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Relating numeric cognition and language processing: Do numbers and words share a common representational platform?

Martin Lachmair [a,*], Carolin Dudschig [b], Irmgard de la Vega [b], Barbara Kaup [b]

[a] Knowledge Media Research Center, Tübingen, Germany
[b] University of Tübingen, Germany

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ABSTRACT

Numerical processing and language processing are both grounded in space. In the present study we investigated whether these are fully independent phenomena, or whether they share a common basis. If number processing activates spatial dimensions that are also relevant for understanding words, then we can expect that processing numbers may influence subsequent lexical access to words. Specifically, if high numbers relate to upper space, then they can be expected to facilitate understanding of words such as *bird* that are having referents typically found in the upper vertical space. The opposite should hold for low numbers. These should facilitate the understanding of words such as *ground* referring to entities with referents in the lower vertical space. Indeed, in two experiments we found evidence for such an interaction between number and word processing. By eliminating a contribution of linguistic factors gained from additional investigations on large text corpora, this strongly suggests that understanding numbers and language is based on similar modal representations in the brain. The implications of these findings for a broader perspective on grounded cognition will be discussed.

1. Introduction

A central topic in cognitive science concerns the question on how information that is captured in symbolic systems is processed to create meaning in the human mind and how this meaning is then mentally represented (e.g., de Vega, Glenberg, & Graesser, 2008). Prototypical examples of such symbol systems are words and numbers. Interestingly, the research in these fields runs largely in parallel with only a few points of contact. This may be due to the fact that these symbol systems are attributed to different purposes, namely communication and mathematical reasoning. However, in terms of creating and representing meaning, there is good reason to assume a stronger relationship between the two symbol systems. Before turning to the arguments concerning this relationship, we will take a look at research concerned with the question how words and numbers are understood and represented.

With respect to language, there is a lively debate on how meaning is created and represented in the human mind. For illustrative purposes we will frame this debate as a dichotomy between two competing views. According to the symbolic view, the meaning of a word is represented by means of abstract, arbitrary and amodal symbols (Fodor, 1975; Kintsch, 1974). The meaning of larger phrases or sentences is computed by combining the meanings of the individual words according to their syntactic structure, with the result being a propositional meaning representation (Engelkamp, 1976; Kintsch, 1974). Many proponents of the symbolic view assume that both word and sentence meaning reside within memory systems that are separate from the brain's modal systems (e.g., perception, action, introspection) that give rise to knowledge in the first place (e.g., Tulving, 1972). In contrast, according to the embodied view of language processing, sensory-motor representations play a crucial role for language understanding and meaning representation. According to this view, meaning representations during language processing are of a similar nature as the representations created when directly experiencing one's environment (Barsalou, 1999). It is assumed that every interaction with the world leaves multimodal experiential traces in the brain that capture information concerning the corresponding objects, situations and events. As experiencing these entities often goes hand in hand with experiencing the linguistic labels used to refer to these entities (e.g., a mother pointing to a dog and uttering "look there is a dog"), the experiential traces for the entities presumably get associated with the experiential traces of the words. Later, the words automatically reactivate the corresponding multi-modal memory traces and the meaning of a word is then given by these memory traces. Thus, according to the embodied language processing view, comprehension is tantamount to mentally simulating the described entities (e.g. Zwaan & Madden, 2005). As mentioned above, we framed the debate as a dichotomy between two incompatible views mainly for illustrative purposes. This should not gloss over the fact that several researchers in Cognitive Science in fact propose intermediate positions. Paivio's (1977) dual-coding theory

* Corresponding author at: Leibniz-Institut für Wissensmedien, Knowledge Media Research Center, Schleichstr. 6, 72076 Tübingen, Germany. Tel.: +49 7071 979 273; fax: +49 7071 979 100.
E-mail address: m.lachmair@iwm-kmrc.de (M. Lachmair).

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may serve as an example here (see also Mahon & Caramazza, 2008, for a discussion).

