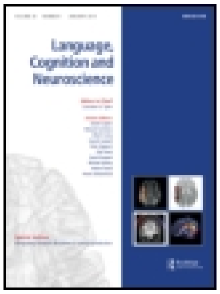

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Cassandra L. Jacobs[a] & Gary S. Dell[a]
[a] Department of Psychology, University of Illinois, 603 E. Daniel St., Champaign, IL 61820, USA

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'hotdog', not 'hot' 'dog': the phonological planning of compound words

Cassandra L. Jacobs* and Gary S. Dell

Department of Psychology, University of Illinois, 603 E. Daniel St., Champaign, IL 61820, USA

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Do we say *dog* when we say *hotdog*? In five experiments using the implicit priming paradigm, we assessed whether nominal compounds composed of two free morphemes like *sawdust* or *fishbowl* are prepared for production at the segmental level in the same way that two-syllable monomorphemic words (e.g. *bandit*) are, or instead as sequences of separable words (e.g. *full bowl* or *grey dust*). The experiments demonstrated that nominal compounds are planned as a single sequence, not as two sequences. Specifically, the onset of the second component of the compound (e.g. /d/ in *sawdust*) did not act as a primeable starting point, although comparable onsets did when that component was an independent word (*grey dust*). We conclude that there may be a *dog* in *hotdog* at the morpheme level, but not when phonological segments are prepared for production.

Keywords: compound words; phonological planning; morphology; serial order; language production

Language is productive; new combinations are always being formed from existing words and parts of words. An example of productivity at the morphological level is seen in compounding. Compounds are sometimes created on the fly, such as *wind table*, meaning a plateau of air that is formed by strong winds. Most of the compounds that we use, though, are familiar and often written as single words, (*sawdust, hotdog*). The central goal of psycholinguistic research on compounds and, indeed, all morphologically complex words has been to determine how the words' structure (e.g. *sawdust* consists of the words *saw* and *dust*) affects their production and comprehension. In this paper, we focus on production and ask whether familiar compounds are produced as one or two phonological sequences.

In studies of auditory and visual word recognition, there is reason to believe that the constituent parts within a compound word function somewhat independently of each other. For example, the frequency of the first noun of a nominal compound affects the ease of word recognition and comprehension (e.g. Taft & Forster, 1976). Although production has been studied less often, the morphological structure of the compound matters there, as well. Some evidence for the existence of the morphemes within compounds (so, the *saw* and *dust* in *sawdust*) comes from aphasic patients' spoken errors. Blanken (2000), Lorenz, Heide, and Burchert (2014) and Ayala and Martin (2002) examined picture-naming errors made by a variety of aphasic individuals. They found that the separate parts of a compound could slip to semantically or phonologically related words; a word like *birdhouse* could become *birdhome* or *finchhouse*, indicating the separable contributions of the individual terms (e.g. *bird* and *house*) within the target word.

Findings from response-time studies of compound production by unimpaired speakers are, for the most part, consistent with the decompositional perspective suggested by speech error data. Bien, Levelt and Baayen (2005) found that the frequencies of the two constituents of a compound separately affected production latencies in a task in which participants had to retrieve previously memorised compounds from a cue. Although they found a small effect of the frequency of the entire compound as well, the results generally supported the decompositional approach to compound production. Roelofs (1996; see also Roelofs & Baayen, 2002) showed that advance knowledge of the first syllable of a compound, which is a separate morpheme, speeded production more than advance knowledge of the first syllable of a monomorphemic word. Studies of compound production using the picture-word interference paradigm, in which a distractor word can be specifically related to a single morpheme of a target compound, have also demonstrated an influence of the morphological status of the compound's components (Dohmes, Zwitserlood, & Bölte, 2004; Gumnior, Bölte, & Zwitserlood, 2006; Lüttmann, Zwitserlood, Böhl, & Bölte, 2011), as have studies using long-lag priming (e.g. Koester & Schiller, 2008, 2011).

Not all response-time studies, however, have supported the decompositional view. Janssen, Bi and Caramazza (2008) found that only the frequency of the compound itself influenced picture-naming times for compounds and not the constituent parts. They concluded that compounds' lexical representations are retrieved as wholes.

*Corresponding author. Email: cljacob2@illinois.edu

The bulk of the research on compound production, together with studies of the production of prefixed and suffixed words (e.g. Ferreira & Humphreys, 2001; Janssen, Roelofs, & Levelt, 2002; Melinger, 2003), supports the claim that, at least somewhere in the production process, morphologically complex words are planned differently than monomorphemic words. This conclusion is reflected in models of production, as well. For example, Levelt, Roelofs and Meyer's (1999) and Dell's (1986) models both have a morphological layer in the model's lexical network, which sits between the lemma/word layer and the layer at which phonological units are represented. The models' claim that morphological structure is intermediate between a word and a segmental level leads to the central question addressed here. Does morphological structure impact downstream levels? For example, at the phonological level, is *sawdust* planned like multiple words such as *grey dust* or like a single word such as *napkin*?

Some recent work by Cohen-Goldberg (2013) suggests that morphological structure penetrates to levels responsible for the processing of the word's phonological segments. He found that similar phonemes within a word slow production times (e.g. as in Cohen-Goldberg, 2012), but that this interference is smaller when the similar phonemes come from different morphemes. This suggests that morphological boundaries manifest themselves at levels that represent segmental similarity. Although Cohen-Goldberg (2013) did not examine the production of compounds specifically, his claim of low-level morphological influences is assumed to apply generally, potentially to compound words like *sunshine*, which he used as an example to illustrate the potential interactions within and across morpheme boundaries.

