Running Head: GRADED BRAIN RESPONSES TO REGULAR AND IRREGULAR INFLECTION

Continuous Processing of Linguistic Categories: Behavioral and Electrophysiological Responses to Regular and Irregular Verb Inflection in German

1Eva Smolka, 2Patrick Khader, 2Richard Wiese, 3Pienie Zwitserlood, and 2Frank Rösler

1University of Konstanz, Germany
2University of Marburg, Germany
3University of Münster, Germany

Correspondence to:
Eva Smolka
Department of Linguistics
University of Konstanz
78457 Konstanz
GERMANY
Email: eva.smolka@uni-konstanz.de
Phone: +49-7531-88 4834
Fax: +49-7531-88 4898
Abstract

This study examined whether German regular and irregular verb inflection is processed in continuous or categorical ways. Two visual priming experiments contrasted regular (regular stem, regular suffix) with two types of irregular participle formation (regular/irregular stem, irregular suffix). We measured reaction times (RT; Experiment 1) and event-related potentials (ERPs; Experiment 2) and manipulated both the inflectional relation and the meaning relation between primes and targets. Inflected verb targets (e.g., stöhne, ‘moan’) were preceded by themselves, by their participle (gestöhnt, ‘moaned’), by a semantically related verb in the same inflection (seufze, ‘sigh’) or in the participle form (geseufzt, ‘sighed’), and by an unrelated verb in the same inflection (blinke, ‘blink’) or in the participle form (geblinkt, ‘blinked’). The behavioral results showed no distinction between regular and irregular verbs as such, but rather a complex interaction of the factors frequency, meaning, and inflectional relation between primes and targets. The electrophysiological data showed that verb regularity gradually affected priming: regular participles produced a widely distributed frontal and parietal effect, irregular participles a small left parietal effect, with semi-irregular participles in between. The data thus provide evidence that the linguistic categories of verb inflection are not processed categorically but gradually. We present a single-system model that can adequately account for such graded effects.

Keywords: Event-related potentials; inflectional morphology, repetition priming, participle priming, semantic priming; word frequency, lexical retrieval
Continuous Processing of Linguistic Categories: Behavioral and Electrophysiological Responses to Regular and Irregular Inflection in German

Regular and irregular inflection has often been used to investigate how complex words are stored and processed in the mental lexicon. This study investigates whether the brain processes verbs with regular and irregular inflection in categorically distinct systems or within one and the same system.

In English, regularly inflected words, such as *walked*, are easily segregable into the stem (*walk*), which encodes the semantic properties of the verb, and the suffix (-*ed*) that entails the (syntactic) feature for past tense [+past]. Irregularly inflected words, such as *brought*, show no transparent distinction between stem and suffix.

First psycholinguistic evidence that English regular and irregular verbs are processed by two distinct systems was provided by Stanners, Neiser, Hernon, and Hall (1979). In a long-lag repetition-priming paradigm, they compared the influence of inflectional and derivational variations of a verb on its uninflected base form. The base was primed by regular past tense forms just as well as by identity primes. That is, *poured* primed *pour* to the same extent as *pour* primed *pour*. Irregular past tense forms also facilitated their base, such as *bend* priming *bent* or *shook* priming *shake*, but to a lesser extent than identical primes. Similar priming was observed for derivations: *predictable* primed *predict* and *retention* primed *retain*, but to a lesser extent than identical primes.

Stanners et al. (1979) drew a distinction between *full* and *partial* activation that a base may receive and inferred two different mechanisms. In the first system, only the base has a lexical entry, which is shared by all other regularly inflected forms. These are parsed into suffix and base prior to memory access, so that only the base is accessed. This produces *full* activation of the base when a regularly inflected form is encountered. The second system
comprises lexical entries of whole words, both for irregularly inflected forms and derivations. Even though these entries are stored separately, they are nevertheless tightly connected with their respective base, thus producing the partial activation of an irregular base when the past tense form is accessed.

Subsequent priming studies on English regular and irregular past tense forms mostly supported the assumption of two distinct systems: Regularly inflected verbs mostly induced full priming on their base forms (Fowler, Napps, & Feldman, 1985; Marslen-Wilson, 1999; Napps, 1989; Napps & Fowler, 1987), though partial priming was also found (Fowler et al., 1985). The picture was more inconsistent for irregular verbs: Full priming (Forster, Davis, Schoknecht, & Carter, 1987) was found alongside with partial priming (Napps, 1989) or no priming at all (Marslen-Wilson, 1999).

Contrastive data on regular and irregular inflection were in line with Chomsky’s (1970) lexicalist hypothesis, which distinguishes between universal and language-specific (phrase structure and transformational) rules, and information in the lexicon. The psycholinguistic implementation of this hypothesis takes the form of so-called “dual-mechanism” models. As the name indicates, these assume two innately distinct systems, each incorporating a different processing style: the default system parses regular forms into their constituent morphemes, whereas the memory system stores and retrieves all exceptions to the default as undecomposed whole words. A major assumption of dual-mechanism models is that regular and irregular verbs are processed by these two independent systems. Hence, the different processing characteristics of the two systems should be reflected in different performance patterns between regular and irregular verbs (e.g., Clahsen, 1999; Pinker, 1998; Pinker & Ullman, 2002; Prasada & Pinker, 1993; Ullman, 2001). Note that in these models, membership to one of the systems is an all-or-none matter. Hence, regularly inflected forms
Graded Brain Responses to Regular and Irregular Inflection

(e.g., *brings* or *bringing*) of verbs with additional irregularly inflected forms, such as *brought*, must necessarily be handled by the same storage system.

A more recent dual-system model (Marslen-Wilson & Tyler, 1998, 2007; Post, Marslen-Wilson, Randall, & Tyler, 2008) differentiates between regular and irregular inflection on the basis of morpho-phonological differences. It is structurally similar to the dual-mechanism model in assuming two distinct (though interdependent) systems, but does not specify how inputs will map onto these two systems in terms of regularity or irregularity per se, but rather in terms of the presence or absence of overt inflectional morphemes. Words that show the English inflectional rhyme pattern (i.e. voice agreement between a word-final coronal consonant and the preceding segment, like words ending in /st/ or /zd/) are automatically segmented into stem and affixes, whereas words without this pattern are directly mapped onto a lexical representation. On this account, English regulars and irregulars are processed differently, because the irregular forms are not morpho-phonologically complex. The prediction for German regular and irregular forms is that they be processed similarly, because both undergo similar affixation processes (see below).

Because most repetition-priming studies (e.g., Fowler et al., 1985; Marslen-Wilson, 1999; Napps, 1989; Napps & Fowler, 1987; Forster et al., 1987) were conducted in English, several factors concerning the structure of inflected morphology were confounded, such as stem preservation and suffixation. For example, English sound and spelling changes of the stem occur only for irregular past-tense forms. In contrast, suffixation with *-ed* exists only for regular verbs, while irregular past-tense forms are often not suffixed at all (for type frequencies see Table 3 in Marcus, Brinkmann, Clahsen, Wiese, & Pinker, 1995).
German Participle Formation

The German participle system is particularly apt to disentangle stem preservation and suffixation. With regard to affixation, the participle formation follows a complex but systematic pattern: all participles consist of the prefix ge-, a stem, and either the suffix -\( t \) or -\( en \) (Table 1).

The participle stem is either identical to the infinitive stem, or changes the stressed vowel, sometimes accompanied by a consonant change (for a description of these vowel changes see Wiese, 1996a). Both types of stems (infinitive/vowel change) combine with both suffixes (-\( t \)/-\( en \)), so that all possible stem and suffix combinations are found in German (see Table 1). Most importantly, the surface form of a verb does not allow a prediction as to whether or not a stem undergoes a vowel change (and which), or whether -\( t \) or -\( en \) is suffixed.

Given that (a) the infinitival stem is the most frequent stem, (b) the -\( t \) suffix is more frequent than the -\( en \) suffix, and (c) the combination of the two (infinitival stem/-\( t \) suffix) is the most frequent one, as indicated by the type count in Table 1, we label it as ‘regular’, and the other combinations as ‘irregular 1’, ‘irregular 2’, or ‘irregular 3’ verbs according to the labels used in Smolka, Zwitserlood, and Rösler (2007). The label ‘regular’, although motivated differently, coincides with the label ‘default’ in dual-mechanism accounts (Clahsen, 1999; Marcus et al., 1995; Wunderlich & Fabri, 1995). The high type-frequency of the regular combination results from the fact that it is productive and may be applied in ‘elsewhere’ conditions: New verbs (e.g., *simsen*, ‘send an SMS’), denominal verbs (e.g., *filmen*, ‘film’ v., from *Film*, ‘film’ n.), and derived verbs (e.g., *rebellieren*, ‘rebel’ v., from *Rebell*, ‘rebel’ n.) are formed productively in this group. Moreover, low-frequency irregular
participles are regularized into this type (e.g., *geschwollen*, ‘swollen’, resulting in *geschwellt*).

To summarize, the German participle formation is completely systematic regarding its affixation, which may suggest similar storage and processing mechanisms for regular and irregular verb types.

The empirical evidence, however, does not provide a unitary picture. For a long time, a single cross-modal priming experiment on German participles has provided crucial support for the dual-mechanism account. Sonnenstuhl, Eisenbeiss, and Clahsen (1999) compared ‘regular’ and ‘irregular 1’ verbs, which both keep the infinitival stem unchanged. Targets were inflected verbs in the first person singular present (stem + -e suffix; e.g., *warne*, ‘warn’). These were preceded either by themselves (identical prime; *warne*, ‘warn’), by their participle (participle prime; *gewarnt*, ‘warned’), or by an unrelated verb that was also inflected in the first person singular (unrelated prime; *zeichne*, ‘draw’). Results showed the critical regularity by prime type interaction: Regular participles yielded the same amount of priming as identical primes, whereas irregular participles yielded priming less than identical primes. Following the logic of Stanners et al. (1979), the authors concluded that regularly inflected forms are accessed by their base (which is identical, thus producing equivalent facilitation), whereas irregularly inflected forms possess separate lexical entries (thus producing only partial priming effects). Hence, these results were interpreted to support the dual-mechanism account (as put forth by Clahsen, 1999; Pinker, 1998), which has a default system for regular verbs and a storage system for irregular verbs.

However, more recent studies on German participles provide evidence against two distinct processing systems for regular-irregular participles. First, Smolka et al. (2007) demonstrated identical facilitation regular participles and their base (*gekauft*, ‘bought’ – *kaufen*, ‘buy’; 54 ms) as for irregular participles and their base (*gesponnen*, ‘spun’ – *spinnen*,
‘spin’; 52 ms), when priming was measured relative to regular and irregular control participles (e.g., geprüft, ‘controlled’; gepriesen, ‘praised’). To avoid any confounding effects, test and control participles were meticulously matched on participle surface frequency, lemma frequency, number of letters, syllables, neighbors, inflection as well as suffix type.

Second, Smolka, Zwitserlood, Wiese, Marslen-Wilson, and Rösler (2009) demonstrated that whether or not regular participles produce full or partial priming (relative to identical primes) depends on the surface frequency of the participles: infrequent participles yielded full priming, while frequent participles produced partial priming. Given that the infrequent set corresponded to the regular participles employed by Sonnenstuhl et al. (1999), we were able to replicate the interaction between verb regularity and priming pattern (full/partial).

Experiment 1

In this paper, we tested whether linguistic categories of verb regularity are processed categorically, that is, in distinct brain systems—as assumed by dual-mechanism models—or continuously within the same system—as assumed by Smolka et al. (2007) or by connectionist network models (e.g., Joanisse & Seidenberg, 1999; Plaut & Gonnerman, 2000; Plunkett & Juola, 2001; Seidenberg & Arnoldussen, 2003). To test the dual/single system account, we complemented the variables from earlier studies with new ones, concerning verb properties, prime and baseline conditions. These extensions are spelled out below, citing evidence and hypotheses where relevant.

