Aufhören ('stop') activates *hören* ('hear') but not *Musik* ('music')

The difference between lexical and semantic processing of German particle verbs

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This study examines whether the lexical processing of German particle verbs differs from their processing in a semantic network. To this end, we explored whether the processing of particle verbs induces access to the stem (Experiment 1) and to a semantic associate of the stem (Experiment 2). In two cross-modal priming experiments, participants listened to particle verbs that were (a) semantically transparent (e.g. *anhören*, 'listen to'), (b) semantically opaque (e.g. *aufhören*, 'stop'), or (c) form-related (e.g. *aushöhlen*, 'mold') with respect to their stem (e.g., *hören*, 'hear'). Participants made lexical decisions about visually presented stems (e.g., *hören*, 'hear') and about semantic associates to the stem (e.g., *Musik*, 'music') in Experiments 1 and 2, respectively.

Relative to form controls, semantically transparent and opaque particle verbs induced equivalent stem priming (Experiment 1), indicating that the lexical processing of particle verbs occurs via the stem regardless of semantic transparency. However, neither semantically transparent nor opaque particle verbs primed semantic associates of the stem (Experiment 2). These findings indicate that stem access during lexical processing does not extend to a semantic level where the meaning of the stem is processed. We discuss these findings regarding present models of lexical processing.

Keywords: morphological priming, semantic priming, semantic associations, semantic transparency, lexical processing, lexical representation, stem priming, particle verbs, complex verbs

In psycholinguistic research, the phenomenon of semantic transparency has played a key role in testing models on morphological processing. The questions

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concern (i) the processing of complex words such as *to understand*, where the meaning cannot be composed of the parts (*under+stand*), and (ii) whether the processing of such semantically opaque words differs from the processing of words, such as *to underwork*, that are considered semantically transparent because their meaning can be compositionally derived from the meaning of the parts (*under+work*). The processing of complex words such as *to underwork* (transparent) or *to understand* (opaque) has often been linked to claims regarding how these words are represented in the mind and processed in online lexical processing.

In their seminal work, Taft and Forster (1975) claimed that prefixes such as *re-* are stripped from their stems (e.g. *rejuvenate* vs. *repertoire*) in visual word recognition, irrespective of their semantic contribution to the word as a whole. On the other hand, Marslen-Wilson, Tyler, Waksler, and Older (1994) found that, in cross-modal priming experiments, only semantically transparent prefixed words produce priming of their bases like *refill-fill*, while semantically opaque ones like *restrain-strain*, did not. Subsequent overt visual priming studies replicated this contrast in English (Feldman & Larabee, 2001; Rastle, Davis, Marslen-Wilson, & Tyler, 2000), French (Longtin, Segui, & Hallé, 2003), and Serbian (Feldman, Barac-Cikoja, & Kostić, 2002). Proponents of lexicon-based models concluded from the so called "semantic transparency effect" that semantically transparent words like *refill* are lexically processed and represented via their constituents (*re+fill*), whereas semantically opaque words like *restrain* are processed and stored as whole word units (e.g., Marslen-Wilson et al., 1994; Feldman & Soltano, 1999; Diependaele, Sandra, & Grainger, 2009; Xu & Taft, 2015).

The "semantic transparency effect" was further observed when semantic relatedness between complex words and bases was manipulated gradually (rather than binary) in a series of cross-modal priming experiments in English (Gonnerman, Seidenberg, & Andersen, 2007). Strongly phonologically and semantically related word pairs like *preheat-heat* yielded strong priming effects, moderately similar pairs like *midstream-stream* induced intermediate effects, low semantically related word pairs like *rehearse-hearse* yielded no priming, and purely form-related pairs like *coffee-fee* yielded inhibition (or negative effects), all relative to unrelated pairs. In line with the convergence-of-codes view, Gonnerman et al. (2007) concluded that morphological priming effects (between a complex word and its base) occur as an epiphenomenon of shared meaning and shared form. Crucially, lack of priming of opaque verbs was found also in Dutch, which is a structurally similar language to German. In a cross-modal sentence priming study (Zwitserlood, Bolwiender, & Drews, 2005), transparent sentence primes (e.g., *He shouted all sorts of mean things when talking to her*) facilitated transparent (*uitschelden*, 'tell someone names') and ambiguous verbs (that possess both a transparent and an opaque meaning) but not truly opaque verbs (e.g. *kwijtschelden*, 'remit payment'). That is, truly opaque complex verbs were not semantically primed by their stem.

In contrast to the studies in other Indo-European languages, our previous studies in German found no influence of semantic transparency on how complex words are lexically processed and represented. Under overt cross-modal or visual priming conditions, behavioral studies (Smolka, Komlósi, & Rösler, 2009; Smolka, Libben, & Dressler, 2019; Smolka, Preller, & Eulitz, 2014) and electrophysiological studies (Smolka, Gondan, & Rösler, 2015) have found that both transparent and opaque complex verbs facilitate the recognition of their base. Moreover, the priming by opaque verbs on their base (e.g., *verbrechen-brechen*, 'commit a crime'-'break') was equivalent to the priming by transparent verbs on their base (e.g., *zerbrechen-brechen*, 'break into pieces'-'break'). This finding was also replicated when the syntactic, morphological, and phonological differences between prefix and particle verbs were taken into account (Smolka et al., 2019). Furthermore, priming of the base was stronger than the priming between purely semantically related verbs (e.g., *zerbersten-brechen*, 'burst'-'break'), and purely form-related verbs (e.g., *verbrennen-brechen*, 'burn up'-'burn', or *anbrennen-rennen*, 'burn'-'run') even inhibited the recognition of the base. We thus concluded that lexical processing and representation in German refers to the verbal stem, regardless of whether its meaning contributes to the meaning of the whole word.