In contrast, Wheeldon and Lahiri (2002) reported data suggesting that the morphological complexity of compounds did not matter at the phonological and more downstream levels. Their study examined the latencies to produce short phrases after a delay. Compounds such as *ooglid*, (eyelid in Dutch) acted as single phonological words, unlike word sequences such as *oud lid* (old member).

One way to address the question of morphological structure during lower-level speech planning is to consider how serial order of phonological units in compounds is represented. If the phonological segments of *sunshine* are encoded without reference to the morphological boundary, then the serial order process operates over the entire word. There is just one sequence. If there is a potent morphological boundary, though, there are two sequences, one for *sun* and one for *shine*.

Let us consider the model of serial planning in language production proposed by Houghton (1990). It proposes that all words have START and END nodes and that the word's segments are differentially associated with these. So, for the word *sun*, /s/ is associated with START, /n/ with END and /ʌ/ is associated weakly with both START and END. The serial order is realised by activating the START node and then gradually turning it off while turning on the END node. The result is that first /s/, then /ʌ/ and then /n/ are retrieved.

Houghton (1990)'s serial order model has been supported in investigations of spelling by Fischer-Baum, McCloskey and Rapp (2010), as well as Fischer-Baum, Charny and McCloskey (2011). Using spelling perseveration errors generated by dysgraphic individuals, they showed that a letter's serial order is stored in reference to the letter's distance from the word's START and END positions, exactly as proposed in Houghton's model. Fischer-Baum et al. showed that the START-END schema applies across the entire word, not separately within each orthographic syllable. So, a word like *bandit* is a single sequence, not *ban-* and then *-dit*.

Given this background, we can make our central question more concrete: Do compounds like *sawdust* or *sunshine* have a single START-END schema for their phonological segments, or two of them (see Figure 1)? Schiller, Greenhall, Shelton, and Caramazza (2001) addressed the question of one versus two sequences in compounds by examining spelling-error patterns in two dysgraphic individuals. When both individuals spelled words (aloud, written or typed), they tended to make more errors toward the end of the word. When the spelled words were compounds, though, one of the patients tended to get the first letter of the second morpheme more correct than would be expected from its overall word serial position. This result suggests that, at least for this individual, that there is second sequence being generated when a compound is spelled. Of course, spelling involves different units than speaking, and is likely responsive to strategies that do not apply in word production. Consequently, it would be useful to consider the nature of the phonological

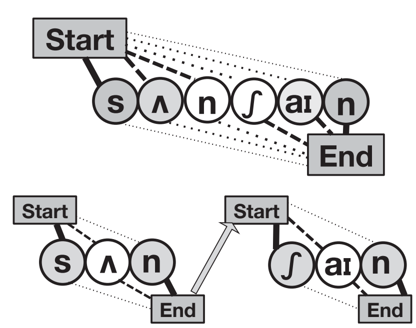

Figure 1. Two accounts of the serial order of phonological segments in compounds, based on start-end serial order schemas (e.g. Houghton, 1990). The production of a sequence begins by activating the start node, which differentially activates the segments with the first most strongly. After each segment is encoded, it is inhibited, making way for the next one. As the sequence is produced, the start node is gradually turned off and the end node is gradually turned on, resulting in a smooth transition through the sequence. The contrasting accounts differ on whether there are separate sequences for the two parts of the compound, or just a single sequence.

sequence in compounds specifically in spoken production. We can do so by using a paradigm that has been used to investigate serial order in language production, the *implicit priming* paradigm (Chen, Chen, & Dell, 2002; Meyer, 1990, 1991; O'Seaghdha, Chen, & Chen, 2010; Roelofs, 1996).

The implicit priming paradigm takes advantage of the serial nature of sub-lexical units (e.g. phonological segments, syllables or morphemes). Participants produce words aloud in response to a semantic cue. For example, for a cue *girl*, participants learn to produce the target *boy*. The cue-target pairs are learned and tested together in blocks. In critical blocks, called *homogeneous* blocks, the targets are phonologically similar in some way. In our studies, as with many others (Meyer, 1991; Roelofs, 1996), the targets all began with the same phoneme. Performance in the critical blocks is compared to performance in mixed (*heterogeneous*) blocks, where cue-target pairs from the various homogeneous blocks are mixed to create blocks that lack this phonological similarity. Faster response times in the homogeneous blocks constitute implicit priming. Importantly, because exactly the same cue-response items are used in heterogeneous and homogeneous blocks, differences in conditions cannot be due to the strengths of the cue-response relations. This feature of the design also gives it the power to detect small priming effects.

Meyer (1990, 1991) developed the implicit priming paradigm and found that one only gets priming if the shared phonological material in homogeneous blocks is at the beginning of the response word, which we will call the *starting point*. The greater the shared initial material, such as from a single phoneme to a whole syllable, the greater the implicit priming. The priming effect can be explained by proposing that phonological processes common to the targets in a block can be prepared in advance, with processing suspended, until the cue to speak is given (Levelt et al., 1999). Because of the advance preparation, the time to begin speaking is then less than in a heterogeneous condition, where none of the initial information is shared.

