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Blueberries and fingerprints: ERP insights into compound structure in production

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ABSTRACT
Prior neuropsychological work provides evidence for morphological complexity in the production of compounds, but questions remain about its locus. We investigate this here by comparing behavioral and ERP picture naming responses of English compounds when preceded by morphological, semantic, and phonological auditory primes. Morphological priming significantly speeded compound naming relative to other conditions, and ERPs showed differences in timing and distribution: morphological priming resulted in a reduced centro-posterior negativity, phonological priming resulted in a late-onset increased frontal negativity, and semantic priming showed only a numerical tendency towards an N400 reduction. These results are consistent with the view that compound production requires operations over morphosyntactic and morphophonological parts, both of which may be responsible for the systematic errors of compound production observed in many patients with aphasia. Such data provide further support for a shift away from a simple dichotomy between lexical activation and sentence production in models of aphasia.

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1. Introduction

Expressions like *airbag* or *government* appear more complex than expressions like *bag* and *govern*. This has been traditionally described by saying that *airbag* is made up of two morphemes, namely *air* and *bag*, and similarly that *government* is made up of *govern* and *-ment*. Indeed, traditional morphemes, intended as the smallest units of form that carry a meaning, have been widely assumed in both linguistics and psycholinguistics. However, both theoretical advancements in morphology and evidence from aphasic patients seem to point to a different picture, where the complexity of each expression can be at the level of meaning, morphosyntax or form.

In the current study, we focus on the case of compounds. Much psycholinguistic evidence on compound production, especially from error patterns in patients and priming effects in healthy adults, suggests that production of compounds involves operations over smaller units (Badecker, 2001; Blanken, 2000; Chiarelli et al., 2007; Koester & Schiller, 2008; Lorenz et al., 2014; Marelli et al., 2012; Semenza et al., 1992, 2011). What is still unclear is whether these operations take place at the level of phonological form only, or also at the level of morphosyntax. Here we compare how ERP responses during naming of compounds are modulated by morphological and phonological primes, in order to provide a new source of evidence towards this question.

Gaining a better understanding of the production of morphologically complex expressions has wider ramifications for production models in general and for models of production deficits in aphasia (Krauska & Lau, 2023). Standard models of language production distinguish the process of accessing or activating individual "lexical items" or "lemmas" from the combinatory process of structuring or sequencing the activated items into a sentence (see Ferreira & Slevc, 2007, for review). Correspondingly, characterizations of language production deficits often define a major division along the same lines, distinguishing anomia -"word-finding" difficulties- from agrammatism - syntactic and morphosyntactic difficulties. However, decades of cross-linguistic research on production deficits in aphasia suggest a complex picture in which error profiles vary across patients and across languages (e.g., Nedergaard et al., 2020), motivating longstanding criticisms regarding the coherence and utility of the "agrammatism" category (Miceli et al., 1989). Similarly, evidence for morphological complexity in production raises serious questions about processing architectures of this kind, because a single unit at one level (e.g., a stored concept) might correspond to more than one unit at another level

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(morphosyntax and/or morphophonology). Careful characterization of the production operations required for morphologically complex expressions like compounds are needed to inform development of alternative models of production which make better predictions about what kinds of deficit profiles are expected in production.

1.2. Insights from theoretical morphology

In the last 30 years, theoretical morphologists across different frameworks have reached a consensus that the traditional notion of morpheme as the smallest unit of meaning and form is not adequate to describe the complexity of morphological systems crosslinguistically (Anderson, 1992; Aronoff, 1994; Aronoff & Sims, 2023; Halle & Marantz, 1993; Haspelmath, 2011; Jackendoff & Audring, 2019). The reasons are empirical: in many cases it is impossible to identify a consistent form with a consistent meaning. For instance, in English, there are many irregular past tense verbs whose stem changes from present to past tense (*sing ∼ sang, win ~ won*) but that have no identifiable morphophonological piece that means "past". English also contains the reverse kind of cases in which an identifiable morphophonological piece doesn't seem to have an independent meaning (e.g., *cran-* in *cranberry*). Moreover, different phonological forms can correspond to the same meaning/morphosyntactic feature. For instance, in English, the morphosyntactic feature PLURAL, is realized by different phonological material in different contexts, namely /-z/ in regular plurals, /-ən/ in *children*, /-ə/ in *bacteria* and ∅ in *fish*.

These morphological patterns, and many others across the world's languages (see Anderson, 1992: Ch 3; Cuonzo, 2025: Ch 2), would be unexpected according to the traditional view that a set of meaning-form "morpheme" units is the input to combinatorial operations. The solution –implemented in slightly different ways across different frameworks– is to give up the morphemes as one-to-one mappings between meaning and form, and instead separate morphosyntactic objects from their context-sensitive morphophonological realizations and meanings. For instance, the morphosyntactic feature PLURAL would map to various forms, namely /-z/, /-ən/, /-ə/ and ∅, and to a meaning like "more than one". In this sense, there is no single piece of form that we can identify as "the plural morpheme". Similarly, for *sing/sang* a single morphosyntactic object would map to two different context-conditioned forms, respectively /sɪŋ/ and /sæŋ/, and to a meaning along the lines of "to produce musical tones by means of the voice". In the case of compounds, like *airbag* or *butterfly*, the question then becomes whether compounds are complex at the level of meaning, morphosyntax, and morphophonology. It seems straightforward that they are complex at the level of form, since it is easy to identify morphophonological pieces in them, e.g., /ɛr/ and /bæg/. However, it is more difficult to determine whether they are also complex at the meaning and morphosyntactic levels.

Indeed, in English, we find both familiar compounds and productive compounds. Productive compounds (e.g., *ferret brush* or *coffee faucet*) are generated on the fly when speakers want to refer to a particular object or type of object that doesn't have a fixed name. In these cases, the head must specify the type of the object (a ferret brush is a brush, not a ferret), and the modifier is understood as being in some semantic relation to the head. Although this semantic relation itself is famously underspecified (e.g., a ferret brush could be, for instance, a brush specially designed for use on ferrets or a human brush with a picture of a ferret on it), productive compounds are still "compositional" in the sense that the meanings of the individual nouns combine in a way that is constrained by the grammar, such that the head contributes differently to the meaning than the modifier (Levi, 1978). On the other hand, familiar compounds (often referred to as "lexicalized" or idiomatic compounds) serve as fixed names for known types of entities, such as *airbag, blueberry* or *jellyfish*. Although one can often reconstruct the rationale for their generation historically (e.g., *airbag*—a bag that fills with air, *jellyfish*—an aquatic creature that appears to be made of jelly), familiar compounds are fixed expressions that name objects by convention. It is thus plausible that the meanings of these familiar compounds are equivalent in complexity to the meanings of simple words. Evidence for this also comes from the fact that compounds are cross-linguistically arbitrary: for instance, where English uses familiar compounds *blueberry* and *jellyfish*, Italian uses simple wordforms *mirtillo* and *medusa*.