The next question that arose was: How deeply is the verbal stem processed when it is encountered in a complex verb? – Is it accessed only or is its meaning processed and retrieved at a deeper semantic level? The aim of the present study was thus to examine whether lexical processing of the stem extends to its processing at a semantic level – the processing of the stem's meaning.

Particle verbs in German

German particle verbs offer a unique opportunity for investigation: First, they are numerous and productive (Eisenberg, 2004; Fleischer & Barz, 1992), because they are free or relatively free morphemes, and most of them can function as prepositions or adverbs.[1] First, they are numerous. There are over seventy verbal particles, such as *an* ('at'), *auf* ('on'), *nach* ('after'), *vor* ('before'), *mit* ('with'), *zurück* ('back').

Second, the meanings of particle verbs lie on a continuum between relatively semantically compositional and relatively semantically opaque. In the case of

1. Those particles, which are not free morphemes, are relatively free in being able to change their position (similar to clitics).

zuhören, one could claim that the meaning of *zu* ('to') and the meaning of *hören* ('hear') can plausibly interact to create a somewhat compositional meaning 'hear' + 'to', which means "to listen (to)". More difficult or uninterpretable, of course, are structurally similar particle verbs such as *aufhören* ('stop'), which is composed of the particle *auf* (roughly meaning "on" or "onto") and the same verb stem *hören*, where it is not at all clear how the meaning of *auf* ('on') or *hören* ('hear') contributes to the whole word meaning "to stop", so that they render the particle verb semantically opaque. That is, not only the meaning of the verb stem but also that of the particle is opaque, with no trace of the meanings of either "to hear" nor of "on(to)".

Third, particle verbs have some characteristics that lead to the expectation that these verbs are morphologically structured in the minds of German speakers. (a) Particles can precede or follow the verb, as in *Sie wollen zuhören* ('they want to listen') and *Sie hören zu* ('they listen'), respectively; (b) they involve the physical separation of the particle and the verb stem in finite forms, as in *Er hört dem Konzert zu* (word-by-word: he hears the concert to); (c) the inflectional prefix *ge-* is inserted between the particle and the past participle, as in *zu-ge-hört*; (d) the preposition *zu*, when requested by the governing verb, is inserted between the particle and the dependent infinitive, as in *Sie plant auf-zu-hören* ('she plans to stop'); and (e) the phonological stress is always placed on the particle, in whatever position, as in *ZUhören*.

By contrast, prefix verbs lack all of these five properties. Altogether, these characteristics suggest that native speakers typically interpret particle verbs as containing a particle (e.g., *zu*) and a main lexical component (the stem *hören*, 'hear'). The extent to which these properties affect lexical and semantic processing is investigated in the two cross-modal priming experiments reported below. Experiment 1 examines the lexical processing of the stem, and Experiment 2 examines the semantic processing of the stem.

Experiment 1 – Stems

The purpose of Experiment 1 was to replicate our findings that the lexical processing of particle verb involves the recognition of the base verb (i.e. stem), irrespective of the semantic transparency of the whole particle verb (Experiment 1 in Smolka et al., 2019). We used the same base verbs and selected particle-verb pairs that held the same stem but varied with respect to their semantic transparency, such as *anhören* ('to listen to') and *aufhören* ('to stop'), the former being semantically transparent and the latter opaque with respect to the stem *hören* ('to hear'), and measured priming relative to a form-related particle verb, such as *aushöhlen* ('to hollow out').[2] Particle verbs functioned as primes and base verbs as targets, so that the primes in all conditions had the same morphological structure (particle+stem) and differed only with respect to their relatedness to the target in terms of morphology, semantics, or form. This within-target manipulation allowed us to directly compare the effect of each type of prime on the same target. Prime conditions are exemplified in Table 1; all critical items are listed in the Appendix.

Three quarters of the materials consisted of unrelated fillers to prevent expectancy and strategic effects (Bodner & Masson, 2003), and the same proportion of form-relatedness was used for primes that were form-related with pseudoverb targets.

To tap into lexical processing and to measure modality-independent representations (for a review see Milin, Smolka, & Feldman, 2017), we applied cross-modal priming with auditory prime and visual target presentation.

In Experiment 1, we tested whether particle verbs in German are processed via their stem. If the lexical representation of particle verbs in German depends on meaning composition or meaning relatedness, as it is assumed for other languages such as English (Rastle et al., 2000; Marslen-Wilson et al., 1994; Taft & Nguyen-Hoan, 2010) particle verbs will be processed via their stem only if they are semantically transparent, but not if they are opaque. Accordingly, the former but not the latter will induce priming to the stem. If however, our previous findings (Smolka et al., 2009, 2014, 2015, 2019; Smolka & Libben, 2017) hold that all complex verbs are lexically processed via their stem and irrespective of semantic transparency, we should find priming of the stem by both transparent and opaque particle verbs.