Verb regularity. Dual-mechanism models maintain a dichotomous differentiation between a regular and an irregular system—indeed the “amount of irregularity”. The models thus predict an interaction between verb regularity and priming pattern. Since regular
participles are parsed and accessed via their stem, they should yield full priming. In contrast, all types of irregular participles are retrieved as whole words and should thus produce partial priming to their base. A dual-mechanism model assumes a strict dichotomy between regular and irregular verbs: subgroups of irregulars should behave like a homogeneous group when contrasted with regular types.

In contrast, Wiese (1999) argued that a dichotomy between ‘regular’ and ‘irregular’ may be too simple. Partial regularities exist alongside true irregularities, necessitating a distinction between ‘irregular’, ‘subregular’, and ‘default’ (presupposing ‘default’ as equal to ‘regular’). In fact, more recently, even proponents of dual-mechanism models suggested that irregular forms may be parsed, if the suffix is regular (e.g., Clahsen, Prüfert, Eisenbeiss, & Cholin, 2002). Accordingly, irregular past tense forms that take the regular past tense suffix (see Table 1) are assumed to be parsed just like participles that take the ‘regular’ -t suffix. In contrast, participles that take the ‘irregular’ -en suffix are expected to be retrieved as whole word units, regardless of their stem.

Previous studies contrasted regular participles with either ‘irregular 1’ (Sonnenstuhl et al., 1999) or ‘irregular 2’ (Smolka et al., 2007) participles, both with the critical –en suffix. In the present study, we contrasted ‘regular’ participles with both ‘irregular 1’ and ‘irregular 2’ participles. By comparing all three possibilities along the gradient of verb regularity, we will assess whether there are more differentiated patterns ranging from completely regular to completely irregular.

Participle frequency. According to the dual-mechanism model, regularly inflected forms are parsed into base and affixes, so that the lexical storage system for regular forms contains only the base forms. Hence, only the base frequency, but not the surface frequency of the whole word, should influence the processing of regular inflection.
However, Baayen, Dijkstra, and Schreuder (1997) have shown that even regular words may be stored as whole word units if they are of high frequency. Indeed, in Smolka, Zwitserlood et al. (2009), we manipulated the surface frequency of regular participles while keeping the lemma frequency constant. Participles in the frequent set produced *partial* priming on their inflected verb targets, indicating that frequent regular participles may be stored as whole words in an associative network. Participles in the infrequent set yielded *full* priming, indicating that these are parsed into constituents. Most importantly, this demonstrated that the surface frequency of participles determines whether or not the participles induce *full or partial* priming. Hence, in the present study, we included such a frequency manipulation for all verb types.

*Semantic effects.* Dual-mechanism accounts (e.g., Clahsen, 1999; Ullman, 2001) assume that irregular participles have their own representations in associative memory, whereas all regular inflections share one lexical representation – and one lexical entry. Facilitation of bases by their irregular participles is assumed to be due to spreading activation between related entries in associative memory, rather than in a lexical network. In the present study we included semantically associated primes in addition to the participle primes to address the question whether the priming by irregular participles indeed resembles that by semantically associated entries.

Semantic priming has often been tested using associated pairs such as *black* and *white* (e.g., Napps, 1989, Exp. 3), which are different in many respects from the verbs used in morphologically relevant conditions. To provide a direct comparison of participle and semantic priming, each target (e.g., *kaufe*, ‘buy’) was combined with its participle (*gekauft*, ‘bought’) and with a semantically associated prime in participle form (*gezahlt*, ‘paid’). Only verbs were used. In addition, as with the morphological primes, semantically associated
Graded Brain Responses to Regular and Irregular Inflection

Primes were also presented in the same person inflection as the target (e.g., *zahle*, ‘pay’); see conditions S and SP, respectively, in Table 2.

Table 2 about here

Traditional comparisons and new baseline. To allow for a direct comparison with previous studies, we employed the same prime conditions as in Smolka, Zwitserlood et al. (2009) and Sonnenstuhl et al. (1999): inflected targets were preceded either by themselves (identity prime, I), by their own participle (participle prime, P), or by an unrelated verb in the same inflection as the target (unrelated prime, U).

Repetition-priming studies (e.g., Smolka, Zwitserlood et al., 2009; Sonnenstuhl et al., 1999; Stanners et al., 1979) typically compare both the identity condition (I: *walks - walks*) and the relevant morphological condition (the participle prime in our study: P, *walked - walks*) with the same unrelated condition (U: *shouts - walks*). Thus, the inflection of prime and target is the same in the identity and the unrelated conditions, so that this comparison measures a difference in semantic relatedness. By contrast, the inflectional form between prime and target differs in the participle condition, so that the comparison between the unrelated and the participle condition involves two dimensions: (a) semantic relatedness and (b) inflectional relatedness, thus confounding semantic and inflectional relatedness between prime and target. For this reason, we introduced an ‘unrelated participle’ condition (UP: *shared - walks*) as additional baseline in the behavioral experiment (Experiment 1). All prime conditions are listed in Table 2. Conditions I, P, and U are the same as those used in Smolka, Zwitserlood et al. (2009) and Sonnenstuhl et al. (1999).

To summarize, we carried out a visual priming experiment to examine whether verb regularity in German is processed categorically or continuously. In particular, we investigated
the influence of the factors participle frequency, semantic relatedness, and inflectional relatedness on the storage and processing of inflected verbs in German.

A dual-mechanism account predicts an interaction between verb regularity and priming pattern. That is, regular participles should yield *full* priming, whereas irregular participles should produce *partial* priming on inflected targets. Moreover, the priming patterns of the irregular subgroups (‘irregular 1’ and ‘irregular 2’) should be homogeneous, and different from those of regular verbs.

A dual-mechanism account predicts an interaction between verb regularity, inflectional form, and participle frequency. Regular participles should yield *full* priming (i.e., equivalent participle and identity priming), regardless of frequency, whereas the participle priming of irregular verbs should be *partial* (i.e., less than identity priming) and frequency-dependent (e.g., Ullman, 2001). Finally, if irregularly inflected forms are indeed stored and retrieved from associative memory (Pinker & Ullman, 2002), priming patterns of irregular participles should resemble those of semantically associated verbs.

To anticipate the results, Experiment 1 showed no distinction between regular and irregular verbs as such, but rather a complex interaction of the factors frequency, meaning, and inflectional relation between primes and targets.

*Methods Experiment 1*

*Participants*

Twenty-one students at Marburg University participated and were paid for their participation. All were monolingual native speakers of German. They were not dyslexic and had normal or corrected-to-normal vision.
Materials

Verb stimuli. The material consisted of 132 German monomorphemic verbs. Half of the verbs were ‘regular’, the other half irregular. Of the irregular verbs, 22 were of the ‘irregular 1’ type (infinitive stem/-en suffix) and 44 of the ‘irregular 2’ type (vowel change/-en suffix; see Table 1). To avoid any confusion with the participle prefix ge-, none of the verbs began with the letters ge- in the infinitive.

Stimuli were matched on participle frequency (PF; CELEX, Baayen et al., 1993), which varied within verb types. Half of the ‘regular’ verbs had frequent participles (PF = 36.7), the other half infrequent participles (PF = 1.8). Similarly, half of the ‘irregular 2’ verbs had frequent, the other half infrequent participles (PF = 48.4, and PF = 1.3, respectively). Because ‘irregular 1’ verbs are mostly high-frequency verbs, and because lemma and participle frequency are correlated, 13 out of 22 had frequent participles (PF = 53.6), while nine had relatively infrequent participles (PF = 2.4).

Target inflection was varied between the first person (stem/-e suffix) and the second person (stem/-st suffix), occurring about equally often within each verb set. However, in the interest of clarity, potential homographs to nouns (e.g., folge, ‘I follow’, vs. Folge, ‘sequence’, n.) were always used in the second person, as the -st suffix does not occur in noun inflection.

Each verb target was combined with six primes, resulting in 792 prime-target pairs. Prime-target relations were defined by two factors: inflectional and semantic relatedness (see also Tab. 2). Primes and targets were either presented in the same inflection (both verbs in either first or second person) or in a different inflection (participle prime combined with first- or second-person target). Semantic relatedness was varied by using (a) unrelated, (b) semantically associated, and (c) identical primes, with identical primes representing the strongest possible semantic relatedness.
Semantic association test. A semantic association test was conducted to establish the relatedness between primes and targets for the semantically related and unrelated prime conditions. For each of the 132 verb targets, the selected semantically related and unrelated verbs were distributed across two lists, so that each list contained only one prime for the same target verb. The verb intended as the prime preceded the target, and both were presented in citation form (stem/-en). Thirty-four participants who did not take part in the experiments proper rated the relationship between the verbs of each pair on a 7-point scale from completely unrelated (1) to highly related (7). Mean ratings were 5.8 for semantically related pairs and 1.7 for unrelated pairs for regular verbs with frequent participles, and 6.1 and 1.6, for regular verbs with infrequent participles. For irregular verbs with frequent participles, mean ratings were 6.0 for semantically related and 1.5 for unrelated pairs, and for the ones with infrequent participles, this was 5.9 and 1.3. A 2 x 2 x 2 ANOVA with between-items factors verb regularity (regular/irregular) and participle frequency (high/low), and relatedness (semantic/unrelated) as repeated measures factor was run on mean ratings. No effects were significant besides the main effect of relatedness, $F(1, 128) = 2732.03, p < .0001$, which was also highly significant when calculated separately for regular and irregular verbs, $F(1, 64) = 1097.12, p < .0001$ and $F(1, 64) = 1762.89, p < .0001$, respectively, and indicated that the ratings were significantly higher for semantically associated than for unrelated verbs.

Because no more than roughly 200 high-frequency verbs exist, semantic and unrelated primes could not be fully matched to the high-frequency verb sets. Hence, the frequencies of the unrelated primes (and their participles) were matched to those of the semantic primes (and their participles).

Pseudoverb stimuli. A total of 792 prime-target pairs had words as primes and pseudoverbs as targets. Pseudoverb targets were constructed by exchanging one or two letters in real verbs, while preserving the phonotactic constraints of German. As with the verb
targets, half of the pseudoverb targets were presented in the first-, and the other half in the second-person inflection. Primes for pseudoverb targets were 396 monomorphemic verbs, each used once in the participle form, and once with a person inflection that corresponded to that of the pseudoverb target. Twelve primes were ‘irregular 3’ verbs and 47 were ‘irregular 1’ or ‘irregular 2’ verbs; 69 had prefixes.

*Fillers.* To avoid that participants were exposed to verbs only, 480 prime-target pairs with nouns as primes were included as fillers. Of these, 240 pairs had nouns and 240 had pseudonouns as targets. The pseudonouns were constructed similarly to the pseudoverbs.

*Apparatus*

Stimuli were presented on a 17” monitor, connected to an IBM-compatible Pentium III personal computer. Response latencies were recorded from the left and right ‘control’ keyboard keys.

*Procedure*

Each participant saw all 132 verbs in all six prime conditions. Primes were rotated over six blocks according to a Latin Square design, with one of the six prime-target combinations in each block, and each block containing equal numbers of stimuli in each condition. The 792 prime-target pairs using pseudoverbs were allocated to the blocks in such a way that the two prime versions of the same verb appeared in different blocks. The fillers were allocated to the blocks accordingly. In total, an experimental session comprised 2064 prime-target pairs presented in six experimental blocks, with 344 prime-target pairs per block. Within blocks, prime-target pairs were randomized separately for each participant. There were 16 practice trials.