The fact that implicit priming works only for shared material at the starting point tells us that, at the processing levels tapped by this task, processing is strongly ordered. It also allows us to identify starting points. It can assess whether the onset of the second part of a compound (the /d/ in *dust* from *sawdust*), is a true starting point, which, if so, suggests that it functions as its own sequence. In our first two experiments, the cue-response pairs will be familiar two-syllable compounds, where the cue is the first morpheme (e.g. *saw*-) and the response is the second one (e.g. –*dust*). In homogeneous blocks, all responses will begin with the same phoneme (e.g. /d/). If the /d/ in –*dust* acts as a second starting point, priming should be obtained. If, instead, compounds are represented as single words with a single starting point (e.g. at /s/), there should be no priming, suggesting that within the context of a compound, the second unit does not function as its own sequence. The three subsequent experiments test alternative explanations and predictions derived from the first experiment's results.

Methods

Participants

10 undergraduate students were recruited from the introductory psychology course subject pool for each of the five experiments. These 50 students were all native speakers of English and were participating for course credit.

Materials

All cues and targets were only a single syllable long. Experiments 1a, 1b, 2 and 3 all used the same response items. Because these experiments varied as to whether or not they showed priming, the fact that they used the same responses makes it very unlikely that this variation in priming was due to properties of what participants produced (see column 5 in Table A1 of the Appendix for the common response items of these experiments). All response items fell into one of five mutually exclusive phonological categories, based on the phoneme at the onset of that morpheme (e.g., the /d/ in –*dust*). Each phonological category contained five items.

Cues for these response items were generated based on their relationship to the target in Experiments 1 through 3. In Experiments 1a and 1b, the cues were the first morpheme of a compound word whose second element is the target item (so, for a compound like *sawdust*, *saw* would be the cue, and *dust* would be the target production). In Experiment 2, the cues were semantically related words (e.g. *sweep* for *dust*), as done in the original paradigm (Meyer, 1990, 1991). In Experiment 3, the cues were pragmatically viable adjectival modifications of the target words (e.g. *grey* for *dust*). The adjectives should be effective retrieval cues for the responses, given that the implicit priming procedure involves a learning phase prior to the test trials. Moreover, there is evidence that experienced adjective-noun pairs are represented and influence the production process (Janssen & Barber, 2012). The cues for Experiments 1–3 are in columns 2–4 of Table A1 of the Appendix.

The materials for Experiment 4 were composed of two-syllable, monomorphemic words, with the 25 items' second syllables falling into one of five mutually exclusive phonological categories based on second-syllable onset phoneme. The first syllables (e.g. the *ban-* in *bandit*) are the cues, and the second syllables (e.g. *dit*) the targets. These are available in column 1 in Table A1 of the Appendix.

Procedure

An implicit priming task modelling the structure from Meyer (1990, 1991) was the basis for our task. Experiment 2 in fact used exactly the same method as Meyer

(1990) in terms of number of participants, items, blocks and trials, and in its use of semantic cues for targets. The only difference between our task and that of Meyer for our other experiments was that, instead of semantic cues, the cues initiated a sequence that the target completed; in those experiments, participants studied cue-target pairs where the cue constituted the first half of a single word or multi-word phrase, and the target was the second half of this word or phrase. By reproducing all of the quantitative aspects of Meyer's original design, which features five different five-item sets and multiple tests of each item both in heterogeneous and homogeneous blocks for a total of 7500 trials per experiment, our experiments have more than adequate power. Implicit priming effects when the prime is a single onset phoneme (e.g. O'Seaghdha et al., 2010) or syllable (e.g. Chen et al., 2002) can be on the order of 10 ms. We shall see that an effect of 8 ms was detected in one of our experiments.

Results

The analyses for all experiments are based on the same principle; a maximum mixed-effects multilevel model was constructed for each of the experiments to assess the effects on production time for *production context* (whether blocks were *heterogeneous* or *homogeneous*). In maximal models, both participants and items are modelled as random intercepts and slopes, a conservative approach to hypothesis testing, which may be required in psycholinguistic studies to avoid Type I errors (e.g. Barr, Levy, Scheepers, & Tily, 2013). The variable trial *block* (which of the 6 blocks the trial appears in) is also examined in the analysis as a control predictor. Although production context is the key contrast, the main effect of block is included as a check on the validity of the experimental paradigm, with lower production times across the course of the experiment indicating learning of the items and/or task. In the analyses reported here, we did not include the interaction between production context and the control predictor, block. In additional unreported analyses that did include this interaction term, it was never found to be a reliable predictor of response times in any experiment. Tests for the production context main effect are directional. Experiments of this sort either result in faster response times for the homogeneous condition, or they fail to do so. Results in the reverse direction are considered to be either spurious, the result of error or the result of an unwelcome strategy. Tests involving the block variable are non-directional, as each direction is an interpretable outcome. Speech onset times were determined from the stored sound files using an algorithm by Bansal, Griffin and Spieler (2001). Only correct responses where the speech onset time was less than the time out period of 1000 ms were included in the analysis of production times.

We used the package *lme4* to build and evaluate the statistical models of production time (Bates & Sarkar, 2007; see also Quené & Van den Bergh, 2004; Baayen Davidson, & Bates, 2008). For each experiment, we will report only maximal models with random intercepts and slopes for the key variable, production context. The overall advantages of the homogeneous production context over the heterogeneous production context for all five experiments can be seen in Figure 2. All models are reported in Tables A2–A6 in the Appendix. Error rates were very low and approximately equal between homogeneous and heterogeneous conditions in all experiments, and hence, other than the error rates themselves, no statistics for errors are reported.