Method

Participants

Thirty-eight students of the University of Konstanz participated for course-credit. All were monolingual native speakers of German, not dyslexic, and reported normal or corrected-to-normal vision and no hearing impairments.

Materials

Critical stimuli

Twenty-four base verbs were selected. Each base verb, such as *hören* ('hear') was paired with three primes. All primes were particle verbs and differed only with

2. Twenty-three of 24 targets and 39 (16 transparent, 13 opaque, 10 form-related) of 72 primes were identical to the items applied in Experiment 1 in Smolka et al., (2019).

respect to their relatedness with the base in terms of morphology, semantics, or form. (a) Semantically transparent (T) particle verbs like *anhören* ('listen to') were meaning related with the base, and (b) semantically opaque (O) particle verbs like *aufhören* ('stop') were not meaning related with the base. Both T and O particle verbs held the same stem as the base, and were real etymological derivations of it; (c) form-related (F) particle verbs such as *aushöhlen* ('hollow out') held a different stem as the target and were related neither in morphology nor in meaning, but differed phonologically by one phoneme. The transparency of the primes was judged by two native speakers of German, and was further confirmed by reference to the association norms in Smolka and Eulitz (2018) or to the lexical paraphrases of the verbs in the DUDEN dictionary (Dudenredaktion, 2009): If the lexical paraphrase of the complex verb refered to the base verb, it was considered as being "semantically transparent" otherwise it was considered as being "semantically opaque".

The semantically transparent and opaque primes were closely matched on number of letters and syllables, as well as on lemma frequency (taken from the CELEX database, Baayen, Piepenbrock, & van Rijn, 1993). A one-way ANOVA conducted on lemma frequencies indicated that there was no difference between the semantically transparent and opaque prime conditions, $F < 1$. Given that form-related primes were selected because of their phonological similarity to the target stem, they could not be matched to the morphological conditions on frequency and were thus less frequent than either the transparent or the opaque condition. The within-target design of this study controls for distributional variables of the target across conditions (e.g., frequency, length, neighborhood size, family size). Table 1 summarizes the stimulus characteristics; the Appendix lists all critical stimuli.

Table 1. Stimulus characteristics of semantically transparent, opaque, or form-related particle verbs as primes and base verbs as targets in Experiment 1

	Target	**Prime**		
	Base verb	**Transparent**	**Opaque**	**Form**
Examples	*hören*	*anhören*	*aufhören*	*aushöhlen*
N	24	24	24	24
Frequency	1875	100	120	52
FrequencyLog	7.0	3.6	3.7	2.4
Letters	6.3	9	9.5	9
Syllables	2	3	3	3

Note. N = number of items used, Frequency = mean absolute lemma frequency from CELEX (Baayen, Piepenbrock, & Van Rijn, 1993), FrequencyLog = log-transformed lemma frequencies; Letters = mean number of letters; Syllables = mean number of syllables.

Fillers

To prevent strategic effects, a total of 208 prime-target pairs were added as fillers, so that the experiment consisted of 232 prime-target pairs, half with verbs and half with pseudoverbs as targets. All primes were complex verbs (i.e. prefix or particle verbs). Ninety-two were combined with (morphologically, semantically, and form-) unrelated verb targets; 116 were combined with pseudoverb targets, of these, 92 were unrelated with the prime, and 24 were form-related with the prime, such as *unterscheiden-*scheigen*. Form-related prime-pseudoverb targets ensured that participants did not respond with 'word' decisions for any trial where prime and target had form overlap. Pseudoverbs were constructed by exchanging one or two letters in the stem of a real verb, while preserving the phonotactic constraints of German. All filler items differed from those of the critical set. Throughout the experiment, all primes and targets were presented in the infinitive (stem + *-en*), which is also the citation form in German.

Overall, the large amount of fillers reduced the proportion of (a) critical prime-target pairs (T/O/F) to 16%, (b) morphologically related prime-target pairs (T/O) to 8%, (c) meaning-related pairs (T) to 0.3%, and (d) form-related pairs (T/O/F-verbs/F-pseudoverbs) to 24% of the whole material set.

Apparatus

Recording of auditory stimuli

A phonetically trained female native speaker of German recorded the primes. Recording took place in a sound-attenuated cabin by means of a microphone (MXL-990) and a digital audio recorder (Tascam HD-P2; sampling rate 44.1kHz, 24bit). All audio files were scaled in intensity using the PRAAT software package (Boersma & Weenink, 2009). Words were segmented and normalized at 95% of the maximum amplitude.

Visual stimuli were presented on a widescreen monitor, connected to an IBM-compatible Dual Core personal computer. Auditory primes were presented via *beyerdynamic* headphones. Stimulus presentation and data collection were controlled by the *Presentation* software developed by *NeuroBehavioral Systems* (http://www.neurobs.com/). Response latencies were recorded from the left and right buttons of a button box.