Participants were tested individually, seated at a viewing distance of about 60 cm from the screen. Stimuli were presented in the center of the screen, in white Sans Serif letters,
point 20, on a black background. Primes were presented in uppercase letters, targets in lowercase. Each trial started with a fixation cross in the center of the screen for 1000 ms. The prime was then presented for 50 ms, followed by an offset (blank screen) for 40 ms, resulting in an SOA of 90 ms. Then the target appeared for 500 ms, followed by a blank screen. The intertrial interval was 2000 ms.

Participants made lexical decisions to the targets, as fast and as accurately as possible. ‘Word’ responses were given with the index finger of the dominant hand, ‘pseudoword’ responses with the subordinate hand. The experiment lasted for about two hours. Participants self-administered the breaks between blocks, and were asked to take at least three longer breaks.

Results Experiment 1

One verb was excluded from analyses due to incorrect coding. Means over word and nonword responses were calculated separately, and RTs exceeding 2.5 standard deviations from a participant’s mean were excluded. One participant whose error rates (17%) exceeded three standard deviations of the overall error mean (3.5%) was removed, so that the data of 20 participants were included in the analyses. There was no speed-accuracy trade-off (RT and error means over participants were not correlated, $r = -.11171, p = .6392$).

Analyses were performed on response-time and accuracy data with participants ($F_1$) and items ($F_2$) as random variables. In the participant analyses ($F_1$), all variables were treated as repeated measures factors; in the item analyses ($F_2$), the variables regularity and participle frequency were treated as between-items factors, and the variables inflection and relatedness as repeated measures factors.

The data analyses will be reported in the following order: First, an ‘overall analysis’ with all factors and levels of factors is presented to give an overview of the data. This
analysis is crucial to demonstrate the complex interactions of variables and indicates that regularity must not be considered as single factor. We then analyze the data according to our experimental questions. The morphological analyses examine (1) whether regular and irregular verbs show different participle-priming effects, (2) whether participle frequency affects participle priming of regular and irregular verbs in different ways, and (3) whether irregular subgroups behave as a homogenous group that contrasts with regular verbs. The semantic analyses assess whether facilitation by regular or irregular participles can be reduced to semantic effects.

**Overall analyses**

In the first analyses, regular verbs were contrasted with subgroups ‘irregular 1’ and ‘irregular 2’, lumped together as irregular verbs. A 2 x 3 x 2 x 2 ANOVA was run on mean RTs and errors with factors verb regularity (regular/irregular), relatedness (identical/semantic/unrelated), inflection (same/different), and participle frequency (high/low). RT and error means are provided in Table 3, the significant effects in Table 4.

Most importantly, the four-way interaction between relatedness, participle frequency, regularity, and inflection was significant in the analysis by participants, $F_1(2, 38) = 7.16$, $p = .0023$, and approached significance in the analysis by items, $F_2(2, 254) = 2.62$, $p = .0750$. This interaction is depicted in Figure 1. It shows that response patterns are strongly dominated by participle frequency, with similar patterns within and differing patterns across the frequency classes:

Verbs with infrequent participles are strongly affected by the relatedness between prime and target: fastest responses for identical stems, intermediate responses for
semantically associated verbs, and slowest responses for unrelated verbs. However, these verbs are not affected by the inflection of the prime (whether the prime is a participle or whether it shares the same inflection as the target). Most importantly, the response patterns are the same for regular and irregular verbs.

In contrast, verbs with frequent participles are neither affected by relatedness nor by inflection, unless prime and target share the identical stem. Regular frequent-participle verbs are facilitated by the identical stem, whether or not prime and target share the same inflection (i.e., by both identity and participle primes), whereas irregular frequent-participle verbs are strongly facilitated only if prime and target share both meaning and inflection (i.e., by identity primes).

Morphological analyses

For the morphological analyses, difference scores for both response measures were calculated for regular and irregular verbs of the two participle-frequency sets. For each subject, participle priming was calculated by subtracting the mean of the participle condition from that of the unrelated participle condition (UP – P). Identity priming was calculated by subtracting the mean of the identity condition from that of the unrelated (same inflection) condition (U – I). These difference scores were entered in three-way ANOVAs, with factors regularity (regular/irregular), participle frequency (high/low), and prime type (identical/participle). In the following, the data will be reported according to our experimental questions. Given that response accuracy did not reveal any significant effects, only effects with response latency will be reported.
Is participle priming different for regular and irregular verbs? The main effect of regularity was significant, $F_1(1, 19) = 15.73, p = .0008; F_2(1, 127) = 7.56, p = .0069$, indicating overall more priming for regular (51 ms) than for irregular verbs (35 ms). The main effect of prime type, $F_1(1, 19) = 13.40, p = .0017; F_2(1, 127) = 5.02, p = .0268$, indicated that identical primes (53 ms) had a stronger impact than participle primes (33 ms). However, in contrast to the predictions of a dual-mechanism account, the interaction between regularity and prime type was not significant ($F_1$ and $F_2 < 1$). Both regular and irregular verbs showed stronger identity priming than participle priming (regular: 61 ms vs. 42 ms; irregular: 46 ms vs. 24 ms, respectively).

Is participle priming affected by frequency? The highly significant main effect of participle frequency, $F_1(1, 19) = 25.80, p < .0001; F_2(1, 127) = 16.56, p < .0001$, demonstrated an overall difference in priming between the two frequency sets (infrequent participle set: 57 ms; frequent participle set: 26 ms). The three-way interaction between regularity, prime type, and participle frequency, $F_1(1, 19) = 12.30, p = .0024; F_2(1, 127) = 4.33, p = .0394$, indicated that the priming patterns of both verb types were strongly affected by participle frequency, though in different ways. Figure 2 depicts this interaction.

Irregular verbs were affected by participle frequency, $F_1(1, 19) = 17.41, p = .0005; F_2(1, 63) = 7.40, p = .0084$, and demonstrated a significant interaction between prime type and participle frequency, $F_1(1, 19) = 7.64, p = .0123; F_2(1, 63) = 3.77, p = .0566$. While there was no participle priming at all for frequent verbs (-1 ms; thus producing a significant difference relative to the identical condition, 41 ms, $F_1(1, 19) = 15.20, p = .0010; F_2(1, 34) = 8.01, p = .0078$), infrequent participles (48 ms) yielded full priming, that is, equivalent to identical primes (51 ms; $F_1$ and $F_2 < 1$).

Regular verbs also showed a strong participle-frequency effect, $F_1(1, 19) = 12.25, p = .0024; F_2(1, 64) = 9.19, p = .0035$, as well as a significant interaction with prime type in the
analysis by participants, $F_1(1, 19) = 4.59, p = .0454; F_2 < 1$. Frequent participles (34 ms) and identical primes (40 ms) induced statistically equivalent effects ($F_1$ and $F_2 < 1$), thus yielding full priming. Infrequent participles produced a smaller effect (49 ms) than identical primes (82 ms), a difference that was significant by participants, and marginally significant by items, $F_1(1, 19) = 15.21, p = .0010; F_2(1, 32) = 3.20, p = .0830$.

Do the irregular subgroups behave as a homogeneous group? Difference scores to measure identity ($U – I$) and participle ($UP – P$) priming were calculated separately for ‘regular’, ‘irregular 1’, and ‘irregular 2’ verbs in the two participle-frequency conditions. The difference scores were entered in three-way ANOVAs with factors regularity (‘regular’/‘irregular 1’/‘irregular 2’), participle frequency (high/low), and prime type (identical/participle).

The interaction between regularity, prime type, and participle frequency was only marginally significant in the analysis by participants, $F_1(2, 38) = 2.99, p = .0624; F_2(2, 125) = 2.30, p = .1046$. Further analyses specified why: Regularity interacted with prime type and participle frequency in the pair-wise analyses of ‘regular’ and ‘irregular 2’ verbs, $F_1(1, 19) = 12.87, p = .0020; F_2(1, 105) = 4.81, p = .0304$, but neither in the pair-wise analyses of ‘regular’ and ‘irregular 1’ verbs, $F_1(1, 19) = 1.48, p = .2388; F_2 < 1$, nor in the analyses of ‘irregular 1’ and ‘irregular 2’ verbs ($F_1$ and $F_2 < 1$). Figure 3 illustrates the hybrid priming pattern of ‘irregular 1’ verbs: for sets with frequent participles, the priming patterns of ‘irregular 1’ verbs are similar to those of ‘irregular 2’ verbs, while for sets with infrequent participles, ‘irregular 1’ verbs show similar priming patterns to those of ‘regular’ verbs.
The participle-priming effects may thus be summarized as follows: ‘irregular 2’ verbs show full priming for infrequent participles and no priming at all for frequent participles; ‘regular’ verbs show the reverse pattern, that is, full priming for frequent participles and partial priming for infrequent participles; and ‘irregular 1’ verbs show a mixture of these types: no priming at all for frequent participles (like ‘irregular 2’ verbs) and partial priming for infrequent participles (like ‘regular’ verbs).

**Semantic analyses**

*Is participle priming different from semantic priming?* To contrast participle with semantic priming, we calculated the interaction \((P – I) (SP – S)\), which tests the null hypothesis that the differences \((P – I)\) and \((SP – S)\) are the same. In terms of semantic and inflectional relatedness, the interaction \((P – I) (SP – S)\) corresponds to (same meaning/different inflection – same meaning/same inflection) by (different meaning/different inflection – different meaning/same inflection). That is, both differences denote the influence of the participle inflection, once when prime and target share their meaning \((P – I)\), and once when prime and target are semantically related \((SP – S)\). Difference scores were calculated for regular and irregular verbs, for the frequent and infrequent participle sets. Three-way ANOVAs with regularity (regular/irregular), participle frequency (high/low), and relatedness (identity/semantic) were conducted on the difference scores.

Relatedness was significant in the analysis by participants, \(F_1(1, 19) = 9.56, p = .0060; F_2(1, 127) = 2.51, p = .1158\), indicating that \((P – I)\) indeed differs from \((SP – S)\). Both effects were significantly different from zero, \(P – I\): 24 ms, \(t_1(79) = 6.83, p < .0001; t_2(130) = 4.56, p < .0001\); \(SP – S\): 10 ms, \(t_1(79) = 2.91, p = .0047; t_2(130) = 2.17, p = .0321\).

Also, the interaction with participle frequency was significant in the analysis by participants, \(F_1(1, 19) = 4.77, p = .0418; F_2(1, 127) = 1.17, p = .2814\). It is depicted in Figure
4. The effect $P - I$ was significantly different from zero, both for the frequent (31 ms), $t_1(39) = 5.42, p < .0001; t_2(67) = 4.44, p < .0001$, and infrequent participles (17 ms), $t_1(39) = 4.36, p < .0001; t_2(62) = 2.06, p = .0438$). The effect $SP - S$ was significant only in the analysis by participants: frequent participles (9 ms), $t_1(39) = 2.19, p = .0347; t_2(67) = 1.52, p = .1328$; infrequent participles (10 ms), $t_1(39) = 1.95, p = .0583; t_2(62) = 1.53, p = .1305$. Most importantly, the interaction with regularity was not significant, indicating that participle priming ($P - I$) differs from semantic priming ($SP - S$) for both regular and irregular verbs.

Interim Discussion

In Experiment 1, we examined whether the factors participle frequency, semantic relatedness and inflectional similarity between primes and targets differently affect the priming patterns of regular and irregular verbs. The overall analyses showed that, on the whole, these factors affect regular and irregular verbs similarly. Only the fourth-order interaction between regularity, participle frequency, semantic relatedness, and inflectional form indicated differential patterns between regular and irregular verbs. Regular and irregular verbs show similar patterns when their participles are infrequent: Responses are mostly influenced by the semantic relatedness, but not by the inflectional similarity, between prime and target. Frequent-participle verbs are only facilitated if prime and target are morphologically related. Most importantly, regular and irregular verbs differ in the following aspect: while irregular verbs are facilitated only if prime and target share both meaning and inflection, that is, by identical primes, regular verbs are facilitated regardless of inflectional similarity, that is, by both identical and participle primes.
This four-way interaction, together with the two-way interactions with semantic relatedness thus suggests that the distinction between semantic and inflectional relatedness of primes and targets is not trivial. To the contrary, any regularity effect turns out to be a combinatorial result of the interacting factors of semantic relatedness, inflectional similarity, and participle frequency. We will provide a detailed discussion on how these factors interact together with the discussion of the electrophysiological results after presenting Experiment 2.

