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Phonetic detail is used to predict a word's morphological composition

--Manuscript Draft--

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Abstract:	<p>An eye-tracking experiment tested the hypothesis that listeners use within-word fine phonetic detail that systematically reflects morphological structure, when the phonemes are identical (dis in discolour (true prefix) vs. discover (pseudo prefix)) and when they differ (re-cover vs. recover). Spoken sentence pairs, identical up to at least the critical word (e.g. I'd be surprised if the boys discolour/discover it), were cross-spliced at the prefix-stem boundary to produce stimuli in which the critical syllable's acoustics either matched or mismatched the sentence continuation. On each trial listeners heard one sentence, and selected one of two photographs depicting the pair. Matched and mismatched stimuli were heard in separate sessions, at least a week apart. Matched stimuli led to more looks to the target photograph overall and time-course analysis suggested this was true at the earliest moments. We also observed stronger effects for earlier trials and the effects tended to weaken over the course of the experiment. These results suggest that normal speech perception involves continuously monitoring phonetic detail, and, when it is systematically associated with meaning, using it to facilitate rapid understanding.</p>
Suggested Reviewers:	<p>Cynthia Clopper clopper.1@osu.edu expertise in perception and production</p> <p>Scott Seyfarth seyfarth.2@osu.edu expertise in phonetic correlates of morphological structure</p> <p>Laura Dilley ldilley@msu.edu expertise in perception, especially of rhythm</p> <p>Lisa Davidson lisa.davidson@nyu.edu expertise in phonetic correlates of morphological structure</p> <p>Mara Breen mbreen@mtholyoke.edu expertise in prosodic rhythm in spoken language</p>
Response to Reviewers:	

Dear Prof Cho,

We thank you and the reviewers for the encouraging and thoughtful comments on our manuscript. We've made several changes in response to your comments that we feel have substantially improved the manuscript, specifically in helping us more clearly describe our methods and stimuli. We've added the original stimuli to the OSF repository along with a new set of supplemental materials describing them. We've also reworked the methods section including the tables and figures to provide more detail and we hope more clarity around our experimental design. The Discussion is also changed as requested. Please see our detailed response to comments below.

Your paper was sent to three experts whose reviews are appended below. All three reviewers agree that the theme of the paper is certainly of interest to the readership of JPhon, and the paper is generally well written with clear exposition. They generally feel that the paper should be publishable after addressing some issues. As you will see them below, the reviewer comments are largely minor and matters of clarification, but Reviewer 1's points would require some substantial revisions. Their points are clearly laid out in their reviews, so I will just highlight some of the Reviewer 1's points for your attention.

Reviewer 1's major comments boil down to the point that understanding the phonetic detail with a more clear-cut differentiation between segmental vs. suprasegmental phonetic differences would certainly make the paper received much better with stronger impact. R1 notes that we are not sure what other acoustic phonetic differences (other than the temporal difference) might underlie the distinction between the true and pseudo prefixes, which may also serve as perceptual cues to the morphological composition. These include the degree of vowel centralization (as can be measured by F1 and F2), and tonal (intonational) difference (as can be measured by F0), which will certainly help understand the nature of the fine phonetic detail.

We agree that the nature of the phonetic differences in our stimuli is a relevant question for the reader to ask. We have now completed a detailed acoustic analysis of our stimuli which we summarize in a new set of supplemental materials. Our analyses are in line with the previous studies which carefully documented the differences between these word types. We have also made some comments in the discussion section on the limitations of our study to note that we can't be sure which of these acoustic characteristics are responsible for listeners behaviour. We hope that these additions are valuable.

With respect to the clearcut differentiation between segmental and suprasegmental phonetic differences you ask for, we feel that distinguishing more explicitly between segmental and suprasegmental differences cannot be meaningfully done for these syllables. When the phoneme sequence is identical, measurable acoustic differences like durations, f0, and arguably even patterns of formant frequencies, fall into most prosodicists' 'prosodic' category. And indeed, we argue that they are best thought of as rhythmic. Yet in our stimuli they are intrinsic to the phoneme-sized segments and what distinguishes them. We do not understand what gain there is in claiming them as either segmental vs suprasegmental, for they are both. So we have reported our measures straightforwardly using acoustic terminology, leaving readers free to think of them as segmental or suprasegmental depending on the context in which they wish to use the information.

Reviewer 1 also rightly ask you to examine whether there is any distal prosodic (intonational) differences prior to the critical prefix, which may be related to the discussion on the rhythm/meter based view. I believe that it is certainly useful for you to explore this possibility and to make some comments on this as you see fit, but I would like to leave it up to you, as examining the effects coming from the global prosodic modification may fall beyond the scope of the study.

We agree that this a very interesting and relevant question. We have addressed it by measuring duration, formant frequencies, and f0 in various ways in the stimuli, and comparing these data between prefixed and pseudo prefixed stimuli. A rather full report is now included in the Supplementary Material, and a summary is given later in this letter, where R1 asks for the information. The Method now includes

brief mention too. We are confident that there weren't substantial systematic differences in the obvious acoustic parameters in the stimuli, and that the design would have prevented any more subtle ones our analyses may have failed to detect from being used. We agree that a formal intonational analysis of our stimuli is beyond the scope of this study.

Reviewer 1's other suggestion is to bring the discussion on the rhythm/meter-based account up to the center, but I feel that the way it is situated in the present set up is rather appropriate, given that the current study, as far as I can see it, does not directly test this view. But I agree that a bit more discussion on how the proposed view may be related to an oscillatory account with differentiation between prosodic and segmental oscillations.

We agree with you, that we don't test the rhythm/meter account directly. For this reason we keep it in the discussion as it is speculative at this point.

Reviewers 2 and 3 also made a number of useful comments which are all merit consideration and need reflecting in full in the revisions.