As far as morphosyntax is concerned, it is more difficult to determine whether compounds are complex or not. While there is generally agreement in the formal literature that productive compounds are syntactically complex, there is debate on whether familiar compounds are syntactically complex (Harley, 2011 among others) or not (Giegerich, 2011 among others). In languages like Vietnamese and Chinese, evidence for the morphosyntactic complexity of familiar compounds comes from the fact that the two components of a compound can be separated. For instance, a verb can intervene between the two components of the compound *nhà cửa* "a (furnished) house" (lit. "house-door"), in a sentence like *Tôi xay nhà xay cửa*, "I build a (furnished) house" (lit. "I build house build door") (Noyer, 1998). In English, the evidence for morphosyntactic complexity of compounds is less blatant (but see Siddiqi, 2006 for discussion). Evidence from aphasic patients can help us shed light on this question, as we will see next.

1.3. Evidence from aphasia

Familiar compounds have been widely investigated in language production because they are morphologically complex forms that can serve as names for objects and thus can be studied using standard picture-naming paradigms. Given that familiar compounds are fixed expressions already known to the speaker, in principle it could have been possible that they are produced just like simplex nouns. However, the patterns of errors tell us otherwise. The naming of objects with compound nouns has been studied in patients speaking German (Blanken, 2000; Lorenz et al., 2014, 2022), English (Badecker, 2001) and Italian (Chiarelli et al., 2007; Semenza et al., 1992, 2011). When people with aphasia produce an incorrect noun for an object, the substituted noun tends to preserve the same structure: if the object has a simplex name, it is more likely to be substituted with another simplex noun, and if the object has a compound name, it is more likely to be substituted with another compound. Moreover, many of the compound errors are neologisms in which one or both of the compound components are substituted with semantically related wordforms (e.g., *water horse* for *seahorse*, *butter flower* for *butterfly*), or in which the components are misordered (e.g., *shoe snow* for *snowshoe*). As illustrated in the examples, such errors occur both for so-called semantically transparent and opaque compounds, and they are not matched by equal rates of syllable substitutions in simplex names. Indeed, several papers report lower accuracy for compound naming than simplex naming overall (Blanken, 2000), or at least in certain participants (Badecker, 2001; Delazer & Semenza, 1998).

Crucial evidence comes from Lorenz et al. (2014) and Marelli et al. (2012). They find that patients who have deficits in verb production also show deficits in producing the verb component of VN compounds whose overall category is nominal. This suggests that the syntactic category information from the compound constituents is still operative in compound production, and points towards compounds being complex not only morphophonologically but also morphosyntactically. As we will see next, conducting experiments on compounds can provide converging evidence.

1.4. Evidence from production experiments in healthy adults

Relative to the massive literature on morphological processing in comprehension (see Amenta & Crepaldi, 2012 for a review), morphological structure remains understudied in production, in part due to the difficulty of eliciting morphologically complex words (such as, for instance, complex verb forms or nouns with case endings) without introducing other aspects of phrasal planning (although see Clahsen et al., 2018; Koester & Schiller, 2008; Schiller, 2020). On the other hand, compounds provide examples of morphologically complex words that can be easily elicited in isolation.

Early work by Zwitserlood and colleagues (Dohmes et al., 2004; Zwitserlood et al., 2000, 2002) used a picture-word interference paradigm (presenting written word distractors along with the picture to be named). They found that compound distractors (e.g., *flowerpot*) reliably facilitated the speed of naming of their constituents (e.g., a picture of a flower), both when the distractor word co-occurred with the picture as well as in a long-lag priming configuration. Dohmes et al. (2004) showed that this facilitation was equivalent when using compound distractors with opaque meanings (e.g., *Zeitungsente* "false report", lit. "newspaper duck", facilitating naming of a picture of a duck), and that facilitation was significantly smaller for distractor words which contained the picture name but were not morphologically related (e.g., *Neurose* "neurosis" as a prime for *Rose* "rose").

In a similar line of work, Döring et al. (2022) showed that compound naming is subject to cumulative semantic interference from its constituents. Cumulative semantic interference occurs when participants are asked to name several nouns belonging to the same semantic category (e.g, *apple*, *banana*, *pear*, *cherry* for edible fruits). The naming of each noun is linearly slowed down depending on how many nouns of the same category have been named. In an experiment on German, Döring et al. (2022) found that the naming of compounds whose modifiers belong to the same category is equally slowed down (*<u>Fuß</u>ball* "football", *<u>Hand</u>schuh* "glove" (lit. "hand shoe"), *<u>Kopf</u>salat* "lettuce" (lit. "'head salad"), *<u>Hals</u>krause* "neck brace" (lit. "neck ruff"), *<u>Arm</u>brust* "crossbow" (lit. "arm chest")). In an ERP recording study using long lag priming of picture naming (text primes to be read were separated from target pictures by 7–10 trials) in Dutch, Koester and Schiller (2008) replicated previous behavioral findings, showing that both semantically transparent and semantically opaque compound primes facilitated subsequent production of its constituents (e.g., *jaszak* "coat pocket" → *jas* "coat"). In the ERPs to the presentation of the target picture to be named, they found a broadly distributed reduced negativity between 350–650 ms when the picture had been preceded by a compound prime. Koester and Schiller (2008) interpreted this reduced negativity as an N400 effect, an ERP modulation commonly observed for semantic priming paradigms in comprehension (see Kutas & Federmeier, 2011 and Lau et al., 2008 for reviews). No facilitation or ERP modulation was found when the prime was related in form only (*jasmijn* "jasmine" → *jas* "coat").

Many of the prior studies used compounds as the distractor or prime, while the actual target name to be produced was simplex. However, other work has demonstrated similar morphological priming effects on the naming of compound targets when preceded by constituent primes. Most relevant for the current work is a seminal study by Lorenz et al. (2021), the only prior study we are aware of to date that has investigated compound naming itself with ERPs. Lorenz and colleagues used a picture-word interference paradigm. Replicating previous behavioral work (Lorenz et al., 2018, 2019), they found that both modifier (*sun* → *sunflower*) and head (*flower* → *sunflower*) distractors speeded compound naming. They also found a standard semantic interference effect (slowed compound naming) when the distractor was a noun in the same semantic category as the whole compound (*tulip* → *sunflower*). However, they did not find any interference when the distractor was a noun in the same semantic category as the modifier (*moon* → *sunflower*). In the ERPs to the target picture, they observed significant effects of morphological (constituent) distractors between ∼330ms-600 ms, as well as somewhat weaker effects of semantic (whole-compound) distractors in a slightly later time-window.