Recent literature investigating word and sentence comprehension indeed provides a lot of evidence for the idea that sensory-motor representations are involved in comprehension. For instance, neuropsychological studies indicate a considerable overlap between the mental subsystems used for representing linguistically described situations and the mental subsystems that are active during direct experience (e.g., Buccino et al., 2007). Moreover, behavioral studies demonstrate interactions between the content of linguistic stimuli and non-linguistic aspects of the experimental task. For example, Glenberg and Kaschak (2002) found that participants were faster to respond to a sentence such as “close the drawer” when the required response movement matched the movement implied by the sentence (e.g., a movement away from the body) than when it mismatched (e.g., a movement towards the body) and vice versa. This suggests that mechanisms recruited for action planning are also recruited when comprehending sentences describing actions (see also Taylor & Zwaan, 2008; Zwaan & Taylor, 2006). Similarly, a study by Boulenger et al. (2006) with individual words shows a crosstalk between action word processing and overt motor behavior, suggesting that action words and motor action share common cortical representations. In a recent study conducted in our lab (Lachmair, Dudschig, De Filippis, de la Vega, & Kaup, 2011), we observed interactions between object words and motor responses. More specifically, we found a compatibility effect between the processing of words that refer to objects typically encountered in the upper or lower part of vertical space and subsequent hand responses on a vertical spatial axis. Words referring to entities that are typically located in the upper visual field (e.g. *bird*) facilitate upward hand responses (e.g., pressing an up-key). In contrast, words referring to entities that are typically located in a lower position (e.g. *worm*) facilitate downwards responses. Analog results have been found when investigating verbs that imply an upward or downward motion (e.g., *rise* vs. *fall*) (Dudschig, Lachmair, de la Vega, De Filippis, & Kaup, 2012a). These results fit well with the view that linguistic labels are associated with particular experiences which are activated when the words are processed. There are many studies of this sort providing evidence for the embodied view of language comprehension with respect to spatial aspects of experiences (e.g., Bergen, Lindsay, Matlock, & Narayanan, 2007; Dudschig, Souman, Lachmair, de la Vega, & Kaup, submitted for publication; Estes, Verges, & Barsalou, 2008; Pecher, Van Dantzig, Boot, Zanolie, & Huber, 2010; Thornton, Loetscher, Yates, & Nicholls, 2013; Zhang et al., 2013). This may come of no surprise considering that spatial attributes are central for almost all of our daily experiences (Levinson, 2003).

Interestingly, there is also strong evidence for a relationship between number processing and space. The representation of magnitude is proposed to be grounded in a horizontal mental number line (MNL), which is oriented typically from the left (low numbers) to right (high numbers) in space (Dehaene, Bossini, & Giraux, 1993). Behavioral evidence for these assumptions comes from different experiments with numbers and lateralized hand responses. Dehaene and colleagues show that responses with an effector to the left side are faster after processing numbers less than five, whereas responses with an effector to the right side are faster after processing numbers greater than five (SNARC effect—spatial number associated response code). The SNARC effect and its representational metaphor of a horizontal MNL have been investigated in numerous studies (e.g., Fischer, Castel, Dodd, & Pratt, 2003; Zorzi, Priftis, & Umilta, 2002; cf. Wood, Nuerk, Willmes, & Fischer, 2008).

Interestingly, there are also studies showing that the representation of numbers in the horizontal spatial dimension is not sufficient for all aspects of representing numerical meaning. In many everyday experiences numbers are oriented in a vertical spatial dimension. For instance when taking a lift in a building lower numbers are encountered in lower vertical space and higher numbers in higher vertical space. If experiences of this type are as relevant to meaning representations in numerical cognition as they are to meaning representations in the language domain, then numbers should be associated not only with horizontal space but also with vertical space. Based on these considerations, Schwarz and Keus (2004) posed the question whether there is a vertical equivalent of the horizontal number line (see also Walsh, 2003; cf. Lakoff & Núñez, 2000). In a parity judgment task these authors indeed showed a vertical saccadic SNARC effect. Low numbers lead to faster downwards saccades whereas high numbers lead to faster upwards saccades. In fact, in this study the vertical SNARC effect was similar in strength to the horizontal one. A similar result was presented in a study by Holmes and Lourenco (2012). In an experiment in which the numerical tasks were primed by a story that let participants think about numbers in the context of referring to floors in a multi-story building, a stable vertical SNARC effect was observed which was oriented from the bottom (i.e. low numbers) to top (i.e. high numbers). All in all, these results provide strong evidence for an association between number processing and spatial cognition. As in the language domain, these associations seem to have their basis in physical experiences (e.g., Fischer, 2008, 2012) and suggest multimodal representations for number magnitude. Recent neuropsychological evidence from rTMS-studies supports the view of there being a strong relation between bodily processes and mathematical cognition (see Soylu, 2011).

Taken together, converging evidence suggests that language and number processing are closely comparable regarding their relationship to space, in particular in the vertical dimension. In both cases, a wide range of studies show direct influences of language/number comprehension on perception and action in vertical space (e.g., Boulenger et al., 2006; Estes et al., 2008; Fischer et al., 2003; Ito & Hatta, 2004; Tschentscher, Hauk, Fischer, & Pülvermuller, in press). Besides, even the paradigms used to investigate the relationships of numbers and language to spatial processing are often identical. However, up to date these effects have always been reported independently from each other, and it therefore remains open whether these spatial associations are similar in nature or fully independent phenomena. According to Barsalou (2008) all meaning representations are grounded in perception and action independent of the particular cognitive processes that are involved. He suggests a common modal representational system for various types of knowledge.

The current study will investigate this proposal. The aim is to find out whether the associations between number processing and vertical space and those between language processing and vertical space are related to each other. In particular, we are interested in whether number processing and word processing interact, as would be predicted by the view that there is a common representational platform for all cognitive processes based on experiential simulations (Barsalou, 2008). More specifically, we predict that a word such as *bird* as well as a high number such as *9* elicits experiential simulations involving upper vertical space. Conversely, processing a word such as *worm* as well as processing a low number like *1* elicits experiential simulations involving lower vertical space. If the experiential simulations activated for the words and the numbers involve the same representational platform then we can expect to see interactions if participants process a word that is associated with vertical space subsequently to having processed a number that is associated with vertical space. In other words, if the number *1* activates spatial representations that are also functionally relevant for understanding a word such as *worm*, then processing *worm* should be facilitated after having processed *1*. Similarly, if the number *9* activates spatial representations that are also functionally relevant for understanding a word such as *bird*, then processing *bird* should be facilitated after having processed *9*.