Reviewer 3 pointed out some places where the methods were not sufficiently clear. We've worked hard to address this by substantially changing the methods section. We've added new figures and tables to clarify the design. We've also added an overview section at the beginning of the methods that describes our design and all of the factors in our analysis.

My own assessment of the ms is largely in line with the reviewers', and I believe that the present study, if revised as suggested by the reviewers, will eventually make an important contribution to the field. So I would like to encourage you to revise and resubmit the manuscript.

A few editorial comments

- - Thank you for providing the supplementary materials. I would appreciate it if you could provide a DOI number.

this has been included

- - The current Acknowledgements section includes authors' contribution statements. Now a section of "CRediT authorship contribution statement" is available. Please move the contribution statements to this section.

we have separated the Acknowledgements and Contribution Statement sections

- On p.24, there are couple of cases with missing citation information: (...Hay, xx; Plag, xx?..)

We have deleted these words. The next sentence describes the Plag et al paper, and begins 'For example' which seems preferable. We apologize for not deleting the place holder words before our original submission.

- Plag I. & ben Hedia, S. (2018). --> Please also include the following JPhon paper which is readily available to the JPhon reader.

Ben Hedia, S. and Plag, I. (2017). Geminata and degeminata in English prefixation: Phonetic evidence for morphological organization. Journal of Phonetics, 62, 34-49

done, the citation was in the manuscript but had been missing from the reference list.

When revising your manuscript, please consider all issues mentioned in the reviewers' comments carefully: please explain every change made in response to their comments and provide suitable rebuttals for any comments not addressed. Please note that your revised submission may need to be re-reviewed.

Reviewer #1: Summary

In their manuscript entitled "Phonetic detail is used to predict a word's morphological composition" the authors provide evidence that during speech comprehension, fine-phonetic detail is used to predict morphological structure. In a visual world paradigm, the authors compared percentages of looking times to target vs. distractor images matching with either truly or pseudo-affixed morphological complex verbs. Verbs were modified by cross-splicing to either result in matching combinations of true and pseudo-prefixes with corresponding stems or in mismatching combinations. Independent of prefix-type (phoneme change or not), matches led to larger proportion of looking times to the target pictures than mismatches. The results are interpreted as evidence for fine-phonetic detail to be used for predicting morphological structure in online speech comprehension. Furthermore, a potential "carrier" of this effect is proposed to be rhythmic/metrical structure, assigning differing beat-strengths to real- vs. pseudo-prefixes.

Evaluation

In general, the authors present a carefully designed experiment with a sound theoretical background. Analyses follow state-of-the-art statistical procedures and hypothesis-testing is complemented with explanatory analyses e.g. regarding development of effects over time. The manuscript is clearly interesting for the interface between phonetics and morphology, but in its current status, it lacks some detailed phonetic analyses which would make the overall impact stronger. I try to elucidate this in the following: Major issues

- The authors state that the cross-splicing of prefixes and stems as carried out during stimulus construction led to mismatches that were based on fine-phonetic detail. The actual acoustic-phonetic consequences of this mismatch, however, are only explored on the basis of timing differences. These were rather substantial. Where there further acoustic-phonetic differences (e.g. vowel centralisation, devoicing of consonants) and effects beyond single-segments (e.g. intonation contours)?

This is an important point and we thank the reviewer for raising it. We have completed a substantial analysis of the acoustics of our stimuli. For the critical pseudo and true prefixed syllables (e.g. dis-) we followed the analyses in prior work, e.g. Smith, Baker, Hawkins (2012). We found the expected differences in segmental duration and formant frequencies in the vowel, as well as in f_0 , consistent with the claim that true prefixes have a stronger rhythmic beat than pseudo prefixes. This was expected given the care with which the stimuli were constructed. We did not examine devoicing of consonants since, for the speech register used, this would only apply to the /d/ of dis-, whose degree of closure-internal phonation in this accent is heavily context dependent, and seldom strong.

Because this would take up substantial space in the manuscript to describe we have included a report of this acoustic analysis in additional materials available on the OSF archive. We have also included the stimuli so that others can see and hear the differences for themselves. We have made reference to these new analysis in section 2.7 in the paper where we include the summary of durational differences.

- Related to the aforementioned issue, it would be interesting to assess potential differences prior to the critical prefix. It could be the case that prosody, rhythm and meter provides already clues for one or the other continuation. The mismatch could also result from unexpected changes in the intonation contour

There can indeed be audible metrical differences on the critical syllable's realisation due to context. For example the length of the preceding foot can affect the prominence of a 're-' critical syllable. Other influences include, of course, speech rate and intonational variation, and there are differences dependent

on the number of syllables in the word itself. These and other potential influencing factors were controlled for during stimulus selection and creation: the metrical structures used, the identity of the words before the critical syllable, and selection of actual stimuli from six or more candidate tokens of each, using phonetically trained listeners and some acoustic measurement. However, some decisions were not easy and some minor compromises were necessary, between, say, overall pitch and overall speech rate. So we thank R1 for asking for more objective evidence of comparability between stimulus pairs. We have done our best to provide it by comparing prosodic/rhythmic properties before and after the critical syllable.

We have analysed supra-segmental factors in a number of ways, especially on the matched sections before the critical syllable. This included the speech rate (overall durations), time between accented syllables and the critical syllable, and f_0 and formant frequencies on accented syllables. We compared these matched sections for sentences originally produced with a true prefix vs those originally produced with a pseudo prefix and find them to be equivalent. See below for a more detailed description and summary, and the supplemental materials for full details.

It is also worth noting that visual inspection of figure 5 (the main effect of Match) doesn't reveal any differences in the looks to the target or competitor before the critical word onset or even 200 ms after this point. While we haven't done a statistical test on this, it does suggest that listeners weren't able to make predictions before they had heard the critical syllable.