Lorenz et al. (2021) take their priming experiments as evidence that compounds are complex only at the morphophonological level. According to the lemma model (Levelt et al., 1999), absence of semantic modifier priming and absence of interactions with semantic transparency in morphological priming argues against compounds being complex at the lemma level. This is because in the lemma model, there is a 1-to-1 mapping between concepts and lemmas and, thus, lemmas are activated by concepts during the first stage of word production and subsequently compete for selection. To capture complex expressions like compounds within this model, one can introduce the notion of a "superlemma", which somehow collects multiple lemmas under it (Marelli et al., 2012). Under these assumptions, activating the distractor concept "moon" would activate the lemma "sun", which would in turn activate the superlemma "sunflower". Therefore, Lorenz and colleagues conclude that absence of constituent semantic priming argues against the superlemma model of compounds.

On the other hand, contemporary theories of morphology do not assume a 1-to-1 mapping between concepts and syntactic elements. Implementing this intuition in a production model would mean allowing the concept identified by a compound like *airbag* to directly activate the two morphosyntactic parts that correspond to it. Thus, for models like these, morphosyntactic complexity does not predict constituent semantic priming. This means that lack of effects due to semantic manipulations do not yield conclusive evidence about whether compounds are morphosyntactically complex (see Krauska & Lau, 2023 for an overview of the challenges that the lemma and superlemma models more generally face in accounting for morphosyntactic complexity).

1.5. Current study

The aim of the current study was to further investigate the locus of complexity in compound production with a more direct comparison of the effects of morphological and phonological priming on compound naming, using auditory rather than text primes.

Koester and Schiller (2008) showed that phonological form overlap (*jasmijn* "jasmine" → *jas* "coat") did not have the same effect as morphological overlap (*jaszak* "coat pocket" → *jas* "coat") on behavior or ERPs. Here we aimed to replicate and extend this work by investigating whether the same contrast would hold when compounds are the targets of production, rather than the primes. In the morphological priming condition we used compound heads as primes (e.g., *bag* → *airbag*), and the corresponding phonological primes were designed to share the onset and nucleus of the first syllable of the compound head (e.g., *bat* → *airbag*). If morphological priming were primarily due to morphosyntax, then we would expect qualitatively different behavioral and ERP effects from the phonological priming condition. If morphological priming were primarily due to morphophonology, then we would expect to see similar behavioral and ERP effects for the morphological priming and phonological priming conditions, although perhaps of greater magnitude in the morphological condition corresponding to the greater amount of phonological overlap in that condition.

Prior work has shown varying effects of phonological primes on picture naming reaction times, as a function of stimuli and task parameters. An influential early study (Schriefers et al., 1990) showed no priming when phonological primes preceded target pictures, but significant facilitation when phonological primes co-occurred with target pictures. However, later studies showed phonological priming over a wider time range (e.g., Starreveld & La Heij, 1996), and Damian and Martin (1999) found that these timing effects were further modulated by whether the prime word was presented with text or speech. In other cases, phonological overlap has been shown to result in interference, with slower naming RTs relative to baseline, perhaps when task parameters put a greater burden on control processes (e.g., Breining et al., 2016; Nozari et al., 2016; Sullivan, 1999). Nozari et al. (2016) also point out that an important stimulus parameter is whether the overlap occurs in the phonological onset vs. the rest of the form: if the speaker can anticipate the phonological onset of the target, they can begin preparation for articulation, reducing RTs even without any impact of the prime on consideration of specific wordforms. On the other hand, phonological overlap in other parts of the wordform can only act to facilitate or interfere with the process of identifying specific candidates for naming. Relatively few ERP studies have thus far examined phonological priming of picture naming, although one prior study using single phoneme onset overlap in text primes failed to show any significant ERP effect (Blackford et al., 2012).

In the current study we presented primes in the auditory modality, in order to increase the degree of form overlap between primes and the representations engaged by the production process, and to maximize our chances of detecting phonological priming effects on naming. Although reading is thought to involve an indirect orthography-phonology route as well as a direct orthography-lexical route, it is unclear that the phonological route is used by all participants for all orthographic words. On the other hand, using auditory primes necessarily engages morphophonological representations and can shed light on auditory processing that occurs in speech. By manipulating morphological and phonological priming on the second syllable of the compound only (*bag* → *airbag* or *bat* → *airbag*), we limited the (morpho)phonological priming effects to mechanisms related to selecting candidate wordforms, obviating any articulatory facilitation associated with onset priming. On the other hand, we hoped that the use of auditory primes and the greater phonological overlap (syllable onset + nucleus) would increase the likelihood of detecting any true effects of the phonological prime on the ERP.

We also included a semantic priming condition in order to rule out the possibility that the origin of priming in the morphological condition could be due simply to semantic relatedness between the head of the compound and the compound as a whole. Thus, we used semantic primes that were semantically associated with the entire compound (*car* → *airbag*). However, since the meaning relation between head and compound as a whole can vary quite a lot (*bag* → *airbag* vs *man* → *snowman*), we resorted to various kinds of meaning relatedness in the semantic condition too (*manicure* → *nailpolish* vs *zucchini* → *eggplant*). Prior studies have shown variable effects of semantic distractors naming depending on the timing of the distractor presentation and the type of semantic relationship (Lorenz & Zwitserlood, 2016; Mahon et al., 2007; McDonagh et al., 2020; Python et al., 2018a, 2018b, among others). Moreover, existing work suggests that N400 effects of semantic priming are substantially smaller in amplitude for production than comprehension (Blackford et al., 2012; Dirani & Pylkkänen, 2020). Thus, we were unsure what effect this would engender behaviorally and we expected a small, if any, N400 effect.

2. Methods

2.1. Participants

Participants were 36 right-handed native speakers of American English between the ages of 18 and 30 who reported having normal or corrected-to-normal vision, recruited from the University of Maryland community. Participants received money or course credit for their participation. Two participants were excluded for giving less than 60% correct responses (across both targets and fillers), three participants were excluded due to technical error, and three participants were excluded for excessive artifact in the EEG recording (impacting over half of the trials). The final sample included 28 participants (10 male, mean age 20.1, range 18 - 27 years). The study received approval from the University of Maryland Institutional Review Board.

2.2. Materials

We chose 116 photographs of objects corresponding to English compound nouns, spanning a variety of semantic categories (animals, tools, food, etc.). 102 photographs were taken from the THINGS image database (Hebart et al., 2019), while 14 photographs from other sources were used in the few cases in which the THINGS database did not contain an image that seemed appropriate. Nameability norming data is provided for all images in the THINGS database. In order to compute nameability values for our stimuli set as a whole, we asked 10 native speakers to name the 14 additional photographs. Mean naming agreement for all 116 photographs was 86% (standard deviation 16%).

We used a phonological diagnostic, stress retraction (*a white HOUSE* vs. *the WHITE House)*, to determine compound status. Many of the items are orthographically represented in English without a white space between the components (e.g., *firetruck*), but others are not (e.g., *life jacket*). Items were selected such that both elements were attested and relatively familiar words in English. We avoided using compounds in which the head noun alone would be perceived as a likely label for the imaged object in the context of a picture naming experiment (e.g., a picture of a bookshelf might felicitously be labeled *shelf*).[1] Item names varied in length: in the final set of 116 items, 92 of the compounds had 2 syllables, 23 of the compounds had 3 syllables, and 1 compound had 4 syllables. The full list of items is included in Supplementary Materials.