Electrophysiological Evidence for Processing Differences between Regular and Irregular Verbs

Experiment 2 examined whether the graded effects found in Experiment 1 can be substantiated by means of event-related brain potentials. Neural correlates of morphological differences between regular and irregular verbs come from data from aphasic patients (e.g., Marslen-Wilson & Tyler, 1998, 2007; Ullman et al., 1997; Ullman et al., 2005) from brain-imaging studies (for a short review see Lavric, Pizzagalli, Forstmeier, & Rippon, 2001) using PET (Jaeger et al., 1996) and event-related fMRI (Beretta et al., 2003; for different findings see Sach, Seitz, & Indefrey, 2004). Ullman and colleagues (Ullman, 2001; Ullman et al., 1997, 2005) postulated that the two systems of dual-mechanism models are implemented in different brain areas. The default system corresponds to a procedural system in left-frontal structures (including Broca’s area and left basal ganglia), involved in the parsing of regular inflection. The lexical storage of irregular word forms is part of the declarative-memory system in left temporal/temporo-parietal structures.

Another dual-system/dual-process type of model, developed by Marslen-Wilson, Tyler, and colleagues (e.g., Marslen-Wilson & Tyler, 1998, 2007), argues that a specific left-hemispheric neural system supports processes of regular inflectional morphology, while whole-form and stem-based access processes have a broader bi-hemispheric substrate. In
contrast to the dual-mechanism account, the morpho-phonological account assumes that the two systems are driven by the presence or absence of overt inflectional morphemes. Morpho-phonologically complex forms trigger automatic segmentation, whereas morpho-phonologically simple forms are directly mapped onto their lexical representation. On this account, English regulars and irregulars will be processed by different systems, due their difference in morpho-phonological complexity, whereas German regular and irregular participles should be processed by the same system, because they are both decomposable into stems plus inflectional affixes. These inflectional affixes should, on the Marslen-Wilson and Tyler (2007) model, obligatorily engage the same left hemisphere systems specialized in parsing overt inflectional complexity (see also Post et al., 2008).

Patient and fMRI studies may provide functional and topographic dissociations between regular and irregular verbs. In addition to these, event-related potentials (ERP) provide an excellent temporal processing resolution. Furthermore, certain ERP-components are associated with linguistic processes, so that these components may be used as ‘marker’ for certain linguistic processes. The dual-mechanism model of Ullman and colleagues assumes that regular forms are parsed in frontal areas, whereas irregular forms are retrieved from declarative memory in parietal areas. Mapping the parsing and retrieval processes onto ERP components, parsing processes of regular inflections should be reflected in left anterior negativities (LAN; e.g., Krott, Baayen, & Hagoort, 2006), whereas the retrieval of irregular forms should be reflected in centro-parietal negativities that peak around 400 ms after target onset (N400; e.g., Bentin, McCarthy, & Wood, 1985; for an overview of language-related ERP components, see Kutas & Federmeier, 2007). However, findings on morphological processing by ERPs are far from unequivocal and have not yielded specific ERP effects. Regarding regular and irregular inflection, most studies that interpreted their findings in light of a dual-mechanism model indeed observed a processing dissociation between regularly and
irregularly inflected forms. However, other than postulating a difference, the ERP effects found did not always correspond to the predictions put forth by a dual-mechanism account. To illustrate cases in point, we will briefly review the ERP data on verb inflection in the two main paradigms: Violation and priming/repetition paradigms.

Violation paradigms

Several distinct effects surfaced when verb inflections were studied by means of violation paradigms, ranging from null effects, to LAN, left (but not anterior) negativities, right anterior positivities, N400, as well as P600 effects.

For example, Allen, Badecker, and Osterhout (2003) examined incorrect past-tense use of regular and irregular English verbs in sentence context (e.g., The man will work/*worked on the platform vs. The man will stand/*stood on the platform). The grammatical violations showed up in form of P600 effects for both regular and irregular verbs. Surface-frequency effects were found for regular and irregular verbs, in form of N400 modulations, and frequency interacted with regularity and grammaticality, with a later onset of the grammaticality effect for regular than for irregular verbs. The authors concluded that this was the result of a computationally demanding parsing process for regular verbs, where the suffix independently encodes tense information in addition to the lexical meaning information provided by the stem. Newman, Ullman, Pancheva, Waligura, and Neville (2007) used a similar design and presented uninflected regular or irregular verbs in sentence contexts that required past-tense forms (e.g., Yesterday I frowned/*frown at Billy vs. Yesterday I grind/*grind up coffee). Relative to correct verb forms, regular violations elicited a left anterior negativity between 300 and 500 ms, and irregular violations produced a left posterior negativity. Both violations elicited later positivities (P600) that were similar in time course and scalp distribution. In spite of non-significant interactions between regularity and violation
in any of the regions of interest, the authors interpreted the LAN effect for regular (but not for irregular) violations to indicate “the existence of at least partially distinct neurocognitive processes in the processing of the two verb types” (Newman et al., 2007, p. 441).

A different type of violation concerns incorrect combinations of stems and suffixes, embedded in sentences. Penke, Weyerts, Gross, Zander, Münte, and Clahsen (1997) examined the incorrect application of either the regular (default) participle suffix -t or the irregular suffix -en to verb stems in German. When the default suffix -t was incorrectly applied to ‘irregular 1’ participles, such as *aufgeladet, a LAN effect was measured relative to the correct form aufgeladen (‘loaded on’). In contrast, no effects were found when the irregular -en suffix was incorrectly applied to default participles, *durchgetanzen, as compared to their correct form, durchgetanzt (‘danced through’). The authors interpreted the LAN effect to indicate that participles with the default suffix -t are decomposed into stem and affix, and the null effect for the overapplication of the irregular suffix -en as indication that irregular participles are stored in memory as whole words. However, since incorrect forms like *durchgetanzen cannot be assumed to be stored in memory, it is not clear why no brain response whatsoever should occur.

A similar violation design was applied to Italian participle formation (Gross, Say, Kleingers, Clahsen, & Münte, 1998), comparing default participles of 1st conjugation verbs (parl-a-to, theme vowel -a-, affix -t) with regular participles of 3rd conjugation verbs (dorm-i-to, theme vowel -i-, affix -t) and irregular participles of 2nd conjugation verbs (preso, no theme vowel, no suffix). The overapplication of the default theme vowel -a- and the -t suffix to irregular 2nd conjugation verbs (*prend-a-to) induced a widespread N400 (lateralized to the right temporal region). However, no effect at all was found for the overapplication of theme vowel -a- to regular 3rd conjugation participles (*dorm-a-to). Contrary to the authors’ expectations, the incorrect application of the theme vowel -i- to default participles (*parl-i-
to) also induced a right anterior negativity at temporal sites as compared to their correct forms.

Finally, in Catalan (Rodriguez-Fornells, Clahsen, Lleo, Zaake, & Münte, 2001), default formation of 1st conjugation participles (cant-a-t, theme vowel -a-, suffix -t) was compared with regular participle formation of 2nd (tem-u-t, theme vowel -u-, suffix -t), and 3rd (dorm-i-t, theme vowel -i-, suffix -t) verb conjugations and irregular 2nd conjugation (admes, no theme vowel, no suffix). The incorrect overapplication of theme vowel -a- produced a left early (though not anterior) negativity as well as a right anterior negativity for regular 2nd conjugation participles (*tem-a-t), and a left early (though not anterior) negativity as well as a late positivity for 3rd conjugation participles (*dorm-a-t). The overapplication of the theme vowel -a- and suffix -t produced a late positivity for irregular 2nd conjugation participles (*admet-a-t). A late positivity was also found for the incorrect application of theme vowel -i- to default participles (*cant-i-t) as compared to their correct forms.

To summarize, in spite of the numerous and diverse effects found – and in part left unexplained – the above studies concluded that, in line with a dual-mechanism account, the overapplication of a default stem or default inflection causes combinatorial effects in form of LAN/P600 effects, whereas the application of irregular inflection does not show violation effects, since irregular inflection is not parsed but rather retrieved from memory.

**Repetition priming**

The repetition of a written word within a list has been found to reduce the N400 amplitude on the second presentation relative to the first presentation. This effect has been interpreted to represent—similar to behavioral priming—the facilitated lexical access of a word relative to its unprimed presentation (e.g., Bentin & Peled, 1990). Using this logic in a long-lag priming design, Weyerts, Münte, Smid, & Heinze (1996) were the first to investigate
inflection by means of ERPs. German regular participles, either preceded by themselves (e.g., *getanzt* – *getanzt*, ‘danced – danced’) or by their infinitive (e.g., *tanzen* – *getanzt*, ‘dance – danced’), showed a reduction in the N400 and post N400 range, relative to the first (unprimed) presentation of the participle. Irregular participles also showed N400 reductions when preceded by themselves (e.g. *geboten* – *geboten*, ‘bid – bid’) or by their infinitive (e.g. *bieten* – *geboten*, ‘bid – bid’), though some 100 ms later than regular participles. Differences between regular and irregular verb inflection thus mainly showed in latencies of the N400.

While the patterns identity and infinitive priming were similar for regular verbs (which was interpreted to indicate full priming for regular verb inflection), irregular infinitive priming had a later onset and a more positive amplitude than irregular identity priming (which was interpreted to indicate partial priming for irregular verbs).

Münte, Say, Clahsen, Schiltz, and Kutas (1999) used repetition priming without an identity condition but with an unrelated baseline (e.g., *walked* – *stretch*) instead. Relative to this baseline, regular verb stems preceded by their past tense (e.g., *stretched* – *stretch*) showed a reduction in the N400 negativity as well as a right frontotemporal positivity. In contrast, participle priming for irregular verbs (e.g. *fought* – *fight* vs. *sang* – *fight*) showed a later occurring, right centroparietal positivity. Finally, in a study on stem alternations in Spanish (Rodriguez-Fornells, Münte, & Clahsen, 2002), regular verbs that shared the same stem (e.g., *ando* – *andar*), repetition of that stem produced the expected N400 reduction relative to an unrelated condition (e.g., *ando* – *lavar*; note that this study used an unrelated-target baseline and not, as usual an unrelated-prime baseline). In contrast, irregular verbs with alternated stems (e.g., *entiendo* – *entender* vs. *entiendo* – *querer*) did not show any effect.

To summarize, only one of the repetition priming studies included an identity condition to measure full versus partial priming, while two studies measured whether or not regular and irregular inflectional forms prime each other (relative to an unrelated baseline).
Even though repetition priming produced diverse effects in the processing of regular and irregular verbs, the authors took an N400 reduction to indicate that “regular verb forms can directly access their unmarked base forms as a result of morphological decomposition”, and the lack of an N400 reduction to indicate that irregular verbs “possess lexical entries separate from their corresponding base forms and can therefore access these only indirectly” (Rodriguez-Fornells et al., 2002). Similar to violation paradigms, other effects present were left unexplained.

Experiment 2

The purpose of the above summary of ERP studies was, on the one hand, to reveal how diverse effects elicited by regular and irregular verb inflection are, and on the other hand, to point to the neglect of many of these effects in favor of rather simplified but straightforward dual-mechanism interpretations. In contrast to most ERP studies cited above, we wanted to go beyond stating a mere difference between regular and irregular verbs, and investigated the complex influence of semantic relatedness, inflectional relatedness, as well as participle frequency on verb regularity. We elaborate our experimental hypotheses in the following.