We have kept all of this discussion for the report in the supplemental materials rather than the main text. But for ease of judging whether our response satisfies, here is a more extensive synopsis than that above. We distinguish two types of comparison. First, we compared the durations, median and average f_0 in three relatively long regions (hereafter sections) that together comprise the whole utterance: from the start of the utterance up to the splice point (i.e. start to immediately after the critical syllable), from the splice point up to the end of the word or foot, as appropriate, and from that point to the end of the utterance. Consistent with the focus on prosodic as well as segmental structure in stimulus construction, there were no differences between true and pseudo matched stimuli within any of these three sections, for duration, median and average f_0 , neither across all syllable types, nor within each type (*dis*, *mis* and *re*). Observed f_0 differences within a section amounted to about 5 Hz or less (with the expected mild f_0 declination evident across the three sections.)

Second, we identified four points of interest in each token to use to assess prosodic/rhythmic similarity: two prominent (usually accented) syllables before the critical syllable, the vowel of the critical syllable itself, and the vowel of the next syllable in the target word—that is, the syllable immediately following the splice point. Where there were more than two accented syllables before the critical syllable we used only the first and the last; where there was only one, then of course we did not have a second point before the critical syllable. Stimulus design and the controlled talking style ensured that the number and identity of accented points was identical in each member of a pair of stimuli. Because we are interested in perceived rhythm, we did not measure at the vowel midpoint, but closer to the onset (avoiding microprosodies), if possible where f_0 was maximal, supplemented if necessary by intensity and waveform envelope amplitude (for reasons, see Hawkins, S. (2014) in the main references). These points are available for inspection in tier 3 of the textgrids provided in the supplementary materials. There was some unavoidable subjectivity in point placement. To control for criterion drift, each point was identified on its own merits, but having placed the points independently, the two members of each pair were compared for similarity of point placement (not for similarity of acoustic parameter values).

These 3 or 4 points were then compared (between true- and pseudo- prefixed sets) as follows: differences in duration and in f_0 between successive points; absolute f_0 at each point; formant frequencies at the first two accented points and in the critical syllable. (Formant frequencies in syllable 2 of the target word are not necessarily expected to be comparable so were not measured.) As with the other analyses, each of these measures was made on all the stimuli together, and on each of the three prefix types (*dis*-, *mis*-, and *re*-). Overall results showed strongly consistent patterns for each of these measures, and no significant differences between prefix and non-prefix sentences. For example, the medians and ranges of durations between successive points were almost identical, except for the critical

syllable to the target syllable 2, where the median was shorter for the pseudo-prefix stimuli. This is inevitable given that the critical syllable is shorter when it is a pseudo prefix. Likewise for f0: differences between successive points were almost identical, and mildly negative (indicating expected f0 declination) except for the critical syllable to the target syllable. For this interval, the difference was mildly positive, and greater for the pseudo-prefixed condition. The positive rather than negative change indicates that the target syllable 2 was more intonationally prominent than the critical syllable, and the greater change for the pseudo prefix indicates that true prefixes tend to be more intonationally/rhythmically prominent than pseudo prefixes. (Assuming f0 correlates with intonational prominence, other things equal.)

We conclude that our results are very unlikely to have been caused by metrical, rhythmic or intonational differences before the critical syllable. Furthermore, we found no differences after the target word. This means that the metrical, rhythmic and intonational differences in these stimuli are restricted to the critical syllable and its relationship to the following syllable, as was our intention.

- If included in a revised version of the current manuscript, the two points briefly illustrated could help improving the motivation of the rhythm/meter-based discussion at the end of the article. I think that this discussion is very interesting, but at the moment, it feels rather "additional" than "integral". Why not rooting it in the general setup of the argument, as potential "carrier" of fine-phonetic detail?

We're glad that you found the rhythm/meter-based discussion interesting. We agree with the editor however that our study is not able to test this directly. Therefore, we prefer to leave the motivation as it is, to test whether listeners are sensitive to phonetic details cueing morphological structure. Having shown that, we think there are interesting reasons why the signal might be structured the way it is and why listeners might use the information the way that they do but probing these directly would require other studies.

- I think that a more clear-cut differentiation between segment-based and supra-segmental differences between true and pseudo-prefixes might be useful. Are their intonation differences between the two types of prefixes? What intonation "clashes" are introduced by the cross-splicing procedure? (A more specific question here: Is it the case that the match- condition is essentially the result of cutting the stem from the prefix, and then re-attaching it? Would that not mean that the match-condition is always a condition with no acoustic modification, so that the effect could theoretically just reflect an acoustic modification? This should be clarified!).

Both types of critical syllable carry only weak or no stress, and some of their vowels are so short and low-intensity they have fewer than three or four periods in which f0 can be measured. So we have not tried to describe 'intonation differences' between them, but only measured f0 at one point. As our supplementary material shows, f0 does tend to be slightly lower in pseudo prefixes, consistent with their weaker stress. This means there is normally a bigger difference between f0 in the pseudo prefix and the following, post-splice syllable, than between the true prefix and following syllable. Given the large durational differences that accompany these changes, we have described the data in terms of rhythm, which has to encompass both pitch and duration, whereas intonation is often assessed largely in terms of f0 alone.

As our detailed acoustic analyses show, the cross-splicing did not introduce anything substantial enough to be described as an intonation clash. For example, in the analysis of f0 changes between successive syllables of interest (the first and last accented syllables before the critical syllable, the critical syllable itself, and the first syllable after the critical syllable (and therefore also after the splice point)), median f0 differences overall were about 5 Hz or less, with the biggest ones, for dis-, being less than 10 Hz, and these were largely caused by the intrinsic difference in f0 due to the heavier beat on the prefixed critical syllable: which as explained above, is the crux of the experiment. Impressionistically, cross-splicing to create unmatched stimuli did introduce some unexpected rhythms at times—some were more noticeable than others—but again, that was the point of the experiment. Easily perceptible or not, the cross-splicing in unmatched stimuli did not sound spectacularly awkward or disruptive to comprehension, due to the care in stimulus construction and choice of tokens.