After choosing the compounds, we selected 4 different kinds of auditory primes for each compound: morphological, phonological, semantic and unrelated (Table 1). In the morphological condition, the prime was simply the head of the compound (e.g., *bag* - *airbag*). Most heads were monosyllabic, resulting in a mean syllable count of 1.07 for morphological primes.

In the semantic condition, we selected prime words which were associatively related to the meaning of the whole target compound (e.g., *car* - *airbag*). 20 pairs were taxonomically related, while the remaining 96 were thematically related. In order to confirm that the primes in the semantic condition were indeed more associated with their targets than those in the unrelated condition, we computed cosine similarity values between primes and targets via the pre-trained English word vectors available from FastText (https://fasttext.cc/docs/en/english-vectors.html) using the "wiki-news-300d-1M-subword" dataset, which consists of 1 million word vectors trained with subword information on Wikipedia 2017, UMBC webbase corpus and statmt.org news dataset (16B tokens). There were seven items for which similarities could not be computed between the prime and the compound due to the compound not being present in the vector space. These items were: *polarbear*, *iceskate*, *eggroll*, *jumprope*, *bunkbed*, *candycane*, and *nailpolish*. We found that cosine similarity for the semantic primes with their targets was higher (.505) than for the unrelated primes (.287), as expected. Cosine similarity for morphological primes was also higher (.552) than for unrelated primes, as expected, given that the compound head often carries important categorical information about the meaning of the word even in compounds that are not fully transparent (e.g., *berry* in *strawberry*). Cosine similarity for phonological primes (.288) and for filler primes and targets (.2788) showed values similar to unrelated primes, as expected. Mean syllable length of semantic primes was 1.8.

Table 1. Priming conditions.

Condition	Prime	Target picture
Morphological	bag	
Phonological	bat	
Semantic	car	
Unrelated	soon	

In the phonological condition, the prime was phonologically related to the head of the compound by sharing the onset and the nucleus of the first syllable (e.g., *bat* - *airbag*). In order to ensure such a close phonological control, phonological primes varied in syntactic category, but were always matched with the head of the compound in number of syllables. We excluded phonological primes that shared the whole of the first syllable with the head of the compound, since in most cases this would have resulted in identity between the phonological and the morphological condition. Mean syllable length of phonological primes was 1.07.

In the unrelated condition, the primes were the unused phonological primes from the other 3 lists, scrambled across different target compounds such that there was no obvious relationship between the prime and the target (e.g., *soon* → *airbag*). Thus, in this condition too, primes varied in syntactic category, and mean syllable length of primes was the same as the morphological and the phonological conditions (1.07).

In addition to the 116 compound images, we also chose 162 images of objects whose labels corresponded to monomorphemic English nouns, and paired them with another 162 unrelated auditory prime words. 40 of the filler object names were monosyllabic, 90 were disyllabic, 30 had three syllables, and 2 had four syllables.

All primes were recorded by a male native speaker of American English. After the experiment was conducted, we discovered that one of the intended morphological primes was accidentally recorded with the wrong vowel (/baʊ/ instead of /boʊ/ for *rainbow*). These data were excluded from further analysis.

We arranged the experimental materials in a Latin square design across participants using four lists, one for each prime type, so that for each participant there were 29 items for each prime type, together with the 162 filler items, for a total of 278 items. In each list, number of syllables and compound frequency were roughly equalized across conditions. The order of appearance of pictures was randomized. Although some primes were re-used within a condition, we arranged items across lists such that no prime words were repeated in a given list.

2.3. Procedure

Before beginning the experiment, participants were familiarized with the intended names of the pictures that would be used in the experiment, in order to make it more likely that they would produce the intended forms. Participants were given a list of the items used in the experiment and asked to rate (scale 1-3) how likely they would be to recognize a picture of each of the listed items. Participants did not see or practice naming the target pictures prior to the experiment. Although this resulted in slower naming times and more trials in which participants failed to name the picture, compared to experimental paradigms in which picture naming is practiced in advance, we chose not to familiarize participants with the pictures because we wanted to avoid the possibility that the auditory primes would retrieve the memory of the familiarized picture and in that way facilitate the visual processes involved in picture recognition.

Participants were tested in a quiet room while seated in front of a computer screen. The lights of the room were dimmed to reduce eye strain. Each trial began with a fixation cross presented for 250 ms, followed by the auditory presentation of the prime word, after which the fixation cross persisted for 500 ms. Then, a picture appeared on the screen for 2850 ms, during which period the participants were instructed to name the picture. Participants were given a short break to rest after every 60 trials. Before the experiment began, participants were told that they would hear a word spoken aloud and then see a picture of a different object (not the word they had just heard) appear on the screen, and that they should say the name of the picture aloud. Participants were shown how blinks and movement affected the EEG waves, and were instructed to stay as still and relaxed as possible and to blink after they had named the picture on the screen. Four practice naming trials (non-compounds) were included at the start of the experiment to ensure that participants understood the task.

2.4. EEG

Twenty-nine tin electrodes (O1, O2, P7, P3, Pz, P4, P8, TP7, CP3, CPz, CP4, TP8, T7, C3, Cz, C4, T8, FT7, FC3, FCz, FC4, FT8, F7, F3, Fz, F4, F8, FP1, FP2) were held in place on the scalp by an elastic cap (Electro-Cap International, Inc., Eaton, OH). Bipolar electrodes were placed above and below the left eye and at the outer canthus of the right and left eyes to monitor vertical and horizontal eye movements. Additional electrodes were placed over the left and right mastoids. Scalp electrodes were referenced online to the left mastoid and re-referenced off-line to the average of left and right mastoids. The ground electrode was positioned on the scalp in front of Fz. Impedances were noted before beginning the experiment. Impedances were maintained at less than 10 kΩ for all scalp and ocular electrode sites and less than 3 kΩ for mastoid sites. The EEG signal was amplified by a NeuroScan SynAmps® Model 5083 (NeuroScan, Inc., Charlotte, NC) with a bandpass of 0.05–100 Hz and was continuously sampled at 500 Hz by an analog-to-digital converter.

2.5. Data analysis

2.5.1. Behavioral data

Participant responses were transcribed using either the Google Cloud Speech-to-Text API or the transcription function of AssemblyAI, and transcriptions were manually checked for accuracy. The Montreal Forced Aligner was used to obtain the response latency for each trial, and the alignments were manually inspected and corrected. Incorrect responses were excluded from the analysis; responses that included filler expressions (e.g., "um", "uh"), a self-interruption ("bed—bunkbed"), or an incorrect identification of the picture ("pretzel" in response to an image of "breadstick") were all counted as incorrect. Responses not completed within the 2850 ms recording window ("airba-") were also counted as incorrect. Statistical analyses were conducted in the R environment (R Core Team 2024, version 4.4.1). Naming accuracy was evaluated with a logistic regression across conditions, using the glm function.