2. Experiment 1

Participants performed a lexical decision task with words denoting objects that are typically encountered in the upper or lower vertical space (e.g., *roof* vs. *root*, respectively). These words were preceded by a number, one of the set {*1*, *2*, *8*, *9*}. Correctly responding to the words either required a left or right key press. If the meaning representations of numbers overlap with the meaning representations of words as far as spatial associations are concerned then we would expect an interaction between numbers and words in the way that low numbers facilitate the processing of words denoting a referent with a lower location in the world and slow down the processing of words denoting a referent with a higher location in the world. The reversed pattern should hold for high numbers.

2.1. Method

2.1.1. Participants

Twenty five right-handed German native speakers (14 females; $M_{age} = 27.4$ years, $SD = 5.29$) took part in the experiment. They received course credit or a financial reimbursement of 8 Euros per hour. All participants had normal or corrected-to-normal vision.

2.1.2. Materials and apparatus

Materials consisted of the numbers *1*, *2*, *8*, and *9*, as well as 80 German nouns and 80 pseudo-words. Of the 80 nouns, 40 referred to an object that is typically located in the upper vertical space (referent location: up) and 40 referred to objects that are typically located in the lower vertical space (referent location: down). Nouns were controlled for frequency with the "Wortschatz Portal" of the University of Leipzig (http://wortschatz.uni-leipzig.de), for length and for the typical vertical location of their referent: a group of 49 volunteers who did not participate in the actual experiment rated 104 nouns with respect to the referents' typical location using a five-point Likert-scale ranging from "down" to "up". Word length and frequency were matched across the two categories of vertical position (down vs. up), resulting in 40 up words (letters: $M = 6.08$, $SD = 1.78$), and 40 down words (letters: $M = 6.08$, $SD = 1.78$). Up and down words did not differ significantly with regard to their frequency, $t(78) = 0.36$, $p = .72$, or length, $t(78) = 0.00$, $p = 1$, but did differ significantly for the rated position, $M_{up} = 4.68$, $SD = 0.29$, $M_{\text{down}} = 1.54$, $SD = 0.37$, $t(78) = 41.71$, $p < .001$. The pseudo-words were rated neutral ($M = 2.91$, $SD = 0.89$) and had a similar length as the words (see Lachmair et al., 2011). Words and numbers were presented in white, centered on a black background. The stimuli were displayed on a 17 inch CRT monitor, visual angle varied according to word length between 1.43° and 4.65°. Responses were recorded using a standard keyboard.

2.1.3. Procedure and design

Each item of the wordlist was presented to participants centered on screen, preceded by a one digit number prime. Participants were instructed to perform a lexical decision task. In the first half of the experiment, participants responded with a right hand key press to words and a left hand key press to pseudo-words. In the other half, the response mapping was reversed. The order of the response mappings was balanced across participants. Each trial started with a centered fixation cross (500 ms), followed by 300 ms number prime. Afterwards the word/pseudo-word stimulus appeared immediately and stayed until response. Response times (RTs) were measured as the time from stimulus onset to the key response. Each stimulus was presented four times, resulting in a total of 640 experimental trials (320 word-trials + 320 pseudo-word-trials), subdivided into 8 blocks, separated by a self-paced break with error information. Each experimental half started with a short practice block. To ensure the processing of the digits, the participants were informed beforehand that they should report the numbers they had seen in a short questionnaire at the end of the experiment.

2.2. Results and discussion

All data were analyzed using R (R Development Core Team, 2009). The data of one participant was excluded because of a corrupted datafile. Responses to pseudo-words, responses slower than 200 ms and errors were excluded from further analyses. Responses deviating by more than 2.5 SDs from the mean for that participant were excluded. This reduced the data set by less than 0.001%. Mean RTs are displayed in Fig. 1.

Response times were analyzed by means of a linear mixed effects model with the R packages lme4. As random effects participants and items were included in the model (cf. Baayen, Davidson, & Bates, 2008), and as fixed effects, the numbers, the rating values of the nouns' implicit location in vertical space as well as the interaction of the numbers and these rating values were included. We checked for normality and homogeneity by visual inspections of the plots of residuals against the fitted values. The analysis showed no significant effects for the numbers or the rating values (*ps* > .21). However, the effect of the interaction was significant ($t = -1.97$, $p < .05$). To assess the validity of this mixed effects analyses, a likelihood ratio test was performed comparing the interactive model (described above) with an identical, but non-interactive model. The model with the interaction significantly outperformed the model without the interaction ($X^2 = 3.88$, $df = 1$, $p < .05$).