Experiment 1a (*cue* = *saw*; *response* = ***dust***). This experiment tested whether transparent compounds that were split at the morpheme boundary were treated as two

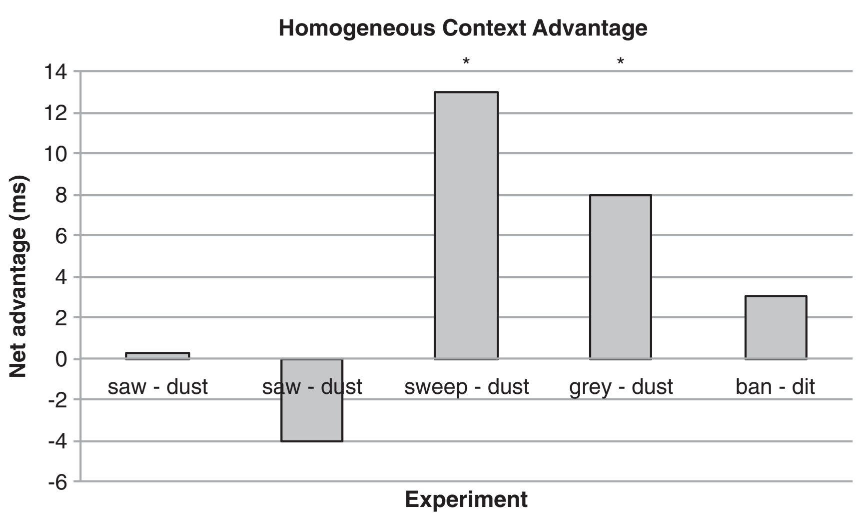

Figure 2. Homogeneous production context advantages for Experiments 1–4.

separate words. We found no effect of implicit priming, with a 0 millisecond advantage in the homogeneous production context compared to the heterogeneous context. The mean error rate was 2.5% (2.9% for the heterogeneous and 2.1% for the homogeneous conditions). Both the average homogeneous and heterogeneous production speech onset latencies were 410 ms. Participants did, however, show learning of the procedure and pairs over time, with a significant decrease in response times over blocks ($p < .001$).

The absence of a priming effect for compounds is most straightforwardly interpreted as support for the claim that the second part of a compound is not true starting point, and hence, compounds are represented as a single whole sequence. Notice that this null result, if it is truly null, is also evidence that the participants are treating the items *as compounds*, because if they were treating them instead as separate words, the homogeneous condition should foster advance preparation of the shared initial consonants of the response word and hence lead to priming.

Experiment 1b (*cue* = *saw*; *response* = ***d**ust*). Because Experiment 1a found no priming effect at all, and because this result was unexpected from theoretical perspectives that allow for morphological structure to influence phonological sequencing, we carried out Experiment 1b, which was simply an attempt to replicate the first experiment.

In Experiment 1b, there was again no advantage for the homogeneous context. Latencies in the homogeneous context were slightly longer than in heterogeneous contexts (426 ms for homogeneous and 422 ms for heterogeneous, with a 3.0% error rate for the heterogeneous condition and a 2.7% rate for the homogeneous condition). Since we are only interested in an *advantage* for the homogeneous condition over the heterogeneous one, no test of the production context variable was conducted. As in Experiment 1a, participants got faster over the course of the experiment ($p < .001$).

From Experiments 1a and 1b, we conclude that cue-target items that correspond to familiar compounds create no implicit priming, and hence that the initial phoneme of the second part of the compound is not a primeable starting point. Our tentative conclusion is that compounds are represented for production as single sequences at the level where segmental order information is represented.

Experiment 2 (*cue* = *sweep*; *response* = ***d**ust*). Given the null effects in Experiments 1a and 1b, it is important to establish that these response items can show an onset-consonant priming effect when the onset is known to be a true starting point. That should be the case if the onset begins an independent word. In this experiment, the response words were cued with a separate word that was semantically associated with the target, as in Meyer (1991).

As expected, there was a 13-millisecond advantage for targets in homogeneous contexts over heterogeneous contexts (heterogeneous = 462 ms; homogeneous = 448 ms) with error rates at 2.8% (3.2% in the heterogeneous condition and 2.6% in the homogeneous condition). This finding is consistent with those of other implicit priming studies when the homogeneous condition involved a single onset consonant (O'Seaghdha et al., 2010). This advantage was statistically significant ($p < .03$) as was the effect of block ($p < .001$).

This result allows us to conclude that the negative results from the first two experiments were not due to a peculiarity of the response items used. It appears that *dust* will be primed in the homogeneous condition (when all responses in the block begin with /d/), provided that *dust* is a separate word cued semantically, rather than the second half of a compound, cued by the first half.

Experiment 3 (*cue* = *grey*; *response* = ***d**ust*). The experiment tested whether the absence of an effect in Experiments 1a and 1b was due to the fact that the cue-target pairs formed a linguistic sequence, rather than the fact that the sequence is specifically a familiar compound. So, the response word in Experiment 3 was cued by a pragmatically viable adjective, making the cue-target pair a sequence, but the response itself a separate word.

Once again, there was an advantage for responses in the homogeneous contexts (heterogeneous = 465 ms; homogeneous = 457 ms) with error rates at 2.1% (2.2% for homogeneous and 1.9% for heterogeneous). The test for the production context variable yielded $p = .052$, which is right at the .05 rejection region. Given that we are using a conservative maximal random effects structure, and that our expected effect size was around 10 ms, we felt justified in rejecting the null hypothesis for this 8 ms difference. As before, there was a significant effect of how far participants were along in the experiment, $p < .001$.