As described below, responses faster than 700 ms (6.8% of experimental trials) were excluded from EEG analyses, and in order to facilitate comparison between behavioral and EEG data, we excluded them from behavioral analyses as well. Response latencies (for correct trials only) were evaluated with a mixed-effects model using the lmertest package in R (R Core Team 2024, version 4.4.1). The Satterthwaite approximation was used to obtain *p*-values; significant *p*-values are reported at $p < 0.05$. Condition (Morphological, Phonological, Semantic, Unrelated) was inserted as a fixed effect, with the unrelated condition as the reference level. We included random intercepts for subjects and target items.[2]

2.5.2. EEG data

We used independent components analysis (ICA) to remove ocular and cardiac artifacts, using the routines in the EEGLAB toolbox (Delorme & Makeig, 2004). ICA weights were computed on each continuous dataset high-pass filtered at 1 Hz, and then manually identified artifactual components were removed from the corresponding unfiltered continuous dataset.

Pre-processing was done using routines provided by the EEGLAB and ERPLAB toolboxes. Epochs were time-locked to the onset of the picture and covered a span of −100:700 ms and were baselined to the −100:0 ms pre-stimulus interval. Bad channels were spherically interpolated on a per-participant basis using the eeg_interp() function from the EEGLAB toolbox. As in the behavioral analysis, only trials with correct responses and reaction times above 700 ms were analyzed, in order to prevent contamination from muscle movement. Remaining high-amplitude artifacts were identified and excluded from the data using a peak-to-peak threshold.

We conducted statistical analyses in two time-windows: the 300–500 ms time-window in which N400 effects are typically observed, and the subsequent 500–700 ms time-window. We used the traditional ERP analysis approach of calculating these values on single-subject ERPs by condition, and entering these values into our statistical analyses. In each time-window we conducted a 4 × 2 (condition x anteriority) ANOVA on a subset of 20 electrodes, those in the two anterior rows of electrodes (FT7, FC3, FCZ, FC4, FT8, F7, F3, F4, F8) and those in the two posterior rows of electrodes (P7, P3, Pz, P4, P8, TP7, CP3, CPz, CP4, TP8) (see Cruz Heredia et al., 2022 for a similar approach). Significant main effects or interactions involving the condition factor were followed up with pairwise comparisons between conditions. Statistical analyses were conducted using the ezANOVA package in R. Here we report all significant main effects and interactions involving the condition factor, but as is standard we do not report simple main effects of anteriority as we have no hypotheses about the distribution of scalp voltages independent of condition. A low-pass filter of 20 Hz was applied offline to the ERPs prior to plotting the data, for visualization purposes only.

3. Results

3.1. Behavioral

Mean reaction times and accuracies by condition are presented in Table 2. Mean accuracy in target picture naming was 79.8%. A logistic regression on the accuracy data with the unrelated condition set as the baseline condition revealed a significant ($p < .01$) effect of condition on accuracy, with participants significantly more likely to answer correctly in the morphological condition compared to other conditions. Accuracy did not vary significantly between the phonological, semantic, and unrelated conditions.

Table 2. Naming accuracy and average response type across participants for correct responses, by prime type. Standard deviations for average RTs in parentheses.

Condition	Accuracy	Average RTs (ms)
Morphological	85.5%	1039 ms (110)
Phonological	78.4%	1083 ms (118)
Semantic	75.7%	1126 ms (149)
Unrelated	79.6%	1113 ms (125)

Mean reaction time for target picture naming across conditions was 1090 ms. This is on the slow side relative to previous picture naming studies, which often report mean naming latencies within 650–900 ms (e.g., Dirani & Pylkkänen, 2020; Koester & Schiller, 2008; Lorenz et al., 2021) although not always (e.g., Blackford et al., 2012; Chauncey et al., 2009). The most likely contributor to the slower RTs observed here was our choice not to familiarize participants with target pictures and their intended labels beforehand; another contributor might be our choice not to emphasize speed in the instructions to participants.

The reaction time model revealed a significant effect of condition, with responses being significantly ($\beta = -74$ ms, $p < 0.001$) faster in the morphological condition than in the unrelated condition. There was a marginal ($\beta = 28$ ms, $p = .068$) slowdown of responses in the semantic condition compared to the unrelated condition. There was no significant difference between the phonological condition and the unrelated one ($\beta = -19$ ms, $p = 0.2$). In sum, among the three related-prime conditions, only the morphological condition demonstrated a reliable priming effect relative to the unrelated baseline. In addition, reaction times in the morphological condition were significantly faster than those in the phonological condition ($\beta = 55$ ms, $p < .001$) and the semantic condition ($\beta = 102$ ms, $p < .001$).

3.2. Event-related potentials

In the 300–500 ms time-window following picture presentation, visual inspection of the ERPs indicated a slightly reduced negativity for the morphological prime and the semantic prime conditions relative to the unrelated condition and the phonological condition (Figure 1; grand-averaged ERPs for each electrode are presented in Supplementary Materials). However, these differences were numerically small, and the omnibus ANOVA across all 4 conditions in this time-window showed no significant effects of condition ($ps > .15$).

In the 500–700 ms time-window following picture presentation, visual inspection of the ERPs indicated