The results were as expected: word processing was significantly influenced by prior number processing. After a large number prime (*8*, *9*), words denoting a referent with a typical location in the upper world, such as *bird*, were processed faster than words denoting a referent with a typical location in the lower word, such as *foot*. The reverse pattern held for low number primes (*1*, *2*). Here words denoting a referent with a typical location in the lower world were processed faster than words denoting a referent with a typical location in the upper world. These findings suggest that word reading can be affected by preceding numbers that are spatially related to congruent positions (e.g. *1*, *2* = down vs. *8*, *9* = up). This in turn is in line with the idea that the meaning representations of numbers overlap with the meaning representations of words in the spatial dimension, and thus supports the notion that there is a common representational platform for representing entities in different cognitive processes.

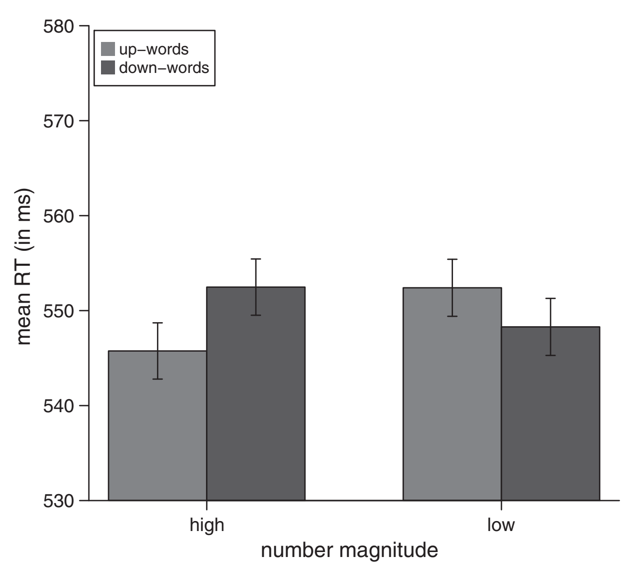

Fig. 1. Results of Experiment 1. Mean response times (ms) of correct responses as a function of numbers and referent location. Error bars represent the 95% confidence interval for within-subject designs (Masson & Loftus, 2003).

3. Experiment 2

The main purpose of Experiment 2 was to replicate the finding of Experiment 1, but this time with a simpler response mapping in a go/no-go paradigm.

3.1. Method

3.1.1. Participants

Twenty-one right-handed German native speakers (16 females; $M_{age} = 23.86$ years, $SD = 3.24$) took part in the experiment. They received course credit or a financial reimbursement of 8 Euros per hour. All participants had normal or corrected-to-normal vision.

3.1.2. Materials

Materials were the same as in Experiment 1.

3.1.3. Procedure and design

The procedure and design were the same as in Experiment 1, except that the task was a go–no-go task. For a word, participants had to perform a key press with the right hand, whereas for a pseudo-word they were instructed to refrain from responding. The amount of pseudo-words was halved to shorten the length of the experiment. Again, each stimulus was presented four times, resulting in a total of 480 experimental trials (320 word-trials + 160 pseudo-word-trials), subdivided into 8 blocks, separated by a self-paced break with error feedback.

3.2. Results and discussion

Responses to pseudo-words, responses slower than 200 ms and errors were excluded from further analyses. Responses deviating by more than 2.5 SDs from the mean for that participant were excluded. This reduced the data set by 2%. Mean RTs are displayed in Fig. 2.

Again response times were analyzed by means of a linear mixed effects model with the R packages lme4. As random effects participants and items were included in the model (cf. Baayen et al., 2008), and as fixed effects, the numbers, the rating values of the nouns' implicit location in vertical space as well as the interaction of the numbers and these rating values were included. We checked for normality and homogeneity by visual inspections of the plots of residuals against the fitted values. The analysis showed the same effects as in Experiment 1. There were no significant effects for the numbers or the rating values ($ps > .40$). However, the effect of the interaction was again significant ($t = -1.98$, $p < .05$). The likelihood ratio test comparing the model with the interaction as fixed effect with a model without this interaction again proved significant ($X^2 = 3.91$, $df = 1$, $p < .05$).

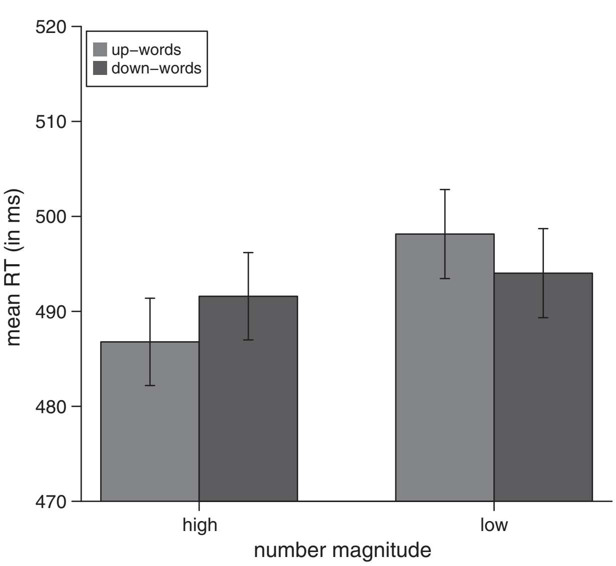

Fig. 2. Results of Experiment 2. Mean response times (ms) of correct responses as a function of numbers and referent location. Error bars represent the 95% confidence interval for within-subject designs (Masson & Loftus, 2003).