Experiment 4 (*cue* = *ban*; *response* = ***d**it*). The preceding analyses suggest that implicit priming for the response's onset consonant only occurs when the response is a separate word, and specifically that compounds act as a single word. Split monomorphemic words, used in the same manner as the compounds, should then also show no effect of implicit priming. Consequently, Experiment 4 split apart two-syllable monomorphemic words, using the first syllable as the cue to produce the second syllable.

Experiment 4 yielded a negligible 3 millisecond advantage for the homogeneous production context (heterogeneous = 471 ms; homogeneous = 468 ms), p = ns, with a 2.0% error rate (2.1% for homogeneous, 1.9% for heterogeneous). This mirrored the results for the compounds in Experiment 1a and 1b. There was the typical effect of practice, $p < .001$.

Discussion

Over the course of our five experiments, we attempted to pinpoint the role of morphological structure in the phonological planning of compounds composed of two free morphemes like *sawdust*, using the implicit priming paradigm.

Experiments 2 and 3 were ancillary studies, designed to verify that the paradigm shows priming with the onsets of whole words. In Experiment 2, we replicated the results of Meyer (1991), O'Seaghdha et al. (2010) and Roelofs (1999), showing that the retrieval of a word from a semantic cue (e.g. cue *sweep* for the response *dust*) is facilitated if the response comes from a block in which all the responses begin with the same phoneme, e.g. /d/. Experiment 3 extended this result to sequential word pairs forming a partial noun phrase, with adjectives serving as the cues for nouns (e.g. cue = *grey*, response = *dust*). We conclude from the results of Experiments 2 and 3 that the onset of the second item of a cue-target pair functions as a clear starting point in the sense proposed by START-END models of serial planning (Fischer-Baum et al., 2010; Houghton, 1990), provided that the onset is the beginning of an independent word.

Experiments 1a, 1b and 4 extended the paradigm to situations in which the cue and the target when concatenated form single words, thus allowing for a test of whether the second part of the word acts as a starting point. Experiments 1a and 1b tested compounds composed of two free morphemes where the first part of a compound was the cue for the production of the second part (cue = *saw*, response = *dust*). Experiment 4 took this one step further, splitting two-syllable monomorphemic words on the syllable boundary (cue = *ban*, response = *dit*). In both Experiments 1 and 4, we failed to find evidence for implicit priming when responses came from conditions in which the onset consonant was homogeneous (e.g. /d/). Altogether, the results suggest that compounds are structured more like single words than like two individual words at the processing level where the sequential planning of phonological units takes place. This result is just what would be expected from Wheeldon and Lahiri's (2002) experimental demonstration that compounds function as single prosodic words during production planning, and from the results of Janssen et al. (2008), who found that the whole-word frequency of compounds retrieved in a picture naming task has more influence on naming times than the frequencies of the compounds' components. Before accepting this conclusion, though, it is important to consider potential limitations of the findings and some possible alternative explanations.

First, consider the fact that the key experiments finding no priming when the cue-response pair formed a compound (Experiments 1a and 1b) are 'null' results. A null result can be difficult to interpret, but such difficulties arise typically when the experiment is underpowered, or when the finding was in the expected direction, or when there has been no attempt to replicate. That is not the case here. The null result of Experiment 1a was replicated in Experiment 1b, and the two findings were convincingly null (0 ms of priming in 1a, and 4 ms in the wrong direction for 1b). Because of the within-subject and within-item design and the 7500 trials per experiment, each of these experiments had the power to detect the expected priming effects. Experiments 2 and 3 had exactly the same designs as the compound experiments and these successfully detected priming effects of 13 and 8 ms (10 ms for single onset-consonant priming effects was expected). Null results can also be problematic when they cannot be easily interpreted. Again, that is not the case here, as the possibility that compounds are treated as a single phonological sequence has precedence in the literature (e.g. Janssen et al., 2008; Wheeldon & Lahiri, 2002). Moreover, we will present more specific theoretical proposals later in the discussion. Finally, null findings best become meaningful when viewed alongside contrasting positive findings. Here, we have positive findings in Experiments 2 and 3, and in a subsequent section make predictions about expected positive effects in other situations. In summary, we feel that the null results of Experiments 1a and 1b with compounds are truly theoretically constraining.

An alternative explanation for our null findings with compounds must be considered, though. Perhaps the effectiveness of an implicit prime depends inversely on the strength of the cue, which conceivably could be stronger for the compound experiments, thus predicting that priming would be weak for compounds. The cue *saw* may so effectively point toward *dust*, that there is no 'room' for priming to occur in a homogeneous initial-consonant context. This account has at least two points against it. First, recall that all cue-response pairs are studied and practiced before they are tested. Such study would be expected to reduce any inherent differences in cue effectiveness. Second, the principal model of how implicit priming works (Levelt et al., 1999) specifically holds that the production context variable (homogeneous vs. heterogeneous context) should not interact with cue strength. Cue strength affects the speed of retrieval of a holistic representation of the response item. By contrast, a phonologically homogeneous production context affects the speed of subsequent phonological encoding. These are different steps in the process of word production, and hence, a speed-up, because of a strong cue, should not diminish priming. Of course, one could argue that this model is not true and assert that the knowledge that the response begins with, say, /d/, could affect an earlier stage of word retrieval. This proposal, though, is unlikely because, as demonstrated by Meyer (1990, 1991), only continuous sequences from the beginning of the response function as implicit phonological primes. Rhyming, for example, creates no implicit priming, despite non-initial primes such as rhymes being very effective cues for lexical retrieval (e.g. Bower & Bolton, 1969). Consequently, the implicit priming effect cannot be the result of the implicit prime cueing lexical retrieval. To summarise the second point, the differences in the strength of the cues across the experiments (e.g. the first part of a compound may be a particularly strong cue) cannot explain differences in priming. The nature of the priming – that it only works at starting points – reveals that priming must occur at a later processing stage than the lexical retrieval stage that would be impacted by cue-response strength.