Design

The three primes of the same critical verb target were rotated over three lists according to a Latin Square design. Participants received only one experimental list and therefore saw each target verb only once, in one of the three conditions, but all three prime conditions overall. For example, list 1 included the prime-target pair *anhören-hören*, list 2 the pair *aufhören-hören*, and list 3 *aushöhlen-hören*.

In total, an experimental session comprised 232 prime-target pairs presented in two experimental blocks, with 116 prime-target pairs per block. Trial presentation within blocks was pseudo-randomized separately for each participant, so that no more than four consecutive word or nonword targets occurred in a row. Twenty-six additional prime-target pairs served as practice trials.

Procedure

Participants were tested individually, seated at a viewing distance of about 60 cm from the screen. Each trial started with a fixation cross in the center of the screen. During the presentation of the prime, the fixation cross remained on the screen. At the offset of the prime, the target was presented in white Sans-serif letters, point 24, in the center of the screen, and remained on the screen until a participant's response. The inter-trial interval was 1000 ms. Participants were instructed to listen to the first word and to make a lexical decision on the visual item as fast and as accurately as possible. 'Word' responses were given with the index finger of the dominant hand, and 'pseudoword' responses with the subordinate hand. Feedback was given on all responses during the practice session, and on incorrect responses during the experimental session.

The experiment lasted for about 18 minutes. Participants self-administered the break between the two blocks.

Results

Two participants whose error rates were higher than 20% on either word or nonword responses were removed, so that the data of 36 participants remained in the analyses. The error rate on all items was 7.96%, and on critical items 1.4%. Because of too few data points (12 errors on critical items), we omitted the error analysis. Only correct responses and response times between 300 ms and 1500 ms were included in the RT data analyses (removing 9 data points).

We used R (R Core Team, 2012) and *lme4* (e.g., Bates, 2005; Baayen, Davidson, & Bates, 2008) to perform linear mixed effects analysis. As random effects, we had intercepts for participants and targets. To remove autocorrelational structure from the residual errors (Baayen & Milin, 2010), we included the response latency at the preceding trial (Previous RT) as control predictor (Previous RTs higher than 2000 ms were set to 2000 ms to avoid losing data points), and tested the influence of other control variables, such as List, Block, Trial, and Duration of the auditory prime. The fixed-effect factor of interest was Prime Type. We further examined the influence of frequency (log-transformed and centered absolute lemma frequencies from CELEX), separately for the prime and the target. We applied a forward procedure for the model selection, starting with a minimal model and adding additional predictors only when they improved the model fit. The best model fit was obtained by comparing the Akaike Information Criterion (AIC) statistics between models, with a difference between models > 4 (Sakamoto, Ishiguro, & Kitagawa, 1986). The best model included the control predictors Previous RT and Block (even though Block was only marginally significant, it significantly improved the model), and the factors Prime Type and Target Frequency, and an interaction of the two. Table 2 summarizes the effects.

Table 2. Fixed effects of the predictors in the linear mixed-effect model for the response latencies in Experiment 1

	Estimate	**Std. Error**	***t* value**	***p***
Intercept	533.28	20.65	25.82	<2.00e-16***
Previous RT	0.16	0.02	9.14	<2.00e-16***
Block 2	−20.82	10.74	−1.94	0.0662
Prime Type opaque	−30.11	10.07	−2.99	0.0029**
Prime Type transparent	−51.63	10.08	−5.12	3.84e-07***
Target Frequency	−36.26	8.30	−4.37	2.80e-05***
Prime Type opaque x Target Frequency	18.53	10.95	1.69	0.0910
Prime Type transparent x Target Frequency	23.43	10.97	2.14	0.0330*

Note. Previous RT = latency at the previous trial, Block 2 = second block (relative to first block), Prime Type = semantically transparent or opaque primes (relative to form-related), Target Frequency = absolute lemma frequency of the target, taken from CELEX (Baayen et al., 1993); significance codes:
*** < .001. ** < .01. * < .05.

Results were straightforward: A faster response at the previous trial predicted a faster response at the current trial, and responses in the second block were faster than in the first block. Most importantly, the fixed-effect factor Prime Type was highly significant (the form-related condition was used as reference level). Responses to targets were faster following both transparent (601 ms) and opaque (621 ms) particle verbs than following form-related primes (650 ms). Post-hoc Scheffé contrasts indicated that the difference between the transparent and the opaque condition was not significant ($SE = 10$, $t = -2.15$, $p = .1008$). This effect of Prime Type is depicted in the upper panel of Figure 1. Also the fixed-effect factor Target Frequency was significant with faster responses to higher frequent than to lower frequent targets. Furthermore, as Figure 2 depicts, Target Frequency interacted with Prime Type, indicating that only lower frequent but not higher frequent targets were primed relative to the form-related condition.