These results nicely replicate Experiment 1 showing that number and word processing interact when words referring to entities with a typical location in the upper or lower vertical space are processed after processing high or low number primes. The results of Experiment 2 thus further support the hypothesis notion that there is a common representational platform for different cognitive processes that is grounded in perception and action.

4. The role of linguistic experiences

Up to now, we pursued an interpretation of our results in terms of the embodied cognition framework. However, a number of researchers have recently argued that some of the compatibility effects that are typically interpreted as evidence for the embodied cognition view may in fact reflect statistical regularities that are present in a particular language (e.g., Louwerse, 2008). As language encodes embodied content it is often hard to tell whether a particular phenomenon reflects processes operating on embodied representations or rather processes operating on statistical regularities in the linguistic system. Statistical regularities may therefore often provide a plausible alternative explanation for embodiment effects. Explanations in terms of statistical regularities have been proposed, both for phenomena based on the relationship between location words and space, as well as for phenomena concerning the relationship between numbers and space.

For instance, Louwerse (2008) proposed an alternative explanation for the finding that the word pair "flower–stem", presented one above the other, yields faster response times than the word pair "stem–flower" which is typically interpreted as evidence for the embodied cognition view (Zwaan & Yaxley, 2004). Words referring to objects higher in vertical space typically precede words referring to objects lower in vertical space in the linguistic input. Thus, in principle it seems possible that the compatibility effect observed for the word pairs is due to participants reading from the top to bottom and preferring a word order that reflects word order frequencies in their language. Similarly, Hutchinson, Johnson, and Louwerse (2011) offered an alternative explanation for the horizontal SNARC effect. Number words referring to low numbers are more frequent than number words referring to high numbers, and moreover, number words referring to low numbers typically precede number words referring to high numbers in the linguistic input. Again it therefore seems possible that preferences concerning responses with the left versus right hand may reflect differences in word- and word order frequencies instead of a horizontal mental number line that captures the meaning of numbers. Thus, the question arises whether the effects observed in the current manuscript could also be explained in terms of statistical regularities in the linguistic system. In principle we see three different possibilities for an explanation in terms of participants' linguistic experiences that we will address in the next paragraphs.[1]

[1] We do not consider simple word frequency here, because the two types of nouns employed in the present study were matched for frequency and an account in terms of word frequency therefore seems implausible despite the fact that there might be frequency differences between low and high numbers.

4.1. Frequencies with which certain number words precede certain object nouns

In principle, it seems possible that words referring to lower quantities more often precede down-words than up-words, whereas words referring to larger quantities more often precede up-words than down words in the linguistic experiences of the readers. If so, then the priming effects observed in the present experiments might indeed reflect linguistic experiences instead of a common representational platform involved in number and word processing. In order to test this possibility we added a factor corresponding to this linguistic experience to our analyses in Experiments 1 and 2. More specifically, for each number–word-pair employed in our experiment, we obtained the log-frequencies with which the corresponding number word precedes the given word in a German corpus and included these log frequencies as an additional factor in the mixed models analyses reported in the results sections of the two experiments above. In order to ensure comparability with the results reported in Hutchinson et al. (2011), we used the German version of the Web1T 5-gram corpus in a first step. In neither of the two experiments did this log-frequency of the number–word pair affect the interaction effect between high/low numbers and up/down nouns ($p_{\text{log-freq/Exp1}} = .17$; $p_{\text{log-freq/Exp2}} = .66$). As many of the log-frequencies were zero for the Web1T 5-gram corpus used by Hutchinson et al., we repeated the described analyses via a web-interface with another well-balanced German corpus, namely the German reference corpus (Kupietz, Belica, Keibel, & Witt, 2010). Again, we looked at log-frequencies of the word-orders in 5-grams. With this corpus, log-frequencies for all number–word pairs were found. Nevertheless, the log-frequencies did not affect our results, neither for Experiment 1 nor for Experiment 2 ($p_{\text{log-freq/Exp1}} = .97$; $p_{\text{log-freq/Exp2}} = .67$; see Appendix B for log-frequencies of number–word pairs). We therefore consider it unlikely that our priming results reflect differences in the frequencies with which high and low number words precede up and down words in the linguistic experiences of the readers.