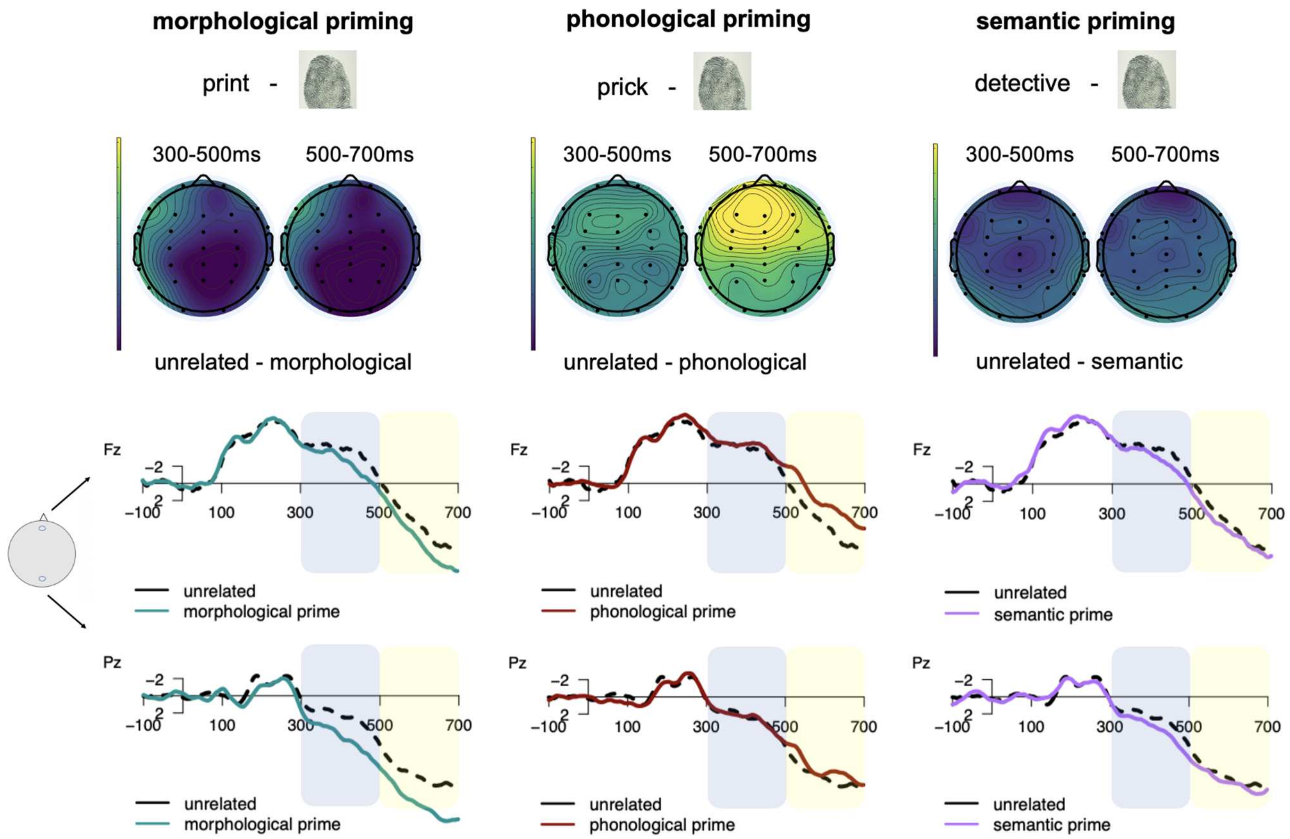

Figure 1. Scalp maps and event-related potentials time-locked to the onset of the target picture for naming. Scalp maps illustrate the mean difference between the response to pictures preceded by an unrelated prime and the response to pictures preceded by the three other prime types. Time windows that were statistically analyzed are highlighted.

that the morphological prime condition was less negative than the other conditions over posterior electrodes, and that the phonological prime condition was more negative than the other conditions over anterior electrodes. The omnibus ANOVA in this time-window showed a significant main effect of condition ($F(3,81) = 5.0$, $p < .01$) and a significant interaction between condition and anteriority ($F(9, 243) = 3.3$, $p < .01$). Follow-up 2 × 2 ANOVAs were conducted, comparing each prime condition against the unrelated condition. For the morphological comparison, we found a marginally significant main effect of condition ($F(1,27) = 3.0$, $p = .09$) and a significant interaction between condition and anteriority ($F(1,27) = 4.4$, $p < .05$). Follow-up one-way ANOVAs at each level of anteriority showed a significant effect of condition in posterior electrodes ($F(1,27) = 6.0$, $p < .05$) but not in anterior electrodes ($p > .15$). For the phonological comparison, we found a significant main effect of condition ($F(1,27) = 4.2$, $p = .05$) and a significant interaction between condition and anteriority ($F(1,27) = 8.9$, $p < .01$). Follow-up one-way ANOVAs at each level of anteriority showed a significant effect of condition in anterior electrodes ($F(1,27) = 8.0$, $p < .01$), but not in posterior electrodes ($p > .15$). Notably, the significant differences between the unrelated control and the morphological and phonological primes were due to amplitude shifts in opposite directions: phonological primes resulted in ERPs more negative than the unrelated control, while morphological primes resulted in ERPs more positive than the unrelated control (see Figure 1). For the semantic comparison, we found no significant effects involving condition ($ps > .15$).

We also conducted an additional set of analyses in order to compare the size of the ERP priming effects for the three related-prime conditions against each other directly. Here we first created difference ERPs for each participant by subtracting each of the 3 prime conditions from the unrelated condition. Then we entered mean amplitudes from these 3 difference ERPs into an omnibus 3 × 2 (priming type x anterior/posterior) ANOVA in the 500–700 ms time-window. We observed a significant main effect of priming condition ($F(2,54) = 8.6$, $p < .001$) and an interaction between condition and anteriority ($F(6,162) = 3.8$, $p < .01$), showing that the size of the ERP priming effects significantly differed from each other as a function of related prime type. A follow-up 2 × 2 ANOVA comparing the morphological priming effect and the phonological priming effect (phonological/morphological × anterior/posterior) showed a significant main effect of condition ($F(1, 27) = 28.3$, $p < .001$).[3] Similarly, a 2 × 2 ANOVA comparing the semantic priming effect and the morphological priming effect directly (semantic/morphological × anterior/posterior) showed a significant interaction between condition and anteriority ($F(3,81) = 4.2$, $p < .01$). Together, these additional analyses confirm that the effect of morphological priming on ERPs was significantly different from both semantic priming and phonological priming.

4. General discussion

In this study, we compared behavioral and ERP effects of morphological, phonological, and semantic priming on compound picture naming using auditory primes. Replicating prior studies, we found that a morphological prime (here, the compound head) robustly facilitated picture naming of a compound target, while in contrast a semantically related prime resulted in a marginally significant slowdown in naming. In the ERP responses, we found that morphological priming led to a reduced centro-posterior negativity in the later time-window (500–700 ms). We observed a very different response in the phonological condition, where effects of segment overlap manifested as an increased negativity over anterior electrodes in the same time-window. Finally, semantic priming showed no significant ERP effects, with only a numerical tendency towards the expected N400 effect in the earlier time-window. These results leave open whether the cause of priming in the morphological condition is due to sharing a whole morphophonological form, sharing a morphosyntactic representation or a combination of both. Below we explore how these results contribute to our understanding of the locus of complexity in compound production, and what impact this has on hypotheses about the source of compound production errors in aphasia.

4.1. Morphological priming in compound production

Consistent with the previous experimental and clinical studies reported above, the current results provide further evidence that compound production involves operations over compound subparts. The profile observed for morphological priming appeared qualitatively different from phonological and semantic priming, indicating that morphological priming is not a simple function of semantic similarity nor simple phonological overlap between the prime and the target. This was especially striking given that in most of the items (92 out of 116), the phonological condition and the morphological condition differed only in one phoneme (*bat* → *airbag* vs *bag* → *airbag*). Despite this, we saw significant facilitation of naming times only for morphological priming, and different ERP polarities and topographies for morphological and phonological priming, with the morphological condition being less negative over posterior electrodes and the phonological one being more negative over anterior electrodes in the same time-window. In other words, the amount and quality of priming are radically different when the prime is the head of the compound as opposed to when it just shares a few phonemes with it.