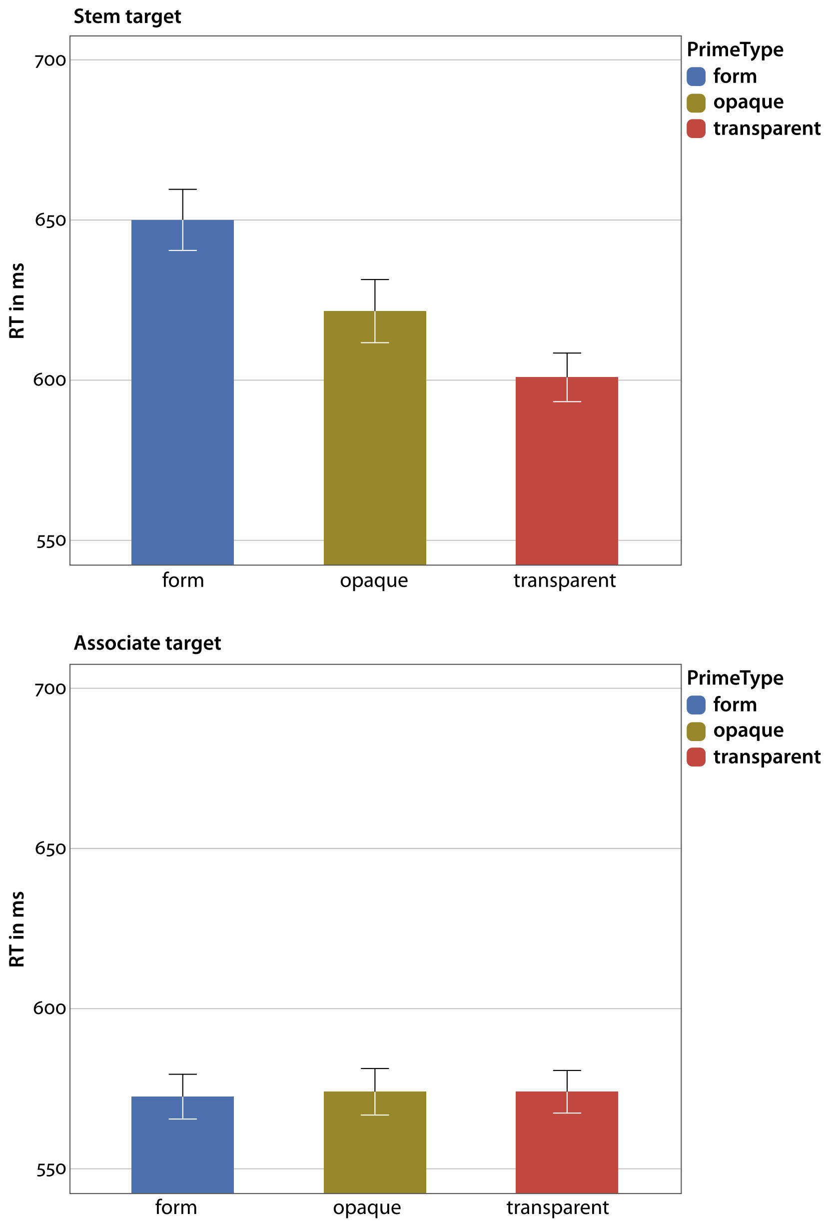

Figure 1. The effect of Prime Type (form/opaque/transparent) in Experiment 1 (upper panel) and Experiment 2 (lower panel). The y-bars indicate the standard error of the mean

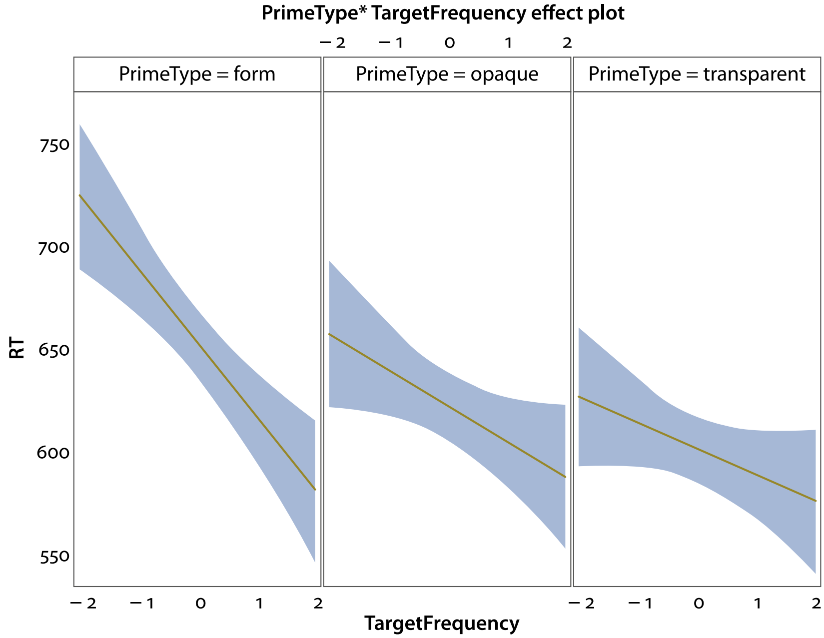

Figure 2. The interaction between Target Frequency and Prime Type in Experiment 1

Experiment 2 – Associates

In Experiment 1, we have shown that – irrespective of their semantic transparency – particle verbs are accessed for their stem during lexical processing and facilitate the recognition of low frequency targets. The purpose of Experiment 2 was to explore whether access to the stem also involves the semantic processing of the stem, that is, the processing of its meaning.