4.2. Appearing early vs. late in the sentence

From the study by Hutchinson et al. (2011) we know that number words referring to small quantities typically precede number words referring to large quantities in the linguistic input. Thus, words referring to small numbers typically appear early in the sentence whereas words referring to large numbers typically appear later in the sentence. If the same is true for our down and up words, respectively, then this might offer an alternative explanation for the reported priming results. Two additional analyses were conducted to test this alternative explanation according to which low numbers prime down words and high numbers prime high words because they share certain commonalities with respect to where in the linguistic input they typically appear. Due to the large item-set that we used in the experiments, separate queries for all combinatory possibilities via a web-interface were not practicable. Since DeReKo is not freely available for download, we instead used the sdewac-corpus for the present purposes (Baroni, Bernardini, Ferraresi, & Zanchetta, 2009). This is a large sentence-based and well-balanced corpus allowing batch analyses. Thus, in a first step, the frequencies with which the nouns appeared in a particular order in the linguistic input were analyzed. More specifically, we compared the frequencies with which each particular up-noun employed in our study preceded each particular down noun employed in our study in the corpus sentences. We then compared these frequencies with the frequencies of the reversed word order. A paired-samples *t*-test showed that our down-words did not appear more often before our up words. In fact, if at all, our up-words on average appeared more often before our down-words (10.6 vs. 11.6), but this difference was not significant ($t(1600) = -0.41$; $p > .65$). Thus, it seems unlikely that our priming results reflect commonalities between high and low number words and up and down object nouns with respect to their typical order in a sentence. However, this analysis only looked at cases in which both an up- and a down word appeared in the sentences. Maybe differences between up- and down-words would become evident when we looked at all kinds of sentences mentioning at least one of the respective word types. Possibly, down-words typically appear earlier in sentences than up-words. If so, this might explain why low numbers (also typically appearing early) prime down words and high numbers (typically appearing late) prime up-words. To find out, we conducted a second analysis looking at the average position at which our up- and down nouns appear in sentences. In order to obtain the necessary information, we looked at the first 16,384 occurrences (due to limitation of analysis-software) of each of our object nouns in the sdewac-corpus and then averaged their occurrences (see Appendix C for the average position per object noun). Comparing the average positions for our up- and down nouns in a paired samples *t*-test did not yield a significant result ($t(39) = -0.93$, $p > 0.35$). Thus, no evidence could be obtained for the view that these differences with respect to the position at which our nouns occur in the linguistic input may be responsible for the observed effects.

4.3. Semantic similarity between number words and up–down nouns

One other way in which our priming results may reflect the linguistic experiences of the readers would be that low numbers are semantically similar to down words and high numbers to up words in the sense that they occur in similar contexts. We used Latent semantic analysis (Landauer & Dumais, 1997) to examine this possibility on the corpus of German wikipedia, which is particularly suitable for this method due to its size and paragraph formatting (see Wiemer-Hastings, Wiemer-Hastings, Graesser, & the Tutoring Research Group, 1999). In particular, we looked at the cosine similarity between our up- and down-words and the number words that correspond to the four numbers used in the stimulus material of the reported studies. The cosine similarities were all very small ("one"-up words: 0.030; "one"-down-words: 0.007; "two"-up words: 0.01954; "two"-down-words: 0.00691; "eight"-up words: 0.050; "eight"-down-words: 0.001; "nine"-up-words: 0.044; "nine"-down-words: 0.002), and an ANOVA with the factors 'number word' and 'vertical location' did not show a significant interaction ($F < 1$). Thus, again we did not find compelling evidence for the view that our priming results reflect linguistic experiences of the readers.

5. Discussion

In two experiments we showed, to our knowledge for the first time, that perceiving numbers affects the subsequent processing of words: low numbers (*1*, *2*) lead to faster processing of words with referents that are typically located in lower locations in our surrounding (e.g. *worm*) and slow down the processing of words with referents that are typically located in upper locations in the world (e.g. *bird*). A similar pattern holds for processing words after high numbers (*8*, *9*): words with referents that are typically located in upper locations in our world are processed faster than words with referents that are typically located in lower locations. This confirms our expectations and shows the strong relationship between the processing of numbers and that of words referring to objects that are typically located in the upper or lower vertical space.

Recent compatibility studies conducted in the context of research on grounded cognition has shown the vertical spatial dimension to be associated with different meaning dimensions, namely typical object location (e.g., Borghi, Glenberg, & Kaschak, 2004; Dudschig et al., 2012a, Dudschig, Lachmair, de la Vega, De Filippis, & Kaup, 2012b; Zwaan & Yaxley, 2004), religious concepts (e.g., Chasteen, Burdzy, & Pratt, 2010), emotional valence (e.g., Meier & Robinson, 2004), and number magnitude (Fischer, 2012; Ito & Hatta, 2004) to name just a few. Compatibility effects of this type are typically attributed to the experiences people have had with the corresponding situations, emotions and entities. Presumably, multi-modal memory traces capturing these experiences get reactivated when people process the corresponding symbols (be it numbers or words) and then facilitate or hamper subsequent perception and action in compatible and incompatible conditions, respectively. Although these compatibility effects are typically observed in similar paradigms, there is little knowledge regarding the relationship between the respective phenomena. If indeed experiences underlie all these associations between symbols and space, and comprehending the symbols indeed involves reactivating these experiences (Barsalou, 2008), then we should see interaction effects between different symbols during processing as long as the symbols share particular experiential dimensions, such as being related to upper or lower vertical space. In the current study we showed such interaction effects of number processing and the subsequent processing of words that refer to entities that are typically located in the upper or lower vertical space. Thus, future studies are necessary to investigate the potential interaction effects between other types of words and symbols presumably sharing an experiential dimension.