If we were to point to a weakness in our data, it would be that the priming effect in Experiment 3 (cue = grey, response = dust) was small, and just barely at the threshold for significance. Despite this, we argue that our results are internally consistent. Across five experiments, there is only priming when the response is a separate word, and never priming when it is the second half of the word that begins with the cue, even when that word is a compound. The conclusion from these studies is quite consistent with other studies of compound production that treat compounds as single sequences at the phonological level (Janssen et al., 2008; Wheeldon & Lahiri, 2002). In the following sections, we consider two additional theoretical questions: (1) What specific mechanisms prevent implicit priming for shared response-initial consonants that are not word starting points? (2) How do our results accord with the many studies supporting a role for decomposition in compound production?

Implicit priming, starting points and representational identity. The 'suspend-resume' account of implicit priming (Levelt et al., 1999) assumes that speakers can build the shared component of the representation of the response item in advance, that is, before they know the cue and hence the identity of the item. The mechanism provides an excellent account of why the shared material must be the response-initial element (or that element plus contiguous elements) to get priming. Although we believe that this is the correct account, it does not explain why we did not get priming in three experiments where the implicit prime was response-initial, but was not the starting point of the word formed by the cue-target sequence. Our amendment to the theory is simple: If you do not know how to represent the shared material in advance of knowing the cue, you cannot build a representation in advance. We propose that *at starting points, it is possible for shared material to be identically represented* in the phonological sequence that guides production, and hence, the system can make use of the sharing. The representation of, say, /d/ in cue = *grey*; response = *dust*, and /d/ in cue = *fat*; response = *dog*, is the same. Both are assumed to be a /d/ in the context of the beginning of a word. Hence, the system knows how to build this in advance, and priming will be obtained. We also propose that seemingly identical phonological material that is not at a starting point may not be representationally identical. The /d/'s in cue = *saw*; response = *dust*; and cue = *bull*; response = *dog*, are not represented the same way. As a result, one cannot plan this /d/ in advance.

When we say that the /d/'s in *sawdust* and *bulldog* are not represented the same way, we do not mean that the system is not working with phonological segments. Rather, the way that the segments are treated is different. To illustrate, in Figure 3, we present an account of this difference based on an incremental segmental spell out model of phonological encoding (e.g. Levelt et al., 1999). The model has representational levels corresponding to whole lexical items, morphemes and phonological segments. In the case of a compound such as *sawdust*, there are morpheme units for *saw*, and *dust*, and their order is represented. Each morpheme unit is associated with its ordered segments. During word-form planning, these segments are retrieved from each morpheme in sequence and placed left-to-right in slots of a sequence store for the word. This store has a single starting point, and there is no boundary indicating the beginning of any second morpheme if the word is a compound. The figure shows a moment in the planning of *sawdust*. The two segments of *saw* are in place, as is the /d/ from *dust*, At this point in the representation, we assume no syllabic or phonetic organisation in keeping with Levelt et al.'s (1999) approach to word-form encoding. This structure is computed later.

Given this model, it is easy to see why the onset of the second morpheme of a compound cannot be put in advance into the structure. The representational uncertainty is positional. One does not know where to put the second-morpheme onset until one has put in the segments of the first morpheme. After *saw*, the /d/ goes in the third slot. But for other compounds, the beginning of the second morpheme could be at the second slot (*eyeball*, assuming that the diphthong is a single unit), the third (*bulldog*) or even sixth (*streetlight*). If the response is an independent word, there is no uncertainty; the shared onset just goes in the first slot.

Of course, one could assume that there is syllabic structure at work during this segmental spell out process. If so, one would then know in advance that the /d/'s in *bulldog* and *sawdust* go in the same slot, the onset of the second syllable. Even so, other factors can create representational variability, when the shared material is not at the starting point. Suppose that each segment's representation contains cues or links to prior segments in the word (e.g. forward chaining, Goldberg & Rapp, 2008). If so, the /d/'s in *bulldog* and *sawdust* would be contextually different, and could not be planned in advance. But if the /d/'s were word-initial, their prior context cues can be assumed to be identical: the word boundary.

This discussion, we hope, illustrates possible mechanisms for why priming may not be possible for shared material that is response-initial but does not correspond to the relevant starting point in the controlling structure. We can go beyond illustration and make a prediction: Implicit priming for response-initial shared material that is not at a starting point should be obtained only if the system knows how to situate the shared material into the representation in advance. This claim can be, and indeed has been, tested in Mandarin Chinese. Implicit priming in Mandarin only