Semantic processing is assumed to occur via the spreading activation across the nodes in a semantic network. In associative semantic-network models similar to that by Collins and Loftus (1975; Dell, 1986; for different accounts see Brunel & Lavigne, 2009), activation spreads from the activated node (i.e., a heard or seen word or concept) to other nodes in the network: The stronger the activation of the first node, the stronger the activation of the surrounding nodes and the further the spread of activation through the network. If access to the stem during lexical processing also involves the processing in a semantic network, (and based on the assumptions of semantic-network models), we expect that activation will spread from an activated base node like *hören* ('hear') to other close nodes in the network, and most probably to semantic associates like *Musik* ('music'). In the present experiment, we ask whether the activation spreading from *hören* to

Musik will occur if *hören* is not the activated node itself but is rather accessed via a particle verb like *anhören* or *aufhören*.

So far, only two overt visual priming studies in Dutch examined the priming between particle verbs and associates of the stem and found that priming was modulated by semantic transparency. When primes were particle verbs, only semantically transparent verbs (e.g. *meebrengen-halen*, 'bring along'-'fetch') but not opaque particle verbs primed associates of the stem (Zwitserlood, Drews, Bolwiender, & Neuwinger, 1996). When the order was reversed, associates of the stem primed only semantically transparent motor-related particle verbs (de Grauwe, Lemhöfer, & Schriefers, 2019).

In Experiment 2, we combined the semantically transparent and opaque particle verbs with the semantic associate of the stem (i.e. *anhören-Musik*, 'listen to'-'music' and *aufhören-Musik*, 'stop'-'music', respectively) and measured priming relative to a form-related particle verb (e.g., *aushöhlen-Musik,* 'hollow out'-'music'). Critical conditions are exemplified in Table 3.

Table 3. Stimulus characteristics of semantically transparent, opaque, or form-related particle verbs as primes and associates of the base verb as targets in Experiment 2

	Target	Prime		
	Associate	**Transparent**	**Opaque**	**Unrelated**
Examples	*Musik*	*anhören*	*aufhören*	*aushöhlen*
N	24	24	24	24
Frequency	1736	100	120	52
FrequencyLog	6.1	3.6	3.7	2.4
Letters	5.3	9	9.5	9
Syllables	1.7	3	3	3
Association Strength	0.3			

Note. Associate = semantic association to the base verb; N = number of items used, Frequency = mean absolute lemma frequency from CELEX (Baayen, Piepenbrock, & Van Rijn, 1993), FrequencyLog = log-transformed lemma frequencies; Letters = mean number of letters; Syllables = mean number of syllables; Association Strength = association strength with the base verb (1 = 100%).

We applied cross-modal priming to examine whether the lexical processing of the stem extends to the semantic processing of the stem. If, as attested in Experiment 1, lexical processing of the particle verbs *anhören* and *aufhören* occurs via the stem *hören*, and if semantic activation spreads from the base *hören* to its close semantic associate *Musik*, we expect to find priming by the particle verbs on the semantic associate of the stem (*anhören-Musik, aufhören-Musik*). If, however, access to the stem during lexical processing does not involve its processing in a semantic network, particle verbs will not prime associates of the stem.

Method

Participants

Fifty students of the University of Konstanz participated for course-credit. All were monolingual native speakers of German, not dyslexic, and reported normal or corrected-to-normal vision and no hearing impairments. They had not participated in Experiment 1.

Materials

Critical stimuli

The stimulus set-up was the same as in Experiment 1 except that semantic associates (instead of base verbs) were used as critical targets. The three prime conditions were identical to those in Experiment 1 and included (a) 24 semantically transparent (e.g. *anhören*, 'listen to'), (b) 24 semantically opaque (e.g. *aufhören*, 'stop'), and (c) 24 form-related (e.g., *aushöhlen*, 'hollow out') particle verbs. Each of the three primes that referred to the same base verb (e.g., *hören*, 'hear') was paired with a semantic associate of that base verb. For example, the semantic associate of the base verb *hören* ('hear') was *Musik* ('music'), which was paired with each of the three primes (*aufhören-Musik, anhören-Musik*, and *aushöhlen-Musik).* The semantic associates were collected in the semantic association task described below. Table 3 provides an overview of the stimulus characteristics; the Appendix lists all stimuli.

Semantic association task

A web-based semantic association task was conducted to establish the semantic associate to each base verb. The web-experiment was constructed by Javascript, and presented to 35 students of the Universities of Aachen and Leipzig. Participants saw a base verb on the screen and typed in the word that came to their mind. Each participant saw all 24 base verbs so that 35 associations were collected for each base verb, resulting in 840 associations. The most frequent response to a base was selected as an associate target in the priming experiment.[3] The final set of associates consisted of 16 simple nouns (two held a plural suffix) and 8 base verbs;

3. When counting the most frequent response, singular and plural forms (e.g. *Hand-Hände*, 'hand'-'hands'), and nouns and verbs of the same stem (e.g., *Sturz-stürzen*, 'fall'-'to fall') were merged. For the verbs *schießen* ('shoot') and *stechen* ('sting'), the targets *Waffe* ('weapon') and *Insekt* ('insect'), respectively, were chosen, even though they were not the most frequent response. "Weapon" was chosen as a generic term to include the given responses *Gewehr* ('rifle'), *Pistole* ('pistol'), and *Revolver* ('colt'); and "insect" included the responses *Mücke* ('mosquito'), *Biene* ('bee'), and *Wespe* ('wasp').

mean association strength of the final set was 30% (range 11%–54%). Absolute lemma frequencies of the targets were collected from CELEX (see Baayen et al., 1993).