In addition, for the embodied cognition view of comprehension it seems relevant to find out to what degree these spatial associations are indeed experience-specific in nature. Considering the wide spectrum of symbol types that have been found to be associated with the vertical dimension (see above), one may come to the conclusion that this dimension is overpopulated. This may cast doubt that these associations with the vertical dimension are specific enough to aid comprehension, as suggested by the embodied cognition view of comprehension. In a recent study, Dudschig, de la Vega, and Kaup (submitted for publication) found that the association between emotion words and the vertical dimension is indeed very experience specific. The vertical dimension was only activated automatically by those emotion words that referred to emotional states that go hand in hand with a particular upright or slouched body posture (e.g., *joy*, *sadness*). For other emotion words (e.g., *angry*) and general valence words (e.g. *friend*), an association with the vertical dimension was only observed when participants were required to judge the valence of the stimuli. These results therefore suggest that the associations with the vertical dimension in this case are indeed quite experience-specific in nature. One task for the future is to find out the degree to which the other associations with the vertical dimension are also experience specific. Only if they are, it seems plausible to assume that these associations indeed aid comprehension rather than constituting an optional by-product with no functional relevance for grasping the meaning of a particular symbol.

One way to interpret the findings of our two experiments is to assume that there is a common representational platform that is used in different cognitive tasks, in particular in word- and number processing. This assumption of a common representational platform is at the heart of Barsalou's proposal and constituted the theoretical basis for the present study. However, alternative explanations for our priming effects between number- and word processing seem possible in principle. For instance, objects in the lower part of vertical space might tend to co-occur with smaller quantities whereas objects in the upper part of vertical space might tend to co-occur with larger quantities. If so, then this would explain our priming effects without the need to postulate a common platform for representing meaning during number- and word processing. Should co-occurrences between lower and higher quantities and lower and higher objects exist, then one might assume to see evidence for this in the co-occurrence frequencies of the corresponding number- and object words. As described above, no evidence for this claim could be found in various text corpora analyses. Nevertheless, we consider it important to keep in mind that alternative possibilities exist (for a general discussion, see also Mahon & Caramazza, 2008).

To conclude, this study supports the view of grounded cognition as proposed by Barsalou (2008). Comprehension is tantamount to reactivating experiences in a representational platform that is common to a whole range of cognitive processes. This common representational platform provides the possibility for interactions between different comprehension processes sharing particular meaning dimensions. In the current paper we demonstrated interactions between number and word processing. However, numbers and words are only one particular pair of stimuli that can be expected to interact. Future studies are necessary to investigate other pairs and other meaning dimensions, strengthening this broader perspective on grounded cognition.

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Appendix A

Experimental items with rating and translation.

Up-word	Rating	Translation	Down-word	Rating	Translation
Dach	4.87	Roof	Erde	2.71	Soil
Burg	4.27	Castle	Gras	1.60	Grass
Nest	4.80	Nest	Wurm	1.40	Worm
Drachen	4.73	Kite	Taucher	1.47	Diver
Wolke	4.80	Cloud	Sumpf	1.67	Swamp
Turm	4.60	Tower	Grab	1.13	Grave
Stern	4.87	Star	Stein	1.67	Stone
Decke	4.20	Ceiling	Fluss	1.93	River
Satellit	5.00	Satellite	Schienen	1.73	Rails
Falke	4.80	Falcon	Hölle	1.21	Hell
Empore	4.29	Gallery	Pfütze	1.73	Puddle
Komet	4.93	Comet	Sohle	1.40	Sole
Giebel	4.23	Gable	Tümpel	1.67	Pond
Alpen	4.93	Alps	U-Bahn	1.07	Subway
Planet	4.6	Planet	Graben	1.60	Trench
Adler	4.93	Eagle	Tiefe	1.00	Depth
Hochebene	4.4	Plateau	Flussbett	1.67	Riverbed
Gipfel	4.93	Top	Keller	1.13	Cellar
Weltall	5.00	Space	Abgrund	1.07	Abyss
Sonne	5.00	Sun	Tunnel	1.73	Tunnel
Mond	4.87	Moon	Gruft	1.13	Crypt
Berg	4.87	Mountain	Maus	1.87	Mouse
Himmel	5.00	Sky	Straße	2.27	Street
Höhe	4.73	Height	Klee	2.07	Clover
Ballon	4.80	Balloon	Gehweg	2.13	Walkway
Vogel	4.60	Bird	Boden	1.67	Ground
Krone	4.07	Crown	U-Boot	1.13	Submarine
Ufo	5.00	UFO	Fuß	1.67	Foot
Höhepunkt	4.14	Highlight	Unterwelt	1.13	Underworld
Hochsitz	4.67	High seat	Schlucht	1.60	Canyon
Hochhaus	4.87	Skyscraper	Schotter	1.87	Gravel
Hochseil	4.80	Tightrope	Fußsohle	1.40	Foot sole
Flugzeug	4.87	Aircraft	Fußboden	1.40	Floor
Hochland	4.20	Highlands	Erdreich	1.67	Soil
Gebirge	4.87	Mountains	Teppich	1.73	Carpet
Vogelnest	4.73	Bird's nest	Katakombe	1.23	Catacomb
Spitze	4.57	Top	Wurzel	1.27	Root
Zeppelin	4.93	Zeppelin	Maulwurf	1.20	Mole
Dachbalken	4.53	Roof beam	Untergrund	1.20	Underground
Palme	4.00	Palm	Erdloch	1.47	Foxhole

Appendix B

Log-frequencies of number–word pairs (German Reference Corpus).