To answer the specific question about cross-splicing, the cross-splicing was always from two different recordings. In the match condition both recordings were of the same sentence in the mismatch condition they were from different sentences. This was already explained in the methods section, but we have added several modifications to make this clearer. First, we added the following sentence in section 2.2:

“Stimuli were always cross spliced from separate recordings. These were separate recordings of the same sentence for ‘match’ stimuli and recordings of different sentences for ‘mismatch’ stimuli.”

Secondly, we replaced Table 1 with a figure (Figure 1) that includes colour coded waveforms to show where they originated from along with subscript numbers to indicate the different originating sentences.

The reason why a differentiation might be useful has to do with an oscillatory account the authors attempt to provide. Current research suggests that there are several oscillatory mechanisms at work

(Giraud, A.-L., & Poeppel, D. (2012). Cortical oscillations and speech processing: emerging computational principles and operations. *Nature Neuroscience*, 15(4), 511-517. doi:10.1038/nn.3063), differing in their cycle length, with prosodic-based oscillations having longer cycles (or lower frequencies) and segment-based oscillations having shorter cycles (or higher frequencies, e.g. Mai, G., Minett, J. W., & Wang, W. S. Y. (2016). Delta, theta, beta, and gamma brain oscillations index levels of auditory sentence processing. *Neuroimage*. doi:10.1016/j.neuroimage.2016.02.064; Teoh, E. S., Cappelloni, M. S., & Lalor, E. C. (2019). Prosodic pitch processing is represented in delta-band EEG and is dissociable from the cortical tracking of other acoustic and phonetic features. *The European Journal of Neuroscience*, 50(11), 3831- 3842. doi:10.1111/ejn.14510).

Oscillations in the gamma frequency band are claimed to reflect the processing of phonetic transitions e.g. between closure and VOT of plosives, and gamma-frequency is modulated by lower frequencies, such as delta, which itself seems to track prosodic and intonational information. I think the argument of the authors is an excellent one when they try to relate the processing of phonetic detail to the oscillatory dynamics of perception and attention. Given that successful processing seems to be based on an interplay of different types of oscillations (e.g. reflected in an optimal nesting of oscillatory frequencies), an optimal metric/rhythmic template may well direct attention to fine phonetic detail in the most ideal way.

Thank you for raising this point. We now briefly discuss Giraud and Poeppel's hypotheses about oscillators at different frequencies relating to different levels of structure (at end of Section 4.2.1). However, it seems to us mistaken to necessarily associate shorter durations with phonological units and longer ones with prosody. Even in our own materials we observe that some *re-* syllables are the same duration of some of the [s] segments. We have also discussed Mai, Minett & Wang (2016) which provides evidence that the units of speech don't always line up with the oscillation frequencies discussed by Giraud and Poeppel. Regardless, oscillations at different rates are likely important to processing of the kind of metric/rhythmic and segmental relationships we explore in this paper. During our revisions, we cited the Teoh paper in a section (4.3) we added on strengths, limitations and extensions of the study, but later deleted that part of the section to limit its length.

Reviewer #2: In the current study, participants' eyes were tracked while they heard words with true prefixes (discover) and pseudo-prefixes (discolour) to determine whether the acoustic information in those prefixes was sufficient to disambiguate the identity of the word. Results demonstrate that participants were faster to look at the intended target when the acoustic information in the prefix matched the word identity.

This study that makes a valuable contribution to the study of speech perception, and the level of detail that listeners are cued into during listening. While previous studies have shown that listeners use phonetic details to predict word identity, the current study explores this at an even lower level by demonstrating that listeners can use fine-grain phonetic detail to determine whether they're hearing a monomorphemic or multi-morphemic word. In addition, the result inform our understanding of the role of rhythmic and metric structure in facilitating word identification during listening.

This is just a lovely paper. The literature review is clear, as is the motivation for the current study and how it improves on prior work. The materials and methods are clearly described and this is an ideal use of the visual world paradigm to assess the time course of processing. I think the statistical models used are all appropriate for the questions being asked, and are described effectively. Therefore, I strongly encourage publication in the Journal of Phonetics.

We thank the reviewer for these kind and encouraging words!

I have only a couple of minor editing suggestions:

- On pg. 3 the authors state "the first syllables of the prefixed words differ in rhythm due to small differences in the acoustic properties of their component segments." I would suggest a rewording because rhythm is not a property of a single syllable but rather a property of a sequence of syllables (as the authors describe in section 4.2.1).

We have reworded this to: "the first syllables of the true prefixed words convey a heavier beat in context due to small differences in the acoustic properties of their component segments."

- Pg. 13, line 495, 'Imertest' should be in italics

fixed, thank you

- Check the use of the factor name "PhonemeChange" vs. "Phoneme Change" throughout

All instances have been changed to PhonemeChange, thank you for catching this.

Reviewer #3: This is a strong paper addressing a compelling hypothesis. The experiment appears carefully done. The writing is strong, and there is a thoughtful and useful introduction and discussion section. The areas for improvement which I see land somewhere between "minor" and "major" revisions. I have selected "minor", where my feedback mostly has to do with clarifying design/methodology features, with those points enumerated below.

We thank the reviewer for this strongly positive assessment. You have pointed out some places where our description of the methods was not sufficiently clear, and we are grateful for this. We have substantially revised the methods section following your suggestions.