**Verb regularity.** A dual-mechanism model (e.g., Ullmann et al., 1997) postulates that regular inflection is parsed within a procedural system in Broca’s area, whereas irregular inflection is stored in declarative memory. Most importantly, a dual-mechanism model assumes a strict dichotomy between regular and irregular verbs and thus predicts different effects for regular participles in contrast to those of all irregular subgroups. In contrast, if regular and irregular participles are processed within the same system, we should find graded effects of participle priming between ‘regular’, ‘irregular 1’, and ‘irregular 2’ participles.
Participle Frequency. The dual-mechanism model assumes storage of only the base forms of regular inflection, hence, the surface frequency of a regular participle should not affect its processing. Since irregular participles are assumed to be stored as whole-word units, a participle-frequency effect is expected. This should result in an interaction between regularity and participle frequency. Accordingly, irregular participles should induce N400 effects that are typically found for a contrast between high- and low-frequency words, with low-frequency primes inducing more negative potentials than high-frequency ones (e.g., Allen et al., 2003). Regular participles should not induce a frequency effect. In contrast, if we assume similar representations of regular and irregular verbs, we should observe frequency effects, in terms of N400 modulations to the targets, for all verb types.

Semantic Effects. Dual-mechanism accounts assume that irregular participles have their own representation in associative memory. In the ERP literature, the N400 is taken to be very sensitive to the semantic proximity of words (their concepts) in the semantic network (for review see Kutas & Federmeier, 2000, 2007; for word-pairs: Bentin et al., 1985). For example, Rösler and colleagues (Khader, Scherag, Streb, & Rösler, 2003; Rösler, Streb, & Haan, 2001) found a reduced N400 for semantically associated verbs relative to unrelated verbs. If the priming of irregular participles indeed relies on the activation of related entries in an associative network, irregular verbs should be primed by their participle in similar ways than by a semantically related participle, whereas this should not be the case for regular verbs and their participles.

Methods Experiment 2

Participants

Twenty-one students of the Marburg university, who did not take part in Experiment 1, gave informed consent and were paid for their participation. All were monolingual native
speakers of German and were not dyslexic. They were right-handed and had normal or corrected-to-normal vision.

Materials

Except for the unrelated participle condition (UP), the verb stimuli and prime conditions of the behavioral Experiment 1 were used, altogether 660 prime-target pairs. These were complemented by an equivalent number of prime-target pairs with pseudoverbs as targets.

Apparatus

Stimuli were presented on a 17” monitor, connected to an IBM-compatible Pentium III personal computer. Responses were recorded from the left and right ‘control’ keyboard keys.

Procedure

Each participant saw all 132 verbs in five prime conditions. Primes of the same target were rotated over five blocks according to a Latin Square; the 660 prime-pseudoverb targets were equally distributed across the blocks. In total, an experimental session comprised 1320 prime-target pairs, with 264 pairs per block. Prime-target pairs in a block were randomized separately for each participant. There were 16 practice trials.

Participants were tested individually, seated at a viewing distance of about 60 cm from the screen. Stimuli were presented in the center of the screen, in white Sans-Serif letters, point 20, on a black background. Primes were presented in uppercase letters, targets in lowercase.

Each trial started with a fixation cross in the center of the screen for 1000 ms. The prime appeared for 50 ms, followed by a blank screen for 40 ms (SOA = 90). Then the target
appeared for 1000ms, followed by a question mark as response prompt. The intertrial interval was 2000 ms. Participants were instructed to refrain from blinking until after the prompt, and to subsequently make their lexical decision as accurately as possible. ‘Word’ responses were made with the index finger of the right hand, ‘pseudoword’ responses with the left hand. The experiment lasted for about four hours. Participants took several breaks in-between blocks.

EEG Recording and Analysis

The EEG was recorded from 61 scalp electrodes using a cap in which Ag/AgCl inserts are fixated by individual electrode supports (System Falk Minow, Munich, Germany). All scalp electrodes were referenced to one earlobe during the recording and re-referenced offline to averaged earlobes. The horizontal and vertical EOG was monitored with appropriate electrode pairs. Impedances of all electrodes were kept below 5 kΩ. Two 32-channel amplifiers (SYNAMPS, NeuroScan) were used for EOG and EEG recording. Band pass was set from DC to 40 Hz and the sampling rate was 500 Hz. The left or right mastoid (counterbalanced across participants) served as ground. Electrophysiological data collection was done by NeuroScan software Acquire. Prior to each experimental block, a DC reset was initiated manually. DC drift was corrected according to the method suggested by Hennighausen, Heil, and Rösler (1983). Eye blinks and trials with other artifacts were removed by applying a threshold criterion (max. voltage range within a trial segment should be lower than 150 μV). Event-related potentials were extracted from the edited set of raw data by averaging single trials separately for subjects, electrodes, and experimental conditions. Average voltage amplitudes were computed for consecutive intervals of 30 ms width (with 15 sampling points each), beginning at the onset of the target word and ending 900 ms later. Post-stimulus intervals were baseline-adjusted to the average amplitude of a 100 ms interval preceding the onset of the prime word. A subset of electrodes resembling the 19
standard electrodes of the 10-20-system entered the statistical analysis. This reduces the number of degrees of freedom in the ANOVA and thus provides more conservative tests for the interactions of the electrode factor.

The statistical analyses of the effects of interest comprised separate ANOVAs for each time interval, including the relevant prime condition as one experimental factor as well as factors participle frequency, regularity and electrodes. In a second step, differences between experimental factors were tested with local $t$ tests for each electrode provided that the time point specific ANOVA had signaled interactions with the electrode factor. This hierarchical procedure prevents an inflation of alpha error, which would occur if only local ANOVAs were run for all combinations of electrodes and time intervals. Alpha error was further reduced by regarding only those effects as substantial that were significant ($p < .05$) during at least two consecutive time slices. All factors were defined as repeated measures. Probabilities of observed $F$ ratios were adjusted according to Huynh and Feldt (1976).

Results Experiment 2

Morphological Analyses

Is participle priming different for regular and irregular verbs? To evaluate whether regular and irregular participles yield different amounts of priming, an ANOVA was computed with the factors relatedness (participle/unrelated), regularity (regular/irregular), electrodes, and participle frequency (high/low). Including the factor frequency necessitated to merge the ‘irregular 1’ and ‘irregular 2’ subgroups because of too few items in the high or low-frequency range, thus reducing the factor regularity to two levels. This analysis, however, yielded no significant interactions between relatedness and frequency, so that a subsequent ANOVA was computed without the factor frequency, but now with all three levels of regularity (‘regular’/‘irregular 1’/‘irregular 2’). This analysis revealed a significant
main effect of relatedness for time intervals 240-480 ms, $maxF(1,14) = 13.27, p = .0027$; $minF(1,14) = 4.83, p = .0454$; $minF$ and $maxF$ referring to the smallest and largest $F$ values within the significant time interval. The significant interaction between relatedness and electrodes for the time intervals 210-360 ms, 420-510 ms, and 600-720 ms, $max F(18,252) = 6.71, p < .0001, \varepsilon(H-F) = .204$; $min F(18,252) = 2.39, p = .0419, \varepsilon(H-F) = .210$, indicated that between 210 and 510 ms after target onset, event-related potentials to targets were more negative when preceded by an unrelated verb than when preceded by their participle. From 210 to 360 ms, this effect was reliable at all frontal and central electrodes, as well as at T3. In contrast, the later interaction from 420 to 510 indicated a shift towards more posterior electrode sites, with significant differences at C3, C4, Cz, F3, O1, P3, Pz, T3, and T5. The interaction from 600 to 720 ms, however, indicated the reverse effect: Unrelated primes produced more positive potentials than participle primes, which is due to a latency difference between the two N400 components, and significant only at C4, Cz, and F4.

Figure 5 illustrates these participle effects and reveals that they are modulated by regularity, that is, they are most strongly pronounced for ‘regular’ participles, less strongly pronounced for ‘irregular 1’ participles, and least pronounced for ‘irregular 2’ participles. This is corroborated by the statistical analysis that revealed a significant interaction between relatedness, regularity, and electrodes from 390 to 480 ms after target onset, $maxF(36,504) = 3.03, p = .0081, \varepsilon(H-F) = .178$; $minF(36,504) = 2.31, p = .0473, \varepsilon(H-F) = .152$. Figure 5 provides the grand averages of the participle-prime (e.g., gekauft – kaufe, bought – buy) and unrelated conditions (e.g., hüpfte – kaufe, jump – buy), separately for all three levels of verb regularity. ‘Irregular 1’ verbs are in between ‘regular’ and ‘irregular 2’ verbs. Widespread frontal, parietal, and temporal effects are visible for ‘regular’ verbs, only the frontal and temporal negativities remain unreduced for ‘irregular 1’ verbs, and hardly any effect is visible for ‘irregular 2’ verbs. Correspondingly, post-hoc tests of the interaction revealed significant
effects at frontal (F3, F4, Fz) and all central, temporal, parietal and occipital electrode sites for ‘regular’ verbs, at frontal electrodes (F3, F7, Fz) as well as C3, T3, and T5 for ‘irregular 1’ verbs, and only at T5 for ‘irregular 2’ verbs.

Is participle priming full or partial? To examine whether regular and irregular participles produce full or partial priming, we conducted an ANOVA with factors regularity, relatedness (participle/identity), and electrodes. This analysis revealed a main effect of relatedness from 360 to 480 ms, \( \text{maxF}(1,14) = 12.42, \ p = .0034; \ \text{minF}(1,14) = 4.73, \ p = .0473, \) and a corresponding interaction between relatedness and electrodes from 360 to 690 ms, \( \text{max F}(18,252) = 5.99, \ p = .0006, \ \varepsilon(H-F) = .164; \ \text{min F}(18,252) = 3.16, \ p = .0108, \ \varepsilon(H-F) = .208, \) but no effects of verb regularity. That is, participle priming was partial for all verb types: it was more negative than identity priming, as indicated by post-hoc tests, in a broad distribution including F4, Fz, and all central, parietal and occipital electrodes (see Figure 6). Again, the interaction from 570-690 ms indicated the reverse effect and is probably caused by an N400 latency difference. This effect was significant at F7, F8, Fp1, and Fp2.

To assess whether the partial priming effects are modulated by participle frequency, we conducted an additional ANOVA with factors participle frequency (high/low), regularity (regular/irregular), and relatedness (participle/identity). In this analysis, no interaction of relatedness and participle frequency was found, showing that the priming by related participles is partial, independent from their frequency.
Semantic Analyses

Figure 7 shows the grand averages of unrelated, semantically related, and identical verb pairs, separately for all three levels of verb regularity. For all three levels of regularity, the curves start to diverge at about 200 ms after stimulus onset, with unrelated targets being most negative, semantically related targets being less negative and identical targets being least negative. The maximal difference is reached between 400 - 500 ms, indicating a modulation of the N400 component by the type of meaning relatedness. Accordingly, an ANOVA with factors relatedness (identity/semantic/unrelated), regularity (‘regular’/‘irregular 1’/‘irregular 2’), and electrodes yielded a significant main effect of relatedness for time intervals 240-510 ms, $maxF(2,28) = 34.12, p < .0001, \varepsilon(\text{H-F}) = .916$; $minF(2,28) = 3.85, p = .0334, \varepsilon(\text{H-F}) = .984$, and a significant interaction between relatedness and electrodes for time intervals 300-540 ms, $maxF(36,504) = 6.56, p < .0001, \varepsilon(\text{H-F}) = .122$; $minF(36,504) = 3.80, p = .0005, \varepsilon(\text{H-F}) = .141$. There was no significant interaction with regularity. To investigate whether semantic priming is significant, post-hoc tests compared the event-related potentials evoked by semantically related (e.g., *zahle – kaufe*, ‘pay – buy’) and unrelated (e.g., *hüpfe – kaufe*, ‘jump – buy’) verb pairs for each electrode, yielding a broadly distributed N400 effect with a maximum at central and parietal electrodes and more negative potentials for unrelated targets at C3, C4, Cz, F3, F4, F7, Fz, O1, O2, P3, P4, Pz, T3, T5, and T6.