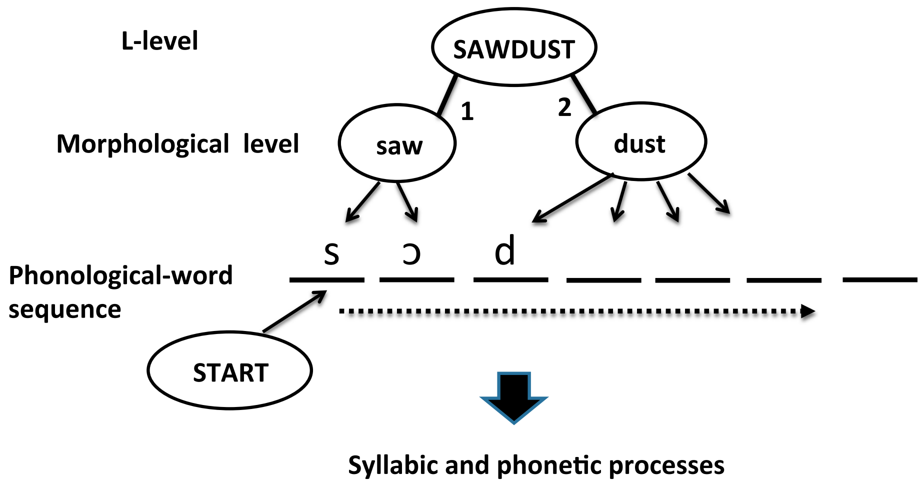

Figure 3. An incremental account of the lack of implicit priming for compounds. Lexicalised compounds such as 'sawdust' are represented at the L-level, and are decomposed into morphemes at the morpheme level. The morphemes are known to be ordered and have access to their phonological segments. The phonological segments are incrementally retrieved and placed into slots in the phonological-word sequence. This sequence has a known starting point (the first slot), but no morphological boundaries. Its slots must be filled incrementally and left to right. Implicit priming resulting from a shared initial response (e.g. /d/) is not possible when the response is the second morpheme of a compound, because the /d/ is not at the starting point in the sequence. It cannot be known in advance where to put the /d/ in the sequence because, before the cue is given, the previous segments in the sequence are not known. If the response is an independent word (e.g. cue = *grey*, response = *dust*), its first segment will always occupy the starting slot of the phonological-word sequence, and if that segment is known in advance, it can be placed in that slot in advance, creating a priming effect.

occurs for syllable-sized units (Chen et al., 2002). Specifically, robust priming occurs when the shared material is the entire first syllable of the response word. Priming also occurs, but is smaller, when the shared material consists of just the segmental content of the first syllables; for example, if all responses begin with the syllable *bing*, but their tone varies, there will be between 10 and 15 ms of priming. This latter case is called 'toneless' syllable priming. Unlike in other languages, priming in Mandarin does not occur for shared syllable onsets. Hence, it is proposed that the sequential structure that guides Mandarin production is made up of syllable-sized units, rather than phonemic units (O'Seaghdha et al., 2010). For two-character words, there are only two slots in the sequence, one for each syllable. Under these circumstances, if the first character is the cue and the second syllable is the response, there should be priming, provided that all of the second syllables of the response set share the syllable's segmental content. This is because the system *does* know where to put the implicit prime, even though it is not at the starting point of structure. There are only two slots, and the shared syllable content is known to occupy the second slot.

Chen and Chen (2013) have carried out exactly this experiment using Mandarin two-character compounds. The cue is the compound's first character, and the response is the second syllable. In homogeneous blocks, the responses (the second syllables), shared phonological content, but not tone; that is, the implicit prime was the toneless syllable. The results showed between 14 and 17 ms of priming, comparable to other findings when word-initial toneless syllables are the prime. This result contrasts with our findings in English, but is exactly what is expected from the account of our results presented in Figure 3. Because the toneless syllable prime can be situated in the syllabic sequence in Mandarin, priming is possible. Notice that this explanation has nothing to do with morphological structure. In fact, we would predict that the same thing would happen with two-character monomorphemic words. Chen and Chen reported this finding, as well. In sum, the procedure in which the cues are the first part of the word, and the response is the second, leads to no priming in English when the implicit prime is the onset of the second syllable, regardless of whether the words are compounds (Experiments 1a and 1b) or monomorphemic (Exp. 4). In Mandarin, the data also patterned similarly for compounds and monomorphemic words, only there, priming was obtained. The differences between Mandarin and English are fully in accord with both our claim that the morphological organisation of the compound does not set up a second starting point at the level of the phonological sequence, and our claim that implicit priming only occurs when it is possible to situate shared material that is not at a starting point.

Morphological decomposition in production? Several studies, using a variety of methods, languages and types of participants, support the claim that the production of compounds is influenced by their morphological organisation, that is, that they are composed of two distinct morphemes (Ayala & Martin, 2002; Bien et al., 2005; Blanken, 2000; Dohmes et al., 2004; Gumnior et al., 2006; Koester & Schiller, 2008, 2011; Lorenz et al., 2014; Lüttmann et al., 2011; Roelofs, 1996; Roelofs & Baayen, 2002; Schiller et al., 2001, but see Chen & Chen, 2006, for discussion of Mandarin, which may differ in this respect). These results support the inclusion of a morphemic level in production. We stress that our findings are entirely consistent with this literature. We simply showed that, when the morphological parts of a compound are spelled out into a phonological sequence, that sequence has a single starting point. Another way to say this is that there is no longer a potent morphological boundary in the sequence. At this level, *sawdust* and *bandit* look the same. But just because they look the same at this level, it does not mean that the prior processes were. In fact, our account of the data presented in Figure 3 specifically assumes morphological decomposition. The segments of *sawdust* are retrieved from two morpheme units, whereas for *bandit*, they are retrieved from one such unit. The existence of distinct nodes for the morphemes of a compound would, in a spreading activation system, have a number of effects. For example, it would explain errors on one morpheme, but not the other (e.g. Ayala & Martin, 2002) and would make words that share a morpheme more similar and hence subject to positive and negative effects associated with that similarity (e.g. as in the picture-word interference paradigm). Moreover, the effects of morphological similarity would be in excess of that expected from just phonological or semantic similarity (e.g. Koester & Schiller, 2008; Roelofs, 1996). Thus, there is little question that morphological structure impacts production generally and the production of compounds specifically. This conclusion would likely be accepted even by advocates of the view that morphological structure emerges from phonological-semantic mappings, rather than being stipulated *a priori*, (e.g. Plaut & Gonnerman, 2000). We are simply proposing that, at the level tapped by our experiments, a structure with two morphemes – the English nominal compound – does not compel the creation of two, rather than one, phonological sequences during production.