First, I found the usage and definition of the term "target" to be not entirely clear. The usage needs to be clarified and probably reiterated within the paper due to some complexity in the design. I presume that what constituted a "target" had a consistent relationship to the morphemic structure of words. However, Table 1 suggested that either morphological structure could be a target, and Figure 3 seemed to be agnostic with respect to the morphemic structures of words (and thus how this related to the "target" vs. "competitor" distinction). Over the course of reading, I came to believe during the Results section that the label "match" blended items of both true- and pseudo-prefix types, as evidenced by the fact that Prefix Status is not separately named until discussion of Figure 6, which shows the result of analysis of potential interaction between Match and Prefix Status. Please revise the paper to make clear what "match" and "target" refer to, and when they do or don't distinguish different prefix statuses.

You are correct that both Match and Target are orthogonal to PrefixStatus. Match refers to whether or not the PrefixStatus matches the Target. Target is the image that matches the continuation of the sentence, after the ambiguous section. To try to make this clearer we have added additional text to the methods section, replaced Table 1 with a figure that includes some enhancements to reinforce this, and added Figure 3 which includes an example trial with Match and PrefixStatus illustrated for that trial.

In the methods section after Figure 1:

“Our main analysis therefore compared the looks to target images (defined as the image consistent with the post-splice continuation of the spoken word and sentence) on trials in which the critical syllable contained acoustic information that either matched or mismatched the target image (factor Match). For example, in Figure 1, the image corresponding to the target for *A swan displaces water when it lands* is the image of a swan landing on water, regardless of the prefix status of the cross-spliced critical syllable. Similarly, the competitor is the image consistent with the sentence’s pair, in this case the two swans (see Figure 1).”

Also, the familiarization procedure needs further clarification. Page 9 gives some details of this procedure, but it’s not enough to understand the process. The semantic distinctions among the members of sentence pairs is rather complex, such that the pictures used to distinguish the meanings/structures would have presumably required exposure to all pictures. However, such an interpretation seems at least partially at odds with the details given. Also, the description refers to "the six sentences from a set", but it's unclear what "set" is being referred to. Can the authors please offer some clarifications?

We have edited the methods section to make the familiarization procedure clearer. We’ve replaced the more generic term ‘set’ with ‘presentation set’ to highlight the fact that these groupings were made for the purpose of presenting trials together. We’ve referred to ‘familiarization blocks’ and ‘test blocks’. We’ve also replaced Figure 1 with a more detailed schematic of the block structure (now Figure 2).

Additional questions/points of feedback:

--What constituted an "item" for purposes of the statistical analysis? Conceivably, either a sentence pair could have been treated as a single item, or else the two sentences in a pair could have been treated as different items, with implications for calculation of the items random factor.

For the purpose of the statistical analysis, an item is a pair of sentences. This is now said explicitly in the section on analysis principles.

--Please move the presentation of overall statistical approach as much as possible to the Methods section. Further, it would assist clarity in my opinion if the Design section (p. 10-11) succinctly presented/summarized the factors in the analysis. This design information would ideally parallel the statistical methods presentation for clarity.

In the spirit of this comment, we’ve moved the summary of the analysis approach up to the first section of the Methods (2.1 Design). This lays out the logic and main factors of the analysis and explains what each of them is before we get into the details. We’ve also included a table (Table 1) summarising these factors. This parallels the analysis, as suggested. We have also moved the statistical analysis principles up to the end of the methods section (Section 2.8).

--I found this to be a strong contribution in spite of the fact that some apparently predicted effects didn’t come out - for instance, if I understood correctly, a Match:PrefixStatus interaction (Fig. 6). I think the discussion would benefit from a bit more consideration in a paragraph, say, of the strengths (e.g. guards

against confounds) but also limitations of the experiment. This was already begun by the thoughtful commentary about learning during the experiment, but it would be beneficial for future consideration to hear the authors' overall opinions on these points in a short summary treatment in discussion.

We've added a section at the end of the discussion '4.3 Strengths, limitations and extensions of the study'.

- Phonemically-identical English true and pseudo prefixes differ in phonetic detail
- Eye movements show listeners use this detail in real time to predict word identity
- Effects reduced during the task as participants learned about cue availability
- Rhythmic properties of true prefixes may help listeners identify them as morphemes

Phonetic detail is used to predict a word's morphological composition

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Abstract

An eye-tracking experiment tested the hypothesis that listeners use within-word fine phonetic detail that systematically reflects morphological structure, when the phonemes are identical (*dis* in *discolour* (true prefix) vs. *discover* (pseudo prefix)) and when they differ (*re-cover* vs. *recover*). Spoken sentence pairs, identical up to at least the critical word (e.g. *I'd be surprised if the boys discolour/discover it*), were cross-spliced at the prefix-stem boundary to produce stimuli in which the critical syllable's acoustics either matched or mismatched the sentence continuation. On each trial listeners heard one sentence, and selected one of two photographs depicting the pair. Matched and mismatched stimuli were heard in separate sessions, at least a week apart. Matched stimuli led to more looks to the target photograph overall and time-course analysis suggested this was true at the earliest moments. We also observed stronger effects for earlier trials and the effects tended to weaken over the course of the experiment. These results suggest that normal speech perception involves continuously monitoring phonetic detail, and, when it is systematically associated with meaning, using it to facilitate rapid understanding.