Is participle priming different from semantic priming? Finally, we investigated similarities between participle and semantic priming by submitting the effects (P – I) and (SP – S; see Table 2) to an ANOVA with factors participle frequency (high/low), relatedness
Graded Brain Responses to Regular and Irregular Inflection

This analysis revealed a significant interaction between participle frequency and relatedness between 330 and 390 ms, $F_1(1,14) = 6.26, p = .0253; F_2(1,14) = 5.15, p = .0395$, but no effect of regularity. As can be seen in Figure 8, participle (P – I) and semantic (SP – S) priming strongly differ when participle frequency is low, but not when participle frequency is high. Post-hoc tests substantiate this dissociation, showing a stronger N400 effect for participle priming compared to semantic priming for infrequent, $F(1,14) = 12.26, p = .0035$, but not for frequent participles, $F(1,14) < 1, p = .9429$.

Figure 8 about here

Discussion of Results of Experiments 1 and 2

The present study investigated whether linguistic verb categories—labeled regular and irregular—are processed in categorical or continuous ways. Our results were straightforward: Both response latencies and event-related potentials provided complex effects for such verb types that contradict a simple all-or-none classification. In the following, we will discuss our findings in the light of our hypotheses and questions, considering the behavioral data together with the electrophysiological data.

Is Participle Priming for Regular and Irregular Verbs Full or Partial?

A categorical processing distinction between regular and irregular verbs should yield different priming patterns for these verb types, which we did not find: Regularity did not interact with effects induced by identical and participle primes, neither in the RT nor in the ERP analyses. That is, both regular and irregular verbs produced partial priming. In the RT analyses, participles produced weaker effects than identical primes. In the ERP analysis, targets showed more negative potentials when preceded by participles than when preceded by
identical primes between 360 and 570 ms at central, parietal, and occipital sites, which corresponds to a broadly distributed N400 effect (see Figure 6). These results, the behavioral ones in particular, replicate our previous findings that regular and irregular participles produce equivalent amounts of priming (Smolka et al., 2007; Smolka, Zwitserlood et al., 2009).

**Does Frequency Affect the Priming of Regular and Irregular Verbs?**

In the ERP data, the *partial* priming effects for both regular and irregular verbs were not modified by frequency (see Figure 6). Note that the frequency variable concerned the primes, not the targets. Although clear effects of target frequency on the N400 are reported in the literature (e.g., Rugg, 1990), we know of no study that looked at effects of prime frequency on N400 amplitudes or latencies.

In contrast to the ERP data, participle frequency strongly affected the latency data, as indicated by the fourth-order interaction with participle frequency: As Figure 2 shows, we observe *full* priming induced by irregular infrequent participles, and no priming at all for irregular frequent participles. In contrast, we obtained *full* priming due to regular frequent participles, but *partial* (i.e., less than identity) priming by regular infrequent participles. These effects were quite different from the ones predicted by a dual-mechanism account (e.g., Clahsen, Eisenbeiss, & Sonnenstuhl-Henning, 1997): Irregular verbs are assumed to be stored as whole-word entries, which facilitate each other in an associative network-like fashion. Therefore, they should yield *partial* priming depending on frequency, relatedness, and inflectional similarity. In contrast, because regular verbs are assumed to access the same base form only, regular verbs should always show *full* priming, independent of frequency and inflectional similarity.
Do Irregular Subgroups Behave as a Homogenous Group in Contrast to Regular Verbs?

In contrast to the all-or-none assumptions of a dual-mechanism account, the present RT and ERP data showed that verb regularity is rather a graded phenomenon. ‘Irregular 1’ verbs produced hybrid result patterns, between those of ‘regular’ and ‘irregular 2’ verbs. In addition, the ERP data (see Figure 5) revealed that the three verb types produce the same basic effect, which is modulated by the time course and by the number of affected electrodes. While ‘regular’ participles showed a broadly distributed ERP effect (with more negative curves for unrelated than for participle primes), extending from frontal, central, temporal, parietal, to occipital electrodes, the effect is reduced to frontal, central, and left temporal electrodes for ‘irregular 1’ participles, and diminished to a single left temporal electrode for ‘irregular 2’ participles. The RT data show the hybrid status of ‘irregular 1’ verbs, though again, dependent on participle frequency. When participle primes are of high frequency, their effects are similar for ‘irregular 1’ and ‘irregular 2’ verbs. When participle frequency is low, effects for ‘irregular 1’ verbs resemble those for ‘regular’ verbs.

Are Semantic Priming Effects Different for Regular and Irregular Verbs?

The RT data showed very small semantic priming effects, in fact, only low-frequency regular verbs produced significant amounts of semantic priming. This lack of semantic priming occurred although the association test had confirmed for all verb types and frequency manipulations that semantic primes were close in meaning to their targets: On a 7-point scale from completely unrelated (1) to highly related (7), mean ratings were 5.8 for regular verbs of high-frequency, 6.1 for regular verbs of low-frequency, 6.0 for irregular verbs of high-frequency, and 5.9 for irregular verbs of low-frequency. Even though we do not know why the semantic effects were weak, this nevertheless replicates the nonsignificant and rather
weak semantic priming effects of German verbs in other studies (Smolka, Komlósi, & Rösler, 2009).

In contrast to the RT data, the ERP data revealed strong semantic effects, namely broadly distributed N400 effects in the time intervals between 300 and 510 ms that reflect the relatedness between prime-target pairs: strongest negativity for unrelated verbs, less negativity for semantically related verbs, and least negativity for identical verbs. Most importantly, these effects of semantic relatedness were alike for regular and irregular verbs.

Is Participle Priming Different from Semantic Priming?

Finally, we tested whether participle priming differs from semantic priming by examining the interaction (P – I) and (SP – S). This interaction tests the null hypothesis that participle and semantic priming are equal. For both RTs and ERPs, the interaction (P – I) and (SP – S) was significant, indicating a qualitative difference between participle and semantic priming. However, there was no higher-order interaction with regularity. That is, in contrast to the assumptions of a dual-mechanism account, participle priming differs from semantic priming for regular as well as for irregular verbs.

General discussion

We investigated priming effects of regular and irregular verbs in German and their dependence on participle frequency, the type of semantic relatedness, and the inflectional relatedness between primes and targets. German participle formation is particularly interesting for these questions. First, regularity is not confounded by parallel stem and suffix behavior: all verbs comprise of a stem (with or without vowel change) and a suffix (-t or -en). Second, German participle formation allows us to test gradation between complete regularity and complete irregularity.
The purpose of the study was to examine several predictions following from the claim of the dual-mechanism account that regularly and irregularly inflected verb forms are stored in and processed by distinct systems. First, do regular and irregular participles produce different amounts of priming? That is, do we find *full* priming (i.e., participle priming equivalent to identity priming) for regular verbs, but *partial* priming (i.e., participle priming less than identity priming) for irregular verbs? Second, do irregular subgroups show homogenous priming patterns that contrast those of regular verbs? Third, are effects of irregular participles, but not of regular ones, modulated by frequency? Fourth, do participle and semantic primes have a similar impact on irregular verbs, but not on regular verbs?

We tried to answer the above questions step by step. Probably the most important finding of the present study was that one question cannot be answered without the other, since verb type, participle frequency, semantic relatedness, as well as inflectional relatedness are found to be tightly interconnected.

We found clear evidence that regular and irregular forms are processed similarly, supporting the idea of a single system: (1) no interaction between regularity and priming patterns; (2) graded effects of participle priming between ‘regular’, ‘irregular 1’, and ‘irregular 2’ participles; (3) participle-frequency effects for both regular and irregular verb types (and their corresponding priming patterns), and (4) participle priming that differed from semantic priming for both regular and irregular verbs. Below, we discuss our findings in the context of previous studies and models.

*Full versus Partial Priming*

We found no differences in participle-priming patterns between regular and irregular verbs as such: both our behavioral and electrophysiological results (see Figure 6) show *partial* priming effects (i.e. participle priming less than identity priming) for regular and
irregular verbs. The *partial* priming effect for regular verbs differs from previous ERP findings in German (Weyerts et al., 1996), where regular verbs invoked *full* priming. In that study, participles were used as targets that were primed either by themselves (identity), by an infinitive, or by an unrelated verb. It is possible that the priming of inflections is not symmetrical (e.g., Schriefers, Friederici, & Graetz, 1992). Importantly, our study also found *partial* priming effects for irregular verbs, which contrasts with other repetition-priming studies that found no effects at all for irregular verbs (Münte et al., 1999; Rodriguez-Fornells et al., 2002). However, since these latter two studies did not make use of identity priming, they cannot decide between *full* and *partial* priming.3

With regard to behavioral data, our finding that regularity does not interact with priming fits with previous studies in English (e.g. Marslen-Wilson & Tyler, 1997), as well as studies on highly inflected languages like German, French, Italian, and Spanish, that showed similar past-tense and participle-priming effects for regular and irregular verbs (Meunier & Marslen-Wilson, 2004; Orsolini & Marslen-Wilson, 1997; Rodriguez-Fornells et al., 2002; Smolka et al., 2007). However, since these studies did not include identity priming, there is no way to determine whether participle priming was *full* or *partial*.

At first glance, our *partial* priming effects seem to conflict with previous findings in German (Sonnenstuhl et al., 1999) and English (Fowler et al., 19851; Marslen-Wilson, 1999; Napps, 1989; Napps & Fowler, 1987) that mainly reported *full* priming for ‘regular’ participles. However, our recent study (Smolka, Zwitserlood et al., 2009) revealed that whether or not regular participles induce *full* or *partial* priming depends on their frequency. Such frequency-dependent priming effects were replicated in the present study, where we found *full* priming for participles that, relative to the infrequent set, were of high frequency (36/million). This frequency range, however, correspond to the ‘low-frequency’ set in
Smolka, Zwitserlood et al. (2009; 26/million), as well as to the set used in Sonnenstuhl et al. (1999; 20/million).

With respect to the priming patterns of irregular verbs, our results—though not expected by a dual-mechanism account—nevertheless replicate the diverse patterns found in the literature, that range from full priming (Forster et al., 1987), partial priming (Napps, 1989; Sonnenstuhl et al., 1999), to no priming at all (Marslen-Wilson, 1999). Again, the frequency manipulation resulted in different priming patterns: Irregular participles of low frequency induced full priming, while high-frequency irregular ones induced no priming at all (this results in partial priming effects when high- and low-frequency participles are merged).

Given these diverse priming effects for both regular and irregular verbs, what are the theoretical implications of these full and partial priming effects? Dual-mechanism accounts assume that full priming indicates that morphologically complex forms access the same shared stem, whereas partial priming indicates whole-word storage. Under this assumption, we would have to conclude that (1) regular participles of high frequency and irregular participles of low frequency are accessed via their stem (full priming), (2) regular participles of low frequency are stored as full forms (partial priming), and (3) irregular participles of high frequency are not stored at all (no priming). Clearly, this is not a theoretically fortuitous conclusion.

Note also that Schriefers et al. (1992) cautioned that full priming of a stem by its morphological relatives is not sufficient evidence for the existence of one lexical entry shared by all morphological relatives. Rather, all relations between morphological relatives have to be tested. If the stem is the only lexical entry through which all other morphological variants are accessed, then full priming should occur symmetrically (between various morphological variants and the stem, and vice versa). Any asymmetrical priming pattern would cast serious doubt on the assumption of a single lexical stem entry for all morphological variants.
Given the above difficulties, we prefer to conclude that full and partial priming patterns must not be taken to indicate a particular storage mechanism.