Fillers

As in Experiment 1, a total of 208 prime-target pairs were added as fillers, so that the experiment consisted of 232 prime-target pairs, half with words and half with pseudowords as targets. All primes were complex verbs (i.e. prefix or particle verbs), two-thirds of the targets were nouns or pseudonouns and one third were verbs or pseudoverbs, corresponding to the critical target set. Of the pseudoverbs, 24 were form-related with the prime.

Apparatus, design and procedure

Apparatus, design and procedure were identical to those in Experiment 1 (with the exception that no feedback was given in Experiment 2).

Results

The same outlier procedure was applied as in Experiment 1. Three participants with high error rates were removed, including the data of 47 participants in the analyses. The error rate on all items was 6.34%, and on critical items 0.975%. Because of too few data points (11 errors on critical items), we omitted the error analysis. Only correct responses and response times between 300 ms and 1500 ms were included in the RT data analyses (removing 5 data points).

As in Experiment 1, we performed linear mixed effects analysis and had intercepts for participants and targets as random effects. Previous RT (Previous RTs higher than 2000 ms were set to 2000 ms) and Block were control predictors. The fixed-effect factor of interest was Prime Type, as well as characteristics of the target associate, such as Associate Frequency (log transformed and centered absolute lemma frequencies from CELEX), Word Category and Association Strength. We applied a forward procedure for the model selection and compared the AIC to obtain the best model fit. The best model included the control predictors Previous RT and Block, and the factors Associate Frequency, Word Category, and Association Strength, as well as an interaction between the latter two. The factor Prime Type had no effect at all and was thus not included in the model. Table 4 summarizes the effects.

As in Experiment 1, a faster response at the previous trial predicted a faster response at the current trial; and responses in the second block were faster than in the first block. Interestingly, the factor Prime Type had no effect at all, which is depicted in the lower panel of Figure 1. By contrast, all factors relating to the asso-

Table 4. Fixed effects of the predictors in the linear mixed-effect model for the response latencies in Experiment 2

	Estimate	Std. Error	*t* value	*p*
(Intercept)	506.95	14.82	34.21	<2.00e-16***
Previous RT	0.09	0.01	6.64	5.01e-11***
Block 2	−32.95	10.91	−3.02	0.0074**
Word Category verbs	22.47	15.70	1.43	0.1696
Association Strength	−15.17	12.84	−1.18	0.2529
Associate Frequency	−54.30	20.11	−2.70	0.0147*
Word Category verb x Association Strength	−89.64	32.62	−2.75	0.0132*

Note. Previous RT = latency at the previous trial, Block = second Block (relative to first Block); Word Category = word category of the associate (relative to nouns); Association Strength = association strength with the base verb; Associate Frequency = absolute lemma frequency of the associate, taken from CELEX (Baayen et al., 1993); significance codes:
*** < .001 ** < .01 * < .05

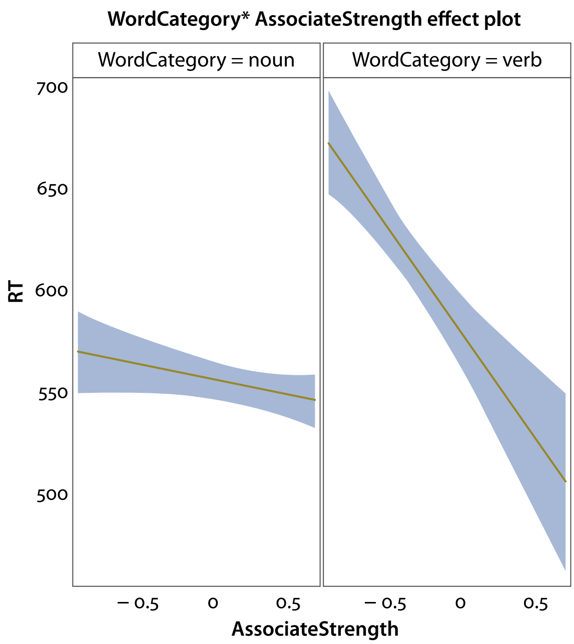

Figure 3. The interaction between Association Strength and Word Category of the associate in Experiment 2

ciate target affected responses: Associate Frequency was facilitatory with faster responses to higher frequent than to lower frequent target associates. Association Strength interacted with Word Category, indicating that Association Strength affected responses only if they were to verb associates but not to noun associates. That is, responses to verb associates were faster when the association strength between the associate and the base verb was high, and responses were slower when the association strength between the associate and the base verb was low (see Figure 3).

General discussion

The present study tested whether the lexical processing of particle verbs involves not only the stem (Experiment 1), but also extends to the semantic processing of the stem (Experiment 2). We applied cross-modal priming experiments in which participants heard semantically transparent and opaque primes and made lexical decisions to the stem (Experiment 1) or to associates of the stem (Experiment 2).