Keywords

perception, spoken language understanding, morphological structure, acoustics

37 **1 Introduction**

1
2 38 There is increasing evidence that morphological differences in phonemically-
3 39 identical words or parts of words are reflected in their phonetic realisation (e.g.
4 40 Hay, 2003, ben Hedia & Plag, 2017; Plag and ben Hedia, 2018; Rose, 2017; Smith,
5 41 Baker and Hawkins, 2012; Sproat & Fujimura, 1993; Seyfarth et al. 2018; see also
6 42 Strycharczuk, 2019 for a review). As such evidence accumulates, questions remain
7 43 unanswered as to whether the observed patterns in production influence
8 44 listeners' perceptual behavior. This paper addresses perception of a
9 45 morphological contrast involving prefixes (e.g. *dis-* in *discolour*, *re-* in *re-joined*)
10 46 and matched non-prefix word-initial syllables that are either phonemically
11 47 identical to the prefix (e.g. *dis-* in *discover*) or contrast in the vowel phoneme (e.g.
12 48 *re-* in *rejoined*). Both types of morphological contrast manifest as two different
13 49 acoustic-phonetic patterns affecting the entire word-initial syllable and beyond, in
14 50 prosodically-controlled fluent lab speech (Smith, Baker, & Hawkins, 2012) and in
15 51 conversational speech in several regional varieties (Hay, Hawkins, Stuart-Smith,
16 52 Smith and Fromont, in prep). The question asked is whether listeners use the
17 53 resultant acoustic-phonetic distinction in real time to facilitate word recognition
18 54 in connected speech. If they do, this would indicate that they use the internal
19 55 acoustic structure of the first syllable of a prefixed or pseudo-prefixed word to
20 56 identify its stem, and by implication the lexical item's morphological structure.
21 57 When the phonemes do not differ, this would amount to identification of bound
22 58 morphemes from very fine differences in the syllable's internal acoustic structure,
23 59 and their use to predict lexical identity.

30 **60 1.1 Phonetics of morphologically complex words**

31
32 61 By far the largest body of relevant experimental work examines temporal
33 62 relationships between acoustic segments or articulatory gestures in suffixed
34 63 words. Compared with phonemically-matched or similar monomorphemic words,
35 64 suffixed words have consistently different phonetic characteristics in their suffix,
36 65 in their stem and at the morpheme boundary. Although a number of studies have
37 66 demonstrated such properties, several have confounded number of morphemes
38 67 with number of syllables and/or foot length (e.g. Kems, Wurm, Ernestus,
39 68 Schreuder, & Baayen, 2005; Lehiste, 1972). The reported differences between
40 69 bimorphemic and monomorphemic words can nonetheless be considered robust
41 70 in that several studies that circumvented these problems showed the same type of
42 71 results (Sugahara & Turk, 2009; Cho, 2001; Seyfarth et al., 2018). These temporal
43 72 relationships have also been shown to affect the articulatory gestures of English
44 73 /l/ at morpheme boundaries resulting in gradient spectral differences in /l/-
45 74 darkness (Sproat & Fujimura, 1993; Lee-Kim, Davidson, & Hwang, 2013;
46 75 Strycharczuk & Scobbie, 2016, 2017; Turton, 2017; Mackenzie et al., 2018)

51
52 76 Prefixes have received less attention than suffixes, but Oh and Redford (2012)
53 77 show durational differences in nasal-nasal sequences dependent on whether the
54 78 sequence includes a morphological boundary as in *un-named* or a word boundary
55 79 as in *fun name*. Smith, Baker and Hawkins (2012) and (Hay et al., in prep)
56 80 document complex, systematic acoustic effects of prefix status for the initial
57 81 syllables of word pairs such as *discolour* vs. *discover* and *mistypes* vs. *mistakes*, in
58 82 which the first member of each pair begins with a true (productive) morpheme

83 whereas the second member does not, despite having the same phoneme
84 sequence. Consequently, the initial syllables of *discover* and *mistakes* are termed
85 pseudo prefixes. Prefixes of this type are particularly interesting for models of
86 speech perception because, if their distinctive phonetic detail¹ is processed
87 differently from that of pseudo prefixes, this would suggest that their properties
88 are directly associated with their status as bound morphemes. In contrast,
89 perceptual studies examining the same type of issue for suffixes typically show
90 listeners' sensitivity to differences in the stem, rather than in the suffix itself, as
91 discussed below.

92 The distinction between true and pseudo prefixes is not completely clearcut, due
93 to a number of interacting influences of quite different types, also discussed below.
94 However, it is possible to control for such influences. Smith, Baker and Hawkins
95 (2012) used criteria that provided tight control over both the type of word and its
96 phonetic and semantic context. They followed Wurm's (1997) strict semantic
97 criteria to select stimulus words: in words such as *discolour* and *mistypes*, the
98 initial syllables, *dis-* and *mis-*, are true prefixes because *colour* and *types* mean
99 roughly the opposite when *dis-* or *mis-* are added. In contrast, the words *discover*
100 and *mistakes* are monomorphemic because *cover* and *takes* do not mean the
101 opposite of *discover* and *mistakes*. Furthermore, each of the prefixed words chosen
102 had a lower frequency than the frequency of its stem, thereby conforming with
103 Hay's (2003) criterion (developed for suffixes) for a relatively strong and
104 unambiguous morpheme boundary.

105 Smith, Baker and Hawkins (2012) elicited such true and pseudo prefix pairs from
106 speakers of Standard Southern British English (SSBE) in fast, casually-spoken
107 scripted dialogues in which the prosodic and segmental structure of the critical
108 utterances were tightly controlled. Acoustic-phonetic measures supported earlier
109 impressionistic claims (e.g. Hawkins, 2010; Ogden et al., 2000; Whitley, cited by
110 Simpson, 2005) [that the first syllables of the true-prefixed words convey a heavier
111 beat in context due](#) to small differences in the acoustic properties of their
112 component segments. As illustrated, for example, in Smith, Baker and Hawkins'
113 (2012) Figure 1, which shows spectrograms and phonological trees for *mistimes*
114 (true prefix) and *mistakes* (pseudo prefix), one very reliable acoustic difference is
115 the duration of aperiodicity for [s] relative to the duration of periodicity of [ɪ]: the
116 [s] takes up a much larger proportion of the syllable in pseudo prefixes. Another
117 is that the second formant frequency of [ɪ] is higher and closer to F3 in the true
118 prefix, suggesting less centralisation. A third is that when a voiceless stop is in the
119 onset of the second syllable of the word, its voice onset time (VOT) is long
120 following the true prefix, but short following the pseudo prefix. In sum, the
121 morphological status is reflected in several phonetic characteristics that affect all
122 segments in the first part of the word. These differences create systematic
123 differences in the overall pattern of relationships between the acoustic segments
124 within the first syllable, termed here its internal acoustic structure, as well as at
125 the syllable juncture and thereafter. The internal structure of the first syllable is
126 such that, though both true and pseudo prefix syllables are metrically weak, true
127 prefixes are more phonetically prominent—indeed, many dictionaries accord
128 some true prefixes a secondary stress, whereas pseudo prefixes are never

¹ See Appendix A for what is meant by 'phonetic detail'.