Rather, to assess whether or not stem access occurs, different methods should be used. Indeed, in a previous study (Smolka et al., 2007) we have used nonword priming to show that irregular participles are accessed via their stems. Nonwords that comprised illegal combinations of stems and suffixes primed their corresponding base verbs to the same extent as correct participles. Since nonwords do not exist and thus cannot be stored in lexical memory, their stems (which, according to a dual-mechanism account are not supposed to be stored) must have been accessed to produce priming on the base verbs. Moreover, since the patterns were the same for regular and irregular verbs, we concluded that both regular and irregular participles are stored and processed within the same system.

Irregular Subgroups in Contrast to Regular Verbs?

Most importantly, both our behavioral and electrophysiological data revealed graded effects between completely regular and completely irregular inflection. In the RT data, these effects further interacted with participle frequency (see Figure 3): in the low-frequency range, ‘irregular 1’ verbs pattern with ‘regular’ verbs, in the high-frequency range with ‘irregular 2’ verbs. Given that the present study is the first to test subgroups of irregular verbs in German together with a frequency manipulation, we cannot refer to other studies for a direct comparison. Nevertheless, graded (behavioral) effects have been previously found in English (Pastizzo & Feldman, 2002) where the gradedness of verb regularity was measured according to the letter overlap between past tense forms and their uninflected stems. Relative to an orthographic control condition (e.g., fill - fall), priming was significant between regular past tense forms and their base (e.g., hatched - hatch) as well as between irregular verbs with high letter overlap (e.g., fell - fall), but not between irregular forms with little letter overlap (taught...
Graded Brain Responses to Regular and Irregular Inflection

- teach). The authors concluded that differentiations between regular and irregular verb formations in English “appear to reflect a confound with degree of form overlap rather than compelling evidence of selective decomposition” (p. 249).

Our electrophysiological data showed graded participle priming relative to the unrelated condition: a strong effect of ‘regular’ participles, an intermediate effect of ‘irregular 1’ participles, and a minimal effect of ‘irregular 2’ ones (see Figure 5). Most importantly, our study revealed an unequivocal effect of gradedness that indicates a single system that generates participle-priming effects.

Graded effects, though different from ours, were also found by a recent auditory repetition priming study in English (Justus, Larsen, De Mornay Davies, & Swick, 2008) that differentiated between regular (looked – look), weak irregular (spent – spend), and strong irregular (spoke – speak) past tense priming. All three verb types showed N400 reductions for primed targets, but the priming of ‘strong’ irregular verbs was stronger than that of ‘weak’ or ‘regular’ verbs. Given the lack of evidence for a categorical distinction between ‘regular’ and ‘irregular’, the authors concluded that the data are more consistent with a single model account.

At first glance, graded effects seem to contrast with previous repetition-priming studies in German, English, and Spanish (Münte et al., 1999; Rodriguez-Fornells et al., 2002; Weyerts et al., 1996) that were interpreted in terms of all-or-none effects between regular and irregular verbs. However, a closer look reveals a more subtle picture. Summarizing across these studies, regular participles showed a reduction in the N400 and post-N400 range, as well as a late right frontal positivity; and irregular participles showed a reduction in the N400 and a late right centroparietal positivity.

Rodriguez-Fornells et al. (2002, p. 449) argued that “the ease of processing is reflected in a reduced N400 amplitude. By this account primed target forms of regular verbs
are easier to process. The most parsimonious explanation for this is that both [regularly inflected] forms actually access the same lexical representation and that this representation is preactivated by the prime. The lack of an N400 effect for the irregular verbs on the other hand suggests that the memory trace that was formed by the prime did not activate the representation of the target sufficiently to yield an N400 reduction.”

Had we considered only the midline electrodes of our data, used coarse-grained time intervals (averaging over 200 or 300 ms) and reduced the analyses to few electrodes only, indeed, the data would confirm an all-or-none-difference between completely regular and completely irregular verbs (see Figure 5). We thus argue that more fine-grained analyses should be used to test binary versus graded differences.

Based on the general assumption of repetition-priming studies (e.g., Rugg, 1990) that a reduction in the N400 deflection corresponds to ease of processing, both regular and irregular participles should facilitate the recognition of a related verb target. According to a dual-mechanism account, this might occur for different reasons: regular participles cause priming, since the same stem is activated as the target, whereas irregular participles cause priming, because—in spite of different lexical entries—they activate the closely related target in associative memory. If the priming of irregular inflection occurs in associative memory, we should see effects similar to those of semantic associates, that is, strong N400 effects for primed irregular verbs (see below).

However, there are alternative interpretations for graded priming effects of participles. Such effects may indicate the facilitation of highly frequent, less frequent, and least frequent stems for the following verb target. Since we have shown before, in a behavioral repetition-priming study (Smolka et al., 2007) that both regular and irregular participles are accessed for their stem, the frequency of the participle stem may also affect the ERP data. Keeping the word-form frequency of participles equal (as we have done in the present study), regular
participle stems will be more frequent than irregular participle stems, since they occur—by definition—not only in the participle but in the whole verb paradigm, such as the infinitive, present tense, past tense, and conditional, while the stems of ‘irregular 2’ participles occur only in the participle. Again, ‘irregular 1’ participles will hold an intermediate position, since their stems occur both in the participle and in the infinitive, and possibly in other verb forms as well. Hence, if all participles are parsed and accessed for their stem, ‘regular’ participles will show the strongest priming, because their stems will strongly activate their lexical representation, while irregular participles will show less priming because their less frequent stems will activate their lexical representation to a lesser degree. Indeed, in our single system model (Smolka et al., 2007; Smolka, Zwitserlood et al., 2009) we assume that the stems of participles are accessed for meaning, both regularly and irregularly inflected ones. Hence, the frequency of a particular stem will influence how much it will be activated as well as how strongly it will pre-activate other closely related stems. Nevertheless, whether the mechanism we see here in form of a left-lateralized N400 is an indication of stem access and stem frequency remains to be tested in future experiments.

Even though we believe our model provides a best fit to accommodate German data, our data may also be incorporated in the dual-system model of Marslen-Wilson and Tyler (2007), who assume that German regular and irregular participles should not be processed qualitatively differently, because they are both decomposable into stems plus inflectional affixes. These inflectional affixes should obligatorily engage the same specialized left-hemispheric brain systems supporting the analysis of morpho-phonologically complex inflected forms (see also Post et al., 2008).
Participle versus Semantic Priming

A further question concerns the storage and processing of irregular participles. A dual-mechanism account holds that irregularly inflected verb forms each have a separate lexical and semantic representation, similar to semantically associated words. Participle-priming effects of irregular verbs should thus resemble semantic priming effects.

Several studies have compared the priming of morphologically and semantically related pairs to test the claim that morphological priming effects are of a semantic nature. For example, Stanners et al. (1979) found partial priming for semantically related pairs, similar to the partial priming of irregularly inflected verbs. This was taken as evidence that irregularly inflected verb forms are connected in a semantic network. However, semantic priming was often tested using word pairs such as black and white, which differ in many respects, most notably in word class, from the verbs used in morphologically relevant conditions. Therefore, in the study reported here we used verbs as primes in the morphological and in the semantic condition. This allowed us to directly compare morphological and semantic effects. Indeed, the interaction (P – I) (SP – S) demonstrated that participle priming is different from semantic priming, for both regular and irregular verbs.

In contrast to strong participle-priming effects, the behavioral data showed hardly any semantic priming at all, in particular regarding regular and high-frequency irregular verbs. Lack of semantic priming (in contrast to the occurrence of participle priming), was also found in a study on Italian past-tense priming (Orsolini & Marslen-Wilson, 1997) and was interpreted as evidence for a processing dissociation between participle and semantic priming. Less semantic priming than morphological priming was also evident in a recent study on German prefixed verbs (Smolka, Komlósi et al., 2009): Under overt prime presentations of 300 ms SOA, morphologically related verbs primed significantly more than semantically related verbs, whereas semantically related verbs induced significant facilitation
in one experiment, but not in another (see also Lüttmann, Zwitserlood, & Bölte, 2009). Generally speaking, it seems that semantic priming of verbs shows relatively instable effects when response latencies are measured.

In contrast to the behavioral results, all verb types showed strong semantic priming on the N400, both when comparing semantically related to unrelated and to identical prime-target pairs (see Figure 7). Amplitudes were most negative-going for unrelated prime-target pairs, more positive-going for semantically associated verb pairs, and most positive-going for identical prime-target pairs. Strong semantic-priming effects of verbs in terms of N400 modulations, in contrast to instable effects in the RT data, have been previously documented in German (e.g., Khader et al., 2003; Rösler et al., 2001). This study also revealed graded priming effects between verb pairs due to their association strength (high – medium – unrelated). However, we are not aware of a study that tested whether regular and irregular verbs differ with regard to semantic priming effects.

In addition to the behavioral data, our ERP data also confirmed that participle priming differs qualitatively from semantic priming, as indicated by the interaction (P – I) (SP – S) (see Figure 8). This goes against the assumption of a dual-mechanism account that irregularly inflected forms relate to each other in similar ways as semantic associates such as black and white, or swan and goose. However, it fits the findings of Marlsen-Wilson and Tyler (1998) that regular and irregular past-tense priming showed left anterior negativities, in addition to the N400 effects found for regulars and irregulars, as well as for semantically associated words. The authors concluded that the underlying relationship between past tense forms and their stem is morphological, and that “the irregulars globally parallel the regulars rather than the semantic pairs” (p. 433).
Complementary Effects of Behavioral and Electrophysiological Data

Overall, our behavioral and electrophysiological data yield converging evidence. Obtaining similar effects in two separate studies with two different methods is a strong cross-validation of the effects found in each study and renders the results much more robust and believable. In the present study, this means that the participle-priming mechanisms involve a general cognitive phenomenon that can be captured by different methods. However, besides this general convergence, our data also showed differences between RT and ERP effects. For example, the behavioral experiment yielded a complex interaction between the variables verb type, inflectional relatedness, and participle frequency, whereas the ERP data revealed fine-grained differences between the verb regularities when averaged across prime frequencies. In the ERP data we found strong effects of semantic relatedness in terms of N400 modulations, but no semantic facilitation in the RT data. This shows that behavioral and electrophysiological data do not constitute exact replications, but rather complementary aspects of a complex picture. We thus argue that, to receive a complete picture of the cognitive mechanisms underlying participle priming, both types of data are required.

Summary and Models

To summarize, we have shown that regularity, word frequency, meaning relatedness, and inflectional similarity all exert their influence on the representation of verb inflection. The obvious linguistic distinction between regular and irregular word forms does not have a one-to-one mapping onto behavioral or electrophysiological processing principles.

Our data may thus be incorporated in a dual-system model (Marslen-Wilson & Tyler, 1998, 2007; Post et al., 2008) that allows German regular and irregular participles to be processed within the same left hemisphere system that supports analysis of morphophonologically complex inflected forms. Even so, we believe that our German data are best
accommodated in a single-system model that allows for the interplay of diverse factors. Our single-system model (Smolka et al., 2007; Smolka, Komlósi et al., 2009) allows for stem access in both inflections and derivations, regardless of regularity and semantic transparency. The frequency of the stem as well as the frequency of different stem-affix combinations will affect both lexical access and activation effects within the lexical network.
References


Author Notes

This study was supported by the German Research Foundation (DFG), grant FOR 254/2 to Richard Wiese and Frank Rösler.

Correspondence concerning this article should be addressed to Eva Smolka, Department of Linguistics, University of Konstanz, 78467 Konstanz, Germany. Email: eva.smolka@uni-konstanz.de
Footnotes

Footnote 1: The distribution of ge- is entirely prosodically conditioned and is thus not focused upon here: ge- must occur, if the first syllable of a stem carries the main stress, otherwise it must not (Wiese, 1996b, chap.4.1.2.).