The results of Experiment 1 were straightforward: Relative to form-related particle verbs, semantically transparent and opaque particle verbs facilitated the recognition of their stem, without an effect of semantic transparency (see the upper panel of Figure 1; the numerical difference between the priming by transparent (49 ms) and opaque (29 ms) particle verbs was not statistically significant).

Also target frequency affected responses and interacted with prime type so that only lower frequent targets were primed by semantically transparent or opaque primes, but not high frequent ones (see Figure 2). This interaction resembles previous findings where target frequency interacted with prime type when primes were prefix verbs (Experiment 2 in Smolka et al., 2019) but not when primes were particle verbs (Experiment 1).

Overall, the lack of a semantic transparency effect in Experiment 1 replicates our previous findings under visual (Smolka et al., 2009, 2014, 2015) and cross-modal priming conditions (e.g., Experiment 2 in Smolka et al., 2014; Experiment 1 and Figure 1 in Smolka et al., 2019). It provides evidence for modality-independent shared lexical representations (Rueckl & Galantucci, 2005) between morphologically related particle verbs and their common bases, including semantically opaque ones. Following the logic of lexicon-based models, we may conclude that the lexical processing of both semantically transparent and opaque particle verbs, such as *zuhören* and *aufhören*, respectively, refer to their stem *hören*.

Experiment 2 asked whether access to the stem (as established in Experiment 1) extends to the processing of the stem's meaning. However, the findings of Experiment 2 clearly demonstrate that this is not the case: Neither semantically transparent nor opaque particle verbs facilitated the recognition of a close associate of the stem. In contrast to prime type, various characteristics of the associate, such as its frequency, word category, and association strength, affected responses. As expected, responses were faster to higher frequent than to lower frequent target associates. As indicated by Figure 3, there was a word category effect: when the associate was a verb (not a noun), responses were faster, the higher the association strength with the original base verb, and responses were slower, the lower the association strength. Furthermore, responses in Experiment 2 were overall faster than responses in Experiment 1. We attribute this result to a word category effect, since lexical decisions were mostly on nouns or adjectives in Experiment 2 and on verbs in Experiment 1. Indeed, previous findings (Fickel & Smolka, 2014) observed a strong word category effect with faster responses to nouns in comparison to verbs, even though they were matched on frequencies and other distributional variables, and irrespective of whether they were bases or zero derivations (i.e. conversions).

The present observation that particle verbs did not prime associates of their stem differs from previous findings in Dutch, where semantically transparent particle verbs primed the stem associates (Zwitserlood et al., 1996) or where stem associates primed semantically transparent motor-related particle verbs (de Grauwe et al., 2018). The reasons for this difference are manifold. First, these studies applied a different language and different modalities of prime presentation. Indeed, Pastizzo and Feldman (2002) demonstrated that visual prime presentation augments the pattern of morphological effects observed cross-modally. Relative to the visual prime presentation in the Dutch studies, the auditory prime presentation in the present study may have considerably weakened the effects so that they became untraceable. Unfortunately, we are not aware of further studies that examined the effects of complex verbs on associates of the stem. We thus urge the conduction of future experiments to examine whether cross-modal priming conditions are capable of detecting associative priming effects (e.g. *hören-Musik*, 'hear'-'music').

Another interpretation of the lack of priming effect is that stem access during lexical processing does not extend to a semantic level at which the meaning of the stem is processed. If we assume that semantic processing occurs via the spreading of activation across the nodes in a semantic network (e.g., Collins & Loftus, 1975; Dell, 1986), activation should spread from an activated node like *hören* ('hear') to a closely associated node like *Musik* ('music'), and we should see this activation spread in the priming of *Musik* by *hören*. Because we do not find any priming of stem associates like *Musik* by their base nodes like *hören*, we may conclude that lexical access to the stem *hören* did not extend to the node *hören* in a semantic network. Indeed, this interpretation fits well with the findings by Ji, Gagné, and Spalding, (2011) who studied the processing of English compounds and have shown that opaque compounds were processed as fast and as accurately as transparent compounds, indicating that they both activate the same representations at the lexical level (see Experiment 3 in Ji et al., 2011), but that this priming effect did not extend to a semantic level.

Taken together, our German findings have repeatedly shown stem priming for complex verbs and compounds, independent of semantic transparency (Smolka et al., 2009, 2014, 2015, 2019; Smolka & Libben, 2017). These findings are at odds with both lexicon-based and connectionist models, claiming that either semantic compositionality or shared meaning and shared form, respectively, are prerequisites for morphological effects (Diependaele, Sandra, & Grainger, 2005; Gonnerman et al., 2007; Marslen-Wilson et al., 1994; Rastle et al., 2000). By contrast, a most recent model that applied naïve discriminative learning (Baayen & Smolka, 2019) was able to simulate the behavioral effects of stem priming without any assumption of stems or morphemes. We assume that language processing depends on the input language, its structure, and the learner's language experience. Indeed, Günther, Smolka, and Marelli (2019) have recently shown in a simulation that cross-linguistic differences between German and English can be attributed to quantitatively-characterized differences in the speakers' language experience. Nevertheless, we further conclude that stem access during lexical processing in German does not extend to the processing of the stem's meaning in a semantic network.

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