The study that most closely resembles the present one is Lorenz et al. (2021), whose results show both similarities and differences from ours. Indeed, Lorenz et al. (2021) found a significant difference between the ERP response to naming after morphological distractors vs. unrelated distractors (in separate comparisons of both modifier priming and head priming) in a similar time-window as observed here (490-600 ms). However, they also observed significant differences in an earlier time-window (330-490 ms). While we observed a numerical but nonsignificant difference between the conditions in this time-window, it may be that these earlier effects were less robust in the current study because naming was slower overall (∼1100 ms in our study vs. ∼800 ms in Lorenz et al. (2021)), likely due to our decision not to familiarize participants with the images prior to the experiment, and perhaps insufficient emphasis in our instructions to participants on the importance of rapid naming.

The morphological priming ERP effect observed by Lorenz et al. (2021) appears similar in topographical distribution and polarity to the current effects between approximately 350–550 ms, with the morphological priming condition more positive over central-posterior electrodes, but had a different distribution and polarity at earlier and later time points. These differences in polarity and distribution are likely due both to differences in the paradigms used as well as differences in choice of EEG reference. Lorenz et al. (2021) used a picture-word interference task, in which a written word onset just 100 ms prior to the picture and remained on the screen with the picture during naming. On the other hand, the current study used a longer SOA auditory priming paradigm, in which a prime word was spoken and its offset was followed by a 500 ms pause before the picture was presented. Given these differences in the polarity and distribution of the morphological relatedness effects in the two studies, it would be interesting for future work to compare the effects of these modality differences directly in the same materials and participants.[4]

We now consider what the present results suggest about the complexity of compound production at semantic, morphophonological, and morphosyntactic levels.

4.2. Does the production of familiar compounds involve semantic complexity?

One possible account of the benefit for constituent priming on compound naming is that naming a familiar compound like *airbag* actually involves combining the concepts that correspond to *air* and *bag*, and that the morphological prime thus facilitates access or retrieval to these concepts. This would make the production of familiar compounds more similar to what is assumed for the production of productive compounds. However, Lorenz et al. (2021) provides strong evidence against this hypothesis by showing that there are no ERP or behavioral effects of priming when the prime is in the same semantic category of the modifier (*moon → sunflower*).

The current ERP results also seem somewhat inconsistent with such an account. Priming manipulations designed to facilitate conceptual access typically observe reductions in the N400 response between 300–500 ms following visual stimulus presentation. Although we did see a numerical divergence in the morphological priming ERP effect during this time-window, it reached its maximum later, in the 500–700 ms time-window. While MEG studies with better spatial resolution will be needed to more clearly discriminate these effects, taken together we believe the evidence currently favors the view that, in contrast to novel compounds, the production of familiar compounds can begin from the single concept that corresponds to the compound, without requiring access to conceptual subparts.

Finally, an additional reason to doubt that morphological priming effects in compound naming have a semantic source is the fact that semantic primes often lead to slowdowns in naming ("semantic interference") rather than facilitation. However, the conditions under which semantic interference effects appear are somewhat complex, and many authors have reported facilitation effects for semantic primes when the relation is thematic/associative rather than taxonomic (e.g., Alario et al., 2000; Sailor et al., 2009). We note that in the current study the majority of our semantic primes were thematic/associative, but we still observed a marginally significant numerical slowdown relative to the unrelated control, which contrasts with the significant facilitation observed for the morphological prime.

4.3. Does the production of familiar compounds involve phonological complexity?

A different account assumes that compound production involves operations over morphophonological wordforms that correspond to the compound subparts, and it is access to these forms that is facilitated in morphological priming. Our results are consistent with this view, but the pattern of results we see here also shows that sharing a morphophonological form is qualitatively different from just sharing a few phonemes. First, morphological overlap, but not phonological overlap, led to significant behavioral priming. Second, the ERP profiles for the two conditions were very different: morphological priming led to a reduced centro-posterior negativity in the 500–700 ms time-window, while phonological priming manifested as an increased negativity over anterior electrodes in the same time-window. Our results clearly show that sharing a few phonemes (*bat → airbag*) is qualitatively different from sharing a full phonological wordform (*bag → airbag*). Thus, these results rule out the possibility that cases of morphological priming already identified in the literature (e.g., in Lorenz et al., 2021) are due to mere phonological overlap.

What remains as a possibility is that compound production is facilitated by priming of full morphophonological wordforms. For example, the Levelt et al. (1999) production model assumes a "form stratum", which is populated by what they term "morpheme nodes" linked to metrical and segmental information, and they suggest that compounds like *blackboard* and *hotdog* contain two "morpheme nodes". An account like this one could assume that morphological priming facilitates compound production by activating the "morpheme node". Crucially though, it would have to assume that phonological segment overlap is not enough to significantly activate the "morpheme node", perhaps because of the relatively long delay between the prime and the picture target. It is unclear to us whether or not the Levelt et al. (1999) production model can accommodate these facts. Future work comparing phonological segment priming for monomorphemic items to phonological segment priming for compounds could further investigate this prediction.

4.4. Does the production of familiar compounds involve morphosyntactic complexity?

A final possibility is that compound production involves operations over morphosyntactic units that correspond to the compound subparts, and that it is access to these morphosyntactic units that is facilitated by morphological priming. As we have seen in section 1.2, there is no disagreement that productive compounds are syntactically complex. There is also evidence crosslinguistically that at least some familiar compounds are morphosyntactically complex. Moreover, studies on aphasia support this view (Lorenz et al., 2014; Marelli et al., 2012). Our results do not directly distinguish between a morphosyntactic or morphophonological origin of the priming (or possibly a combination of the two), but they offer some avenues for reflection, primarily ruling out simple segment overlap as a possible cause of priming. Future experiments should further investigate the origin of priming, for instance determining if the same amount of priming and the same magnitude ERP difference is found in an experiment similar to Koester and Schiller's (2008), but where a simple noun acts as a prime for a compound (*jas* "coat" → *jaszak* "coat pocket") or a non-compound (*jas* "coat" → *jasmijn* "jasmine"). Indeed, while Koester and Schiller (2008) offer invaluable insight into the complexity of compounds, they do so indirectly by having compounds as primes and not as targets to be named. Repeating the same experiments with compounds as targets would strengthen the conclusion that morphological priming is due to sharing a morphosyntactic unit, not just a morphophonological wordform.

4.5 Understanding compound production errors in aphasia

As we have reviewed in the introduction, extensive prior literature has documented systematic errors in production of familiar compounds for patients with aphasia across a number of languages. These production errors, showing rearrangement and substitution of individual constituents, as well as a higher likelihood of whole-word substitution from compound to compound, constitute some of the strongest evidence to date that compound production involves operations over smaller units. But are these units morphosyntactic, or only morphophonological? The answer has broader importance, in terms of developing a better model of the subprocesses required for producing the wide range of morphological patterns observed across languages, and in turn of what subtypes of production deficits would be predicted to occur in aphasia.