129 accorded one. Thus, in any given speech register, the true prefix conveys a heavier
130 rhythmic beat than the pseudo prefix.

131 While these differences are reasonably distinct for any given speech register, there
132 can be 'gradient' effects in cases where the prefix status of a word is in flux (which
133 occurs for a variety of reasons (cf. Hay et al., 2005) and between different speech
134 registers and modes of data collection (Smith, 2012; Hay, 2018; Zuraw &
135 Peperkamp, 2015). Furthermore, while the majority of prefixes behave as
136 described above, a few do not (Plag, 2014). Words whose prefix status was
137 ambiguous were excluded from the present study.

138 In summary, systematic phonetic markers of the internal composition of words
139 are embedded in the speech signal and so are potentially available to the listener.
140 These kinds of cues differ from other acoustic-phonetic effects such as those due
141 to assimilation of place of articulation across word boundaries, in that they occur
142 word-internally in a range of speech registers, including careful, clear speech, and
143 so are integral to the identity of words. The goal of this paper is to determine
144 whether listeners are in fact sensitive to such subtle distinctive patterns and use
145 them to build expectations about morphemic structure and hence word identity
146 as they interpret utterances in real time.

147 **1.2 Perception of acoustic cues to word structure**

148 Lexical identification experiments using gating tasks and cross-modal priming
149 (Davis et al., 2002), and eye-tracking with the visual world paradigm (Salverda et
150 al., 2003), show that listeners' early perceptual responses are sensitive to
151 acoustic-phonetic detail that signals word boundaries. They contrast syllables that
152 are either followed by a word boundary or are part of a longer word as in *cap* and
153 *captain* or *ham* and *hamster*. When hearing syllables such as *cap*, listeners were
154 more biased towards a monosyllabic interpretation when *cap* had been spoken as
155 a monosyllabic word rather than as part of a polysyllabic word. While these
156 studies confirm the importance of phonetic detail to lexical identification, they do
157 not examine influences due to morphological structure within words, and, as
158 summarized at the end of this section, they confound a number of linguistic
159 variables which designs using the true vs pseudo prefix distinction can control.

160
161 Relatively little work has examined perception of morphological structure (i.e.
162 word-internal junctures). Blazej & Cohen-Goldberg (2014) tested whether the
163 effect of number of syllables found for the *ham* versus *hamster* studies extended
164 to words which are also multi-morphemic by virtue of containing suffixes e.g. *clue*
165 and *clueless*. They found the same pattern as studies that examine shorter words
166 embedded in longer monomorphemic words: listeners anticipated the longer
167 word after hearing a shorter first syllable. A pair of similar studies by Kemps and
168 colleagues (Kemps et al., 2005a; 2005b) using lexical decision and a morpheme
169 decision task (singular or plural) found compatible results for embedded stems in
170 plurals in Dutch and for comparatives (e.g. *stronger*) and agent nouns (e.g. *worker*)
171 in Dutch and English. However because the stimuli in these studies compared
172 monosyllabic, mono-morphemic words with polysyllabic, poly-morphemic words,
173 it is impossible to tell whether their listeners were simply anticipating a longer
174 word (an ability previously demonstrated for mono-morphemic words), or

175 whether they were anticipating the poly-morphemic structure of the longer word,
176 or both.

177
178 As described in the next section, the present study of true and pseudo prefix
179 perception circumvents most of these problems. Furthermore, there is intrinsic
180 theoretical interest in distinguishing boundaries within words from those
181 between words, and phonetic support for making that distinction from work on
182 prefixes *un-* and *in-* (Oh & Redford, 2012).

183

184 **1.3 The present study**

185 The present paper uses eye-tracking in a visual world paradigm to test our
186 hypothesis that listeners can use the internal acoustic structure of the initial
187 syllable of a prefixed or pseudo prefixed word to predict morphological structure
188 that itself predicts word identity. The focus on prefixes allows questions of
189 perceptual sensitivity to the morphological status of a syllable to be assessed
190 without the confounds of morphological complexity, polysyllabicity, and word
191 length which characterize the studies cited in Section 1.2. We compare units that
192 are comparable except in morphological complexity: all words are polysyllabic; all
193 boundaries of interest are word-internal; and no first syllable has an independent
194 lexical meaning—pseudo prefixes, comparable to *cap* in *captain*, convey no
195 meaning independent of the rest of the word, while prefixes are not independent
196 lexical items, so though they convey a meaning, it is only properly interpretable in
197 the context of the meaning of the rest of the word. Furthermore, unlike the critical
198 syllables in the *cap* and *captain* studies, our critical syllables are metrically weak
199 (lack primary stress); weak syllables are often thought to play a subordinate role
200 in lexical identification (e.g. Cutler & Butterfield, 1992).