In summary, our experiments show that compounds are produced as one, and not two, sequences at the phonological level. Because the experiments tested only lexicalised (familiar) nominal English compounds that are commonly spelled as a single word such as 'sawdust', our findings properly apply only to this set of compounds. Compounds spelled with two words ('lightning bug,' as opposed to 'firefly') may in fact be phonologically planned as two sequences, either because of a true orthographic influence on phonological processes, or because the probability of a space between the words is predictive of the degree of phonological separation. Also, our results may not generalise to the production of novel compounds, which are very common, and formed spontaneously. Novel compounds, such as *cat dust* (the lingering dander caused by cat ownership) or *thought book* (similar to a diary) may not be subject to the same kinds of planning processes and may instead be produced with two unique starting points, much as might be expected when considering the semantic structure of complex noun phrases, where the morphemes are considered to be their own discrete words. It could be the case, then, that lexicalised compounds are stored as single phonological sequences, while non-lexicalised items would necessarily be derived from the component parts, with this two-part structure being reflected at the phonological level. The nature of the production of compounds generally is therefore still an open question, which merits further investigation.

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Appendix

Table A1. Stimuli for Experiments 1–4.

Cues	Targets Experiment 4	Cues Experiment 1 (Compounds)	Cues Experiment 2 (Semantic cues)	Cues Experiment 3 (Noun phrases)	Targets Experiment 1, 2, 3
bam-	-boo	eye-	game	round	ball
co-	-balt	soy-	meal	red	bean
mor-	-bid	surf-	wood	flat	board
lim-	-bo	fish-	food	hot	bowl
ro-	-bot	sand-	crate	large	box
ban-	-dit	week-	night	hard	day
can-	-did	bull-	cat	fat	dog
ra-	-dish	touch-	up	soft	down
sar-	-dine	saw-	sweep	grey	dust
en-	-dive	out-	close	closed	door
fur-	-nish	gun-	boy	big	man
or-	-nate	door-	feet	wide	mat
tur-	-nip	room-	friend	good	mate
gar-	-net	wind-	grain	nice	mill
har-	-ness	ear-	cold	warm	muff
sham-	-poo	dust-	wok	deep	pan
ram-	-page	tooth-	choose	dull	pick
mag-	-pie	bag-	flow	strong	pipe
car-	-pet	flag-	climb	thin	pole
em-	-pire	air-	ship	old	port
vor-	-tex	thumb-	wall	sharp	tack
mo-	-tel	bob-	mouse	long	tail
lan-	-tern	day-	when	short	time
gui-	-tar	buck-	mouth	white	tooth
pla-	-teau	wash-	sink	full	tub

Table A2. Mixed-effects model for Experiment 1a (Compounds).

Random effects			
Groups	Name	Variance	SD
Participants	Intercept	1373.95	37.08
	Production context	199.66	14.13
Items	Intercept	721.42	26.86
	Production context	306.57	17.51
Fixed effects			
	Estimate	*SE*	*t*
Intercept	429.465	13.18	32.58
Production context	−0.039	6.07	−0.01
Block number	−5.371	0.65	−8.28*

*$p < .05$.

Table A3. Mixed-effects model for Experiment 1b (Compounds).

Random effects			
Groups	Name	Variance	SD
Participants	Intercept	2186.43	46.76
	Production context	206.69	14.38
Items	Intercept	800.81	28.30
	Production context	505.01	22.47
Fixed effects			
	Estimate	*SE*	*t*
Intercept	443.260	16.12	27.51
Production context	3.047	6.80	0.44
Block number	−5.675	0.69	−8.18*

*$p < .05$.

Table A4. Mixed-effects model for Experiment 2 (Semantic cues).

Random effects			
Groups	Name	Variance	SD
Participants	Intercept	5098.26	71.40
	Production context	312.23	17.67
Items	Intercept	702.99	26.51
	Production context	110.50	10.51
Fixed effects			
	Estimate	*SE*	*t*
Intercept	480.597	23.43	20.51
Production context	−12.916	6.51	−1.99*
Block number	−5.530	0.86	−6.40*

*$p < .05$.

Table A5. Mixed-effects model for Experiment 3 (Adjective cues).

Random effects			
Groups	Name	Variance	SD
Participants	Intercept	3011.23	54.88
	Production context	71.53	8.46
Items	Intercept	712.52	26.69
	Production context	50.36	7.10
Fixed effects			
	Estimate	*SE*	*t*
Intercept	482.17	21.80	22.13
Production context	−7.79	4.79	−1.63*
Block number	−4.75	0.98	−4.86*

*$p < .05$.

Table A6. Mixed-effects model for Experiment 4 (Monomorphemic words).

Random effects			
Groups	Name	Variance	SD
Participants	Intercept	5640.51	75.10
	Production context	194.17	13.94
Items	Intercept	522.91	22.87
	Production context	215.51	14.68
Fixed effects			
	Estimate	*SE*	*t*
Intercept	522.918	24.34	21.49
Production context	−4.952	5.704	−0.87
Block number	−8.45	0.64	−13.16*

*$p < .05$.