One strongly suggestive piece of evidence that compound production involves operating over morphosyntactic parts comes from previous observations that patients with aphasia who demonstrate deficits in verb production are also more likely to demonstrate deficits in producing the "verb" component of VN compounds (Lorenz et al., 2014; Marelli et al., 2012), even though the compound itself is of the "noun" category (e.g., Italian *aspirapolvere*, roughly "sucks-dust", as the term for a vacuum cleaner). If the only sub-units involved in compound production were sub-units of phonological form, there would be no reason to predict such effects, in the same way that we don't expect the process of producing of the verb *tackle* to be affected by the fact that one of its substrings (*tack*) corresponds to a noun. The results of the current ERP study of compound production are also consistent with this view, in showing that phonologically priming alone yields a qualitatively different effect on neural measures during picture naming compared to priming the compound with one of its constituents. This would be predicted if compound production involves operating over syntactic units corresponding to each constituent.

Although more work is needed, taken together the current evidence suggests that many of the errors in compound production observed in patients with aphasia may reflect problems in executing the operations required to successfully access and relate the morphosyntactic units that compose the compound. On this view, combinatory syntactic processes continue to be required (and thus continue to be vulnerable to error) even for stored complex expressions with fixed meanings. Such findings motivate the further development of models of aphasia that go beyond simple dichotomies between lexical activation vs. structure building, or "morphology" vs. syntax (e.g., Faroqi-Shah, 2023; Krauska, 2024; Matchin & Hickok, 2020).

4.6. ERP priming effects on picture naming

As the number of ERP studies on primed picture naming in general is still relatively small, the current results also provide some useful data for future research using this methodology. Using auditory primes, we replicate the interesting observation from previous work that N400 effects of semantic priming appear much smaller in picture naming tasks than in comprehension tasks (Blackford et al., 2012; Dirani & Pylkkänen, 2020). Visual inspection of the 300–500 ms time-window suggested a reduction in the N400 effect in this condition, but the effect was so small that it did not reach significance in this sample. One possible explanation might connect this difference to the semantic interference effects often observed in naming reaction times. However, we note that Blackford et al. (2012) also observed relatively small N400 effects for repetition priming of picture naming, even though repetition priming drives robust facilitation in naming speeds. Therefore, this difference in ERP effect sizes remains an interesting target for future research.

The ERP effects of phonological priming observed here are also of independent interest. To the best of our knowledge, phonological effects in ERP production studies have not been previously reported; the one study we are aware of using phonological primes, Blackford et al. (2012), did not identify any effect of phonological overlap in their ERP study of primed picture naming. As we discuss in the Introduction, the prior literature on effects of phonological overlap on naming RTs suggests substantial variation in these effects as a function of text vs. spoken primes, position and amount of overlap, and task parameters. Our study differed from Blackford et al.'s (2012) in all of these dimensions: we used auditory primes, a longer inter-stimulus interval, and greater phonological overlap (onset + nucleus rather than onset alone). While we did not find significant behavioral priming in the phonological condition, we did observe significant ERP effects, with anterior electrodes showing more negative responses in this condition relative to the control. Future studies will be needed to better understand the conditions under which this ERP effect is observed, in order to inform hypotheses about its functional interpretation.

5. Conclusion

In this study, we investigated the locus of complexity in compound production by comparing the effects of morphological, phonological, and semantic priming on compound naming, using auditory rather than text primes. Our behavioral results show facilitation in the morphological condition and a marginal slowdown in the semantic condition. Our ERP analysis showed that the morphological priming led to a reduced centro-posterior negativity in the 500–700 ms time-window, while phonological priming condition demonstrated an increased negativity over anterior electrodes in the same time-window. Our results do not directly distinguish between a morphosyntactic or morphophonological origin of the priming seen in the morphological condition, but they clearly rule out mere segmental overlap. Moreover, they shed light on potential differences between the effects of written vs auditory primes, and provide initial evidence that ERP effects of phonological priming on naming can be found in the auditory modality. Our findings are consistent with the view that the compound production errors observed in patients with aphasia reflect disruption to the processes of retrieving and combining the morphosyntactic elements that compose the compound (Lorenz et al., 2022; Marelli et al., 2012).

Notes

1. We chose not to explicitly manipulate the semantic transparency of the compounds in this study. One reason was simply practical: the number of imageable and easily identifiable objects with compound names in English is limited, and finding a sufficient number to manipulate an additional factor in the current study, given the larger sample sizes required for EEG, would be challenging. As Gagné et al. (2016) discuss, there are also conflicting views in the literature about exactly what semantic transparency is and how it should be operationalized. Semantic transparency could refer to the extent to which a familiar compound's meaning follows from the productive compounding rules of the language, or the extent to which the constituents "keep" their meanings in the compound, or simply to how related (given a theory of semantic relatedness) the meaning of the constituents are to the meaning of the compound. These different forms of semantic transparency have in turn been operationalized in a number of different ways, which yield different results on behavior (see Gagné et al., 2016 for more discussion). Since the focus of the current study is on the format of language representations rather than conceptual knowledge, we preferred not to take a stand on this debate here.
2. Models including random slopes for subjects did not converge. A model including random slopes for items did converge, and showed the same pattern of results as the simpler model, but had a higher AIC.
3. There was no interaction between condition and anteriority ($p > .2$). The absence of the interaction may seem unintuitive, given that the phonological and morphological primes showed such different topographies relative to the unrelated control as seen in Figure 1: the morphological prime led to more positive amplitudes than the unrelated condition at posterior electrodes, while the phonological prime led to more negative amplitudes than the unrelated condition at anterior electrodes. However, when taken together then the relative ordering of the two priming effects with respect to each other is actually constant across both anterior and posterior electrodes (phonological effect more negative / morphological effect more positive).
4. We also note that Lorenz et al. (2021) re-referenced EEGs with an average reference (across all scalp electrodes) while in the current study we re-referenced EEGs to the average of the left and right mastoids. Since re-referencing to the average reference can result in drastically different topographical distributions from referencing to one or two electrodes (Luck, 2014), this difference in reference site is likely responsible for at least some of the differences in topographical distribution of the morphological relatedness effects across the two experiments. Although neither reference choice is more "correct", we chose to use the averaged mastoid approach here because this is what has been most commonly used in previous N400 semantic priming studies and so this allows us to compare the topographical distributions for the priming effects observed here to those effects. Moreover, one challenge of the average reference for comparing across different datasets is that it cannot be applied to the data in a comparable way unless exactly the same scalp array of electrodes are used. Since Lorenz et al. (2021) used a different scalp array of 64 electrodes than the 30 scalp electrode array used in the current study, applying the average reference to the current data would also not yield a directly comparable set of topographies.

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Data availability statement

The data that support the findings of this study are openly available in OSF at https://osf.io/azcu9/.

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