201

202 Our study also differs from studies that have shown effects of phonetic (sub-
203 phonemic or within category) detail on lexical access (e.g. McMurray, Tanenhaus,
204 Aslin & Spivey, 2003; Dahan, Magnuson, Tanenhaus, & Hogan, 2001) in that our
205 phonetic detail contributes primarily to rhythmic and not segmental structure.
206 Furthermore, unlike previous studies that tested phonetic detail using minimal
207 pairs (e.g. McMurray et al., 2003), the present study contrasts word sequences
208 most of whose second and later syllables are not minimal pairs, so listeners in our
209 experiment do not need to use the fine detail of unstressed *mis-* or *dis-* at all in
210 order to distinguish the words or the sentence meanings. Thus ours is a very
211 stringent test of the perceptual salience of phonetic detail: the cues are in weak
212 syllables and they are followed very swiftly by much clearer disambiguating
213 evidence. If we find evidence suggesting that these cues are used despite their not
214 being essential to the task, then we have very strong evidence of the pervasive role
215 of phonetic detail, and rhythmic detail in particular in spoken word recognition.
216 Furthermore, such findings would strengthen the evidence that listeners extract
217 clues to many levels of linguistic structure from the fine phonetic detail in the
218 signal.

219

220 We used four types of prefixes: *mis-* and *dis-* as already discussed, and the prefixes
221 *re-* and *ex-* as in *re-peel/repeal* and *ex-trampoliner/extravagance*. The syllables *re-*
222 and *ex-* follow the same patterns as *dis-* and *mis-*, i.e. the true prefixes are

223 rhythmically stronger, but in this case syllabic reduction in the pseudo prefix
224 happens to cross a phoneme category boundary, whereas the same type of syllable
225 reduction does not produce a category change in the *dis-mis-* set. Consequently,
226 for *re-* and *ex-*, the vowel phonemes in the critical syllables differ: *re-peel* /ri:'pi:l/
227 but *repeal* /rɪ'pi:l/ or /rə'pi:l/; *ex-trampoliner* /ɛks'trampəli:nə/ but
228 /ɪks'travəgəns/ or /əks'travəgəns/in SSBE, the regional variety used here (see
229 Smith et al., 2012 for more explanation). Thus while all prefixes differ rhythmically
230 from the pseudo prefixes, the syllables in *re-* and *ex-* differ segmentally as well.
231 This distinction is represented in our design as the independent variable
232 PhonemeChange, with *re-ex-* changing vowel phoneme, and *dis-mis-* not. As
233 segmental differences are uncontroversially part of the lexical representation, we
234 can predict that the segmental cues to morphological structure will be picked up
235 in spoken word recognition. The *mis-* and *dis-* stimuli are a more stringent test of
236 the hypothesis that non-segmental phonetic detail is important for identifying
237 morphological structure because they share the same first four phonemic
238 segments. However, because discrimination of prefixes has not been tested using
239 eye-tracking before, and their relatively abstract meanings necessitate the use of
240 relatively complex visual stimuli, the *re-* and *ex-* stimuli provide a check that our
241 methods are sensitive enough. Then the question is whether nonphonemic
242 morphological divergence will also be exploited. If so, how strong is it compared
243 with the phonemic effect and does it have the same time course?

244
245 In sum, our experiment was designed to test whether listeners exploit subtle
246 acoustic cues to morphological structure. In particular, do they identify
247 morphological structure, even to the extent of predicting that they are hearing a
248 morphologically-complex word before they have heard the stem, in good listening
249 conditions when the task does not demand it?

250

251 **2 Methods**

252 **2.1 Design**

253 We used cross-spliced spoken sentences to manipulate whether the acoustic
254 information in critical syllables (i.e. in the true or pseudo prefix) was consistent
255 with the morphological structure of the rest of the word. We presented these
256 stimuli to participants and asked them to choose between two pictures, one
257 representing a situation whose description included the true prefixed word and
258 the other a situation whose description included the matched pseudo prefixed
259 word (see Figure 1 for illustration).

260

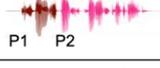
Target word	Match splice type		Target image	Competitor image
	match	mismatch		
displaces	[A swan dis] _{T1} [places water when it lands] _{T2} 	[A swan dis] _{P1} [places water when it lands] _{T2} 		
displays	[A swan dis] _{P1} [plays its plumage to its mate] _{P2} 	[A swan dis] _{T1} [plays its plumage to its mate] _{P2} 		

Figure 1. Construction of match and mismatch stimuli illustrating one pair of sentences. Subscript_T indicates a portion from the original utterance that contained a true prefixed word (e.g. *displaces*, *discolour*). Subscript_P indicates a portion from the utterance originally containing the pseudo prefixed word (e.g. *displays*, *discover*). Subscript numbers refer to different sentence recordings. For each sentence the target and competitor images are given.

The words in a pair of such sentences were identical up to the critical syllable. If perceptual behaviour is influenced by the acoustic information available to signal true vs. pseudo prefixes while it is being heard, then we would expect listeners to be delayed in correctly identifying the target word (and therefore the target image) when that acoustic information does not match the morphological structure of the target word/image. Our main analysis therefore compared the looks to target images (defined as the image consistent with the post-splice continuation of the spoken word and sentence) on trials in which the critical syllable contained acoustic information that either matched or mismatched the target image (factor Match). For example, in Figure 1, the image corresponding to the target for *A swan displaces water when it lands* is the image of a swan landing on water, regardless of the prefix status of the cross-spliced critical syllable. Similarly, the competitor is the image consistent with the sentence's pair, in this case the two swans (see Figure 1).

We also considered whether the effect of the critical syllable (Match) depended on a number of factors. The factors of the design are summarized in Table 1. As discussed above, we tested if Match depended on whether the prefix manipulation entailed a phoneme change as in *re-* or *ex-*, or not as in *mis-* or *dis-* (factor PhonemeChange).

287 Table 1: Summary of factors and their levels in the design.

Factor	Levels	Nesting
Match	match: acoustic information in critical syllable matches the morphological structure of the target word/image mismatch: acoustic information in critical syllable doesn't match the morphological structure of the target word/image	within subjects and items
Interactions with Match		
PhonemeChange	<