Footnote 2: All verbs were complex, with different prefixes attached to the same stem, such as aufladen (load on) and abladen (load off), so as to increase the number of irregular verbs.

Footnote 3: Newman et al. (2007, p.437) incorrectly cite the studies of Münte et al. (1999) and Rodriguez-Fornells et al. (2002) as having measured full and partial priming (i.e., participle priming in comparison to identity priming).
Table 1

*German Participle Formation According to Stem and Suffix Combinations*

<table>
<thead>
<tr>
<th>Verb Type</th>
<th>Citation Form</th>
<th>Participle</th>
<th>Stem</th>
<th>Suffix</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>‘regular’</td>
<td>stöhnen (moan)</td>
<td>gestöhnt</td>
<td>infinitive</td>
<td>-t</td>
<td>1700</td>
</tr>
<tr>
<td>‘irregular 1’</td>
<td>stoßen (push)</td>
<td>gestoßen</td>
<td>infinitive</td>
<td>-en</td>
<td>41</td>
</tr>
<tr>
<td>‘irregular 2’</td>
<td>stechen (sting)</td>
<td>gestochen</td>
<td>vowel change</td>
<td>-en</td>
<td>144</td>
</tr>
<tr>
<td>‘irregular 3’</td>
<td>denken (think)</td>
<td>gedacht</td>
<td>vowel change</td>
<td>-t</td>
<td>15</td>
</tr>
</tbody>
</table>

*Note.* In traditional German grammars, ‘regular’ verbs are called “weak” verbs, ‘irregular 1’ and ‘irregular 2’ verbs are subsumed under “strong verbs”, and ‘irregular 3’ verbs are referred to as “mixed verbs”. All examples are given in their orthographic form, hence -en suffix, and not in their phonetic form, where the letter e is realized as schwa /ə/ or is not realized at all. N = type count of monomorphemic verbs in CELEX (Baayen, Piepenbrock, & Van Rijn, 1993).
Table 2

Examples of Stimuli: Primes with Identical, Semantic or Unrelated Meaning in the Same or Different (Participle) Inflection as the Corresponding ‘Regular’, ‘Irregular 1’, or ‘Irregular 2’ Verb Target

<table>
<thead>
<tr>
<th>Targets</th>
<th>Identity</th>
<th></th>
<th></th>
<th>Semantic</th>
<th></th>
<th></th>
<th>Unrelated</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Same (I)</td>
<td>Different (P)</td>
<td>Same (S)</td>
<td>Different (SP)</td>
<td>Same (U)</td>
<td>Different (UP)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>‘regular’</td>
<td>stöhne (moan)</td>
<td>stöhne (moan)</td>
<td>gestöhnt (moaned)</td>
<td>seufze (sigh)</td>
<td>geseufzt (sighed)</td>
<td>blinke (blink)</td>
<td>geblinkt (blinked)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>‘irregular 1’</td>
<td>stoße (push)</td>
<td>stoße (push)</td>
<td>gestoßen (pushed)</td>
<td>schubse (hustle)</td>
<td>geschubst (hustled)</td>
<td>leide (suffer)</td>
<td>gelitten (suffered)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>‘irregular 2’</td>
<td>steche (sting)</td>
<td>steche (sting)</td>
<td>gestochen (stung)</td>
<td>pikse (prick)</td>
<td>gepikst (pricked)</td>
<td>gieße (pour)</td>
<td>gegossen (poured)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Note. Inflection refers to the distinction between participle and first- or second-person inflection. Primes and targets were either presented in the same inflection (both verbs in either first or second person) or in a different inflection (participle prime combined with first- or second-person target).*
Table 3

Mean Reaction Times in ms (SD in parentheses) to ‘Regular’ and ‘Irregular’ (as well as Subgroups ‘Irregular 1’, ‘Irregular 2’) Verb Targets Preceded by Primes with Identical, Semantic or Unrelated Meaning in the Same or Different (Participle) Inflection as the Target

<table>
<thead>
<tr>
<th>Targets</th>
<th>Identity</th>
<th></th>
<th>Semantic</th>
<th></th>
<th>Unrelated</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Same (I)</td>
<td>Different (P)</td>
<td>Same (S)</td>
<td>Different (SP)</td>
<td>Same (U)</td>
<td>Different (UP)</td>
</tr>
<tr>
<td>‘regular’</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>high</td>
<td>591 (95)</td>
<td>608 (98)</td>
<td>626 (98)</td>
<td>631 (103)</td>
<td>631 (93)</td>
<td>642 (100)</td>
</tr>
<tr>
<td>low</td>
<td>623 (117)</td>
<td>644 (120)</td>
<td>661 (101)</td>
<td>679 (108)</td>
<td>705 (120)</td>
<td>694 (114)</td>
</tr>
<tr>
<td>‘irregular’</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>high</td>
<td>580 (96)</td>
<td>625 (114)</td>
<td>615 (102)</td>
<td>628 (93)</td>
<td>621 (86)</td>
<td>624 (97)</td>
</tr>
<tr>
<td>low</td>
<td>615 (106)</td>
<td>629 (103)</td>
<td>653 (114)</td>
<td>654 (103)</td>
<td>666 (110)</td>
<td>677 (110)</td>
</tr>
<tr>
<td>‘irregular 1’</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>high</td>
<td>581 (104)</td>
<td>631 (124)</td>
<td>608 (95)</td>
<td>637 (91)</td>
<td>623 (91)</td>
<td>626 (103)</td>
</tr>
<tr>
<td>low</td>
<td>602 (113)</td>
<td>637 (131)</td>
<td>673 (118)</td>
<td>668 (119)</td>
<td>680 (115)</td>
<td>682 (101)</td>
</tr>
<tr>
<td>‘irregular 2’</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>high</td>
<td>578 (94)</td>
<td>622 (115)</td>
<td>619 (109)</td>
<td>623 (98)</td>
<td>620 (87)</td>
<td>623 (97)</td>
</tr>
<tr>
<td>low</td>
<td>621 (107)</td>
<td>626 (96)</td>
<td>644 (115)</td>
<td>649 (99)</td>
<td>661 (112)</td>
<td>675 (117)</td>
</tr>
</tbody>
</table>
Table 4

Significant Reaction Time and Error Effects in the Overall Analyses of Experiment 1

<table>
<thead>
<tr>
<th>Effect</th>
<th>RT Effect</th>
<th>Error Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regularity (R)</td>
<td>$F_1(1, 19) = 33.55, p &lt; .0001$</td>
<td>$F_1(1, 19) = 4.13, p = .0564$</td>
</tr>
<tr>
<td></td>
<td>$F_2(1, 127) = 6.47, p = .0122$</td>
<td>$F_2(1, 127) = 3.72, p = .0560$</td>
</tr>
<tr>
<td>Meaning (M)</td>
<td>$F_1(2, 38) = 125.16, p &lt; .0001$</td>
<td>$F_1(2, 38) = 10.75, p = .0002$</td>
</tr>
<tr>
<td></td>
<td>$F_2(2, 254) = 76.23, p &lt; .0001$</td>
<td>$F_2(2, 254) = 12.06, p &lt; .0001$</td>
</tr>
<tr>
<td>Inflection (I)</td>
<td>$F_1(1, 19) = 29.74, p &lt; .0001$</td>
<td>$F_1(1, 19) = 6.18, p = .0224$</td>
</tr>
<tr>
<td></td>
<td>$F_2(1, 127) = 27.27, p &lt; .0001$</td>
<td>$F_2(1, 127) = 10.08, p = .0019$</td>
</tr>
<tr>
<td>Frequency (F)</td>
<td>$F_1(1, 19) = 70.11, p &lt; .0001$</td>
<td>$F_1(1, 19) = 20.36, p = .0002$</td>
</tr>
<tr>
<td></td>
<td>$F_2(1, 127) = 41.75, p &lt; .0001$</td>
<td>$F_2(1, 127) = 13.35, p = .0004$</td>
</tr>
<tr>
<td>Regularity x Frequency</td>
<td>$F_1(1, 19) = 6.68, p = .0182$</td>
<td>ns</td>
</tr>
<tr>
<td></td>
<td>ns</td>
<td>ns</td>
</tr>
<tr>
<td>Meaning x Regularity</td>
<td>$F_1(2, 38) = 5.40, p = .0086$</td>
<td>$F_1(2, 38) = 2.96, p = .0637$</td>
</tr>
<tr>
<td></td>
<td>$F_2(2, 254) = 3.87, p = .0221$</td>
<td>$F_2(2, 254) = 3.14, p = .0450$</td>
</tr>
<tr>
<td>Meaning x Inflection</td>
<td>$F_1(2, 38) = 7.54, p = .0017$</td>
<td>ns</td>
</tr>
<tr>
<td></td>
<td>$F_2(2, 254) = 2.75, p = .0661$</td>
<td>ns</td>
</tr>
<tr>
<td>Meaning x Frequency</td>
<td>$F_1(2, 38) = 13.41, p &lt; .0001$</td>
<td>ns</td>
</tr>
<tr>
<td></td>
<td>$F_2(2, 254) = 8.69, p = .0002$</td>
<td>ns</td>
</tr>
<tr>
<td>M x R x I x F</td>
<td>$F_1(2, 38) = 7.16, p = .0023$</td>
<td>ns</td>
</tr>
<tr>
<td></td>
<td>$F_2(2, 254) = 2.62, p = .0750$</td>
<td>ns</td>
</tr>
</tbody>
</table>

Note. The effects of ANOVAs by participants ($F_1$) and items ($F_2$) with factors regularity (regular/irregular), meaning (identity/semantic/unrelated), inflection (same/different), and frequency (high/low) was run on RT and error data. ns = not significant.
Figure Captions

Figure 1. The effects of meaning and inflectional relatedness between regular and irregular prime-target verbs of high- and low-frequency. Primes were unrelated, semantically associated, or identical with the target verb, and either in the participle form or in the same inflection as the target.

Figure 2. Identity and participle priming effects for regular and irregular verb targets of high and low frequency.

Figure 3. Identity and participle priming effects for regular verbs and two subtypes of irregular verbs of high and low frequency.

Figure 4. The interaction (P – I) (SP – S) that differentiates participle from semantic priming for regular and irregular verbs of high and low frequency (see text).

Figure 5. Grand averages of verb targets preceded by their participle or an unrelated verb, separately for all three levels of verb regularity. In this and the following figures, negativity is plotted upwards.

Figure 6. Grand averages of verb targets preceded by themselves (identity condition) or by their participle, separately for all three levels of verb regularity.

Figure 7. Grand averages of verb targets preceded by an unrelated, semantically associated, or identical prime verb, separately for all three levels of verb regularity.

Figure 8. Difference curves of participle (P – I) and semantic (SP – S) priming for high- and low-frequency verb targets.
Figure 1
Figure 2

![Graph showing priming effects for regular and irregular inflection. The x-axis represents priming (unrelated-related) in ms, while the y-axis represents the priming effect in ms. The bars indicate identity and participle conditions for high and low priming.](image-url)
Figure 3

![Graph showing priming effects in ms for regular and irregular inflections with high and low frequency. The x-axis represents different types of words (regular, irregular 1, irregular 2) and their frequency (high, low), while the y-axis shows priming in ms. The graph compares priming for identity and participle cases.](image-url)
Figure 4
Figure 5

Regular

Irregular 1

Irregular 2

F7  Fz

T3  Cz

T5  Pz

+5 µV

0 200 400 600 ms

--- Participle ---

--- Unrelated ---

+5 µV

0 200 400 600 ms
Figure 6
Figure 7

**Regular**

- Fz
- Cz
- Pz

**Irregular 1**

- Fz
- Cz
- Pz

**Irregular 2**

- Fz
- Cz
- Pz

- Unrelated
- Semantic
- Identity

Time in ms: 0, 200, 400, 600