Word	"1"-word	"2"-word	"3"-word	"4"-word
Abgrund	20	21	0	23
Adler	16	16	16	17
Alpen	19	19	20	19

Appendix B (*continued*)

Word	"1"-word	"2"-word	"3"-word	"4"-word
Ballon	20	21	22	21
Berg	15	15	17	17
Boden	16	16	17	18
Burg	15	16	18	16
Dach	17	17	19	18
Dachbalken	0	0	0	0
Decke	20	19	21	21
Drachen	19	19	21	20
Empore	19	21	24	22
Erde	16	17	18	18
Erdloch	0	23	0	0
Erdreich	21	21	22	24
Falke	19	19	20	20
Flugzeug	18	19	20	20
Fluss	18	18	20	20
Flussbett	22	24	24	0
Fuß	16	16	17	18
Fußboden	22	21	22	24
Fußsohle	24	0	0	0
Gebirge	20	20	21	23
Gehweg	21	20	21	20
Giebel	20	19	21	22
Gipfel	19	17	18	20
Grab	18	18	19	20
Graben	17	18	19	19
Gras	17	17	20	20
Gruft	21	21	0	0
Himmel	16	17	18	17
Hochebene	23	24	24	0
Hochhaus	19	19	19	20
Hochland	21	20	0	24
Hochseil	24	0	0	0
Hochsitz	0	0	0	0
Höhe	14	14	15	14
Höhepunkt	17	17	18	17
Hölle	19	19	21	21
Katakombe	0	0	0	0
Keller	15	15	17	17
Klee	18	18	18	21
Komet	21	20	22	22
Krone	16	18	18	19
Maulwurf	21	21	24	22
Maus	17	17	20	20
Mond	17	17	18	18
Nest	20	20	22	24
Palme	20	20	24	21
Pfütze	0	22	21	21
Planet	17	17	21	18
Satellit	18	19	21	24
Schienen	19	19	20	21
Schlucht	21	22	22	22
Schotter	24	21	0	22
Sohle	21	20	23	23
Sonne	17	17	17	16
Spitze	16	16	18	18
Stein	15	15	17	16
Stern	15	16	19	19
Straße	13	14	13	13
Sumpf	22	22	24	24
Taucher	21	18	21	21
Teppich	19	20	24	21
Tiefe	17	16	17	19
Tümpel	23	24	22	0
Tunnel	18	18	19	18
Turm	17	17	18	17
U-Bahn	18	18	20	19
U-Boot	19	20	21	20
Ufo	20	21	24	24
Untergrund	21	20	22	24
Unterwelt	22	21	23	24
Vogel	16	15	17	18
Vogelnest	0	0	0	22
Weltall	18	18	22	19
Wolke	19	20	21	20
Wurm	19	18	21	22
Wurzel	18	17	21	21
Zeppelin	18	17	21	21

Appendix C

Mean word positions within sentences (sdewac-corpus).

Adler	4.37	Abgrund	4.23
Alpen	5.77	Boden	6.18
Ballon	1.29	Erde	6.01
Berg	8.44	Erdloch	0.26
Burg	10.31	Erdreich	1.49
Dach	9.75	Fluss	8.90
Dachbalken	0.11	Flussbett	0.37
Decke	8.30	Fuß	8.11
Drachen	5.46	Fußboden	2.16
Empore	0.63	Fußsohle	0.31
Falke	0.56	Gehweg	1.29
Flugzeug	10.03	Grab	8.29
Gebirge	3.90	Graben	4.57
Giebel	0.74	Gras	6.06
Gipfel	10.26	Gruft	0.95
Himmel	5.91	Hölle	10.42
Hochebene	0.67	Katakombe	0.11
Hochhaus	1.38	Keller	9.75
Hochland	1.39	Klee	1.44
Hochseil	0.07	Maulwurf	0.61
Hochsitz	0.22	Maus	7.75
Höhe	6.07	Pfütze	0.66
Höhepunkt	6.73	Schienen	7.40
Komet	0.68	Schlucht	2.05
Krone	7.12	Schotter	0.70
Mond	10.63	Sohle	0.91
Nest	3.86	Stein	7.45
Palme	1.49	Straße	6.44
Planet	3.55	Sumpf	2.40
Satellit	1.86	Taucher	1.15
Sonne	5.40	Teppich	4.36
Spitze	7.77	Tiefe	7.97
Stern	9.21	Tümpel	0.53
Turm	7.69	Tunnel	4.96
Ufo	1.57	Untergrundbahn	0.13
Vogel	9.17	Unterseeboot	0.10
Vogelnest	0.06	Untergrund	5.45
Weltall	2.53	Unterwelt	2.45
Wolke	3.12	Wurm	2.18
Zeppelin	0.99	Wurzel	5.23

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