently used for six-digit numbers, the case does not seem to be that clear for three- and four-digit numbers, leading to the observed interindividual differences in processing three-digit (in the present study) and four-digit numbers (Meyerhoff et al., 2012). Therefore, integrating results for three- and four-digit numbers indicates that in the transition from two to longer multi-digit numbers German-speaking participants do not seem to adhere to a homogeneous processing pattern. It remains to be clarified whether this interindividually varying transitional change is specific to languages with consistent orthographies and/or generalizes to inconsistent orthographies as well (possibly showing differences for four-/five-digit numbers). Additionally, it might be interesting to evaluate whether intraindividual differences in other domain-specific as well as domain-general processes (e.g., general cognitive functioning, working memory, perceptual speed, etc.) predict the transition from parallel to at least partially sequential processing.

**Conclusion**

The present study revealed that three-digit numbers - like two-digit numbers (Nuerk et al., 2005; Pixner et al., 2011) - are processed in a decomposed fashion. However, the homogeneity of parallel and sequential decomposed processing components varied between language groups. The present results thereby indicated that language-specific differences go beyond the already described effects for two-digit numbers. Language differences in two-digit number processing have primarily been attributed to the inversion property of German number words. However, we did not observe such general inversion-related differences for three-digit number processing. Rather, differences in reading behavior due to orthographic consistency seemed to have driven differences in the homogeneity of parallel and sequential processing strategies between groups. While the consistent German orthography may support a tendency towards more sequential processing (similar to the initial letter-by-letter reading in children) the inconsistent English orthography may corroborate parallel processing of single digits in multi-digit numbers. These results indicate that the inversion property of number words is only one factor among several influencing multi-digit number processing and that the consistency of the respective orthography needs to be considered as well.

**Acknowledgements**

Julia Bahnmueller and Stefan Huber were supported by the Leibniz-Competition Fund (SAW-2014-IWM-4) providing funding to Elise Klein. Korbinian Moeller and Hans-Christoph Nuerk were principal investigators at the LEAD Graduate School [GSC1028], a project of the Excellence Initiative of the German federal and state governments.

**Compliance with ethical standards**

**Ethical approval**: All procedures performed in this study were in accordance with the ethical standards of the ethics committee of the Department of Psychology, University of York (UK) and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

**Conflict of interest**: The authors declare that they have no actual or potential conflicts of interest concerning this work.

**Informed consent:** Informed consent was obtained from all individual participants included in the study.

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***Figure captions***

**Fig. 1** Hundred-decade- (HDC) and hundred-unit-compatibility (HUC) effects presented separately for the German- and the English-speaking sample. Error bars represent 95% confidence intervals. \*: *p*< .05

**Fig. 2** Relative total reading times for the English-speaking group as well as for both the German-speaking subgroups showing a regular hundred-decade-compatibility effect (G+) and an inverse hundred-decade-compatibility effect (G-). Error bars indicate standard errors of means. \*: *p* < .05

**Figure 1**



**Figure 2**

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1. Note that these results have to be treated with caution. In the stimulus set used, hundred-decade-compatibility was confounded with overall numerical distance. More precisely, hundred-decade compatible number pairs had, on average, a larger numerical distance than hundred-decade-incompatible number pairs (419 vs. 349 respectively). As large overall numerical distance and compatible number pairs both lead to a better performance, it is not clear whether the more pronounced hundred-decade-compatibility effect can be attributed solely to the manipulation of hundred-decade-compatibility. [↑](#footnote-ref-1)
2. As we are dealing with relative probabilities, the probability for fixating unit digits is identical to 1 – the combined probabilities of hundreds and tens being fixated which leads to identical statistics as presented for the univariate ANOVA run on relative TRT on the unit digit. [↑](#footnote-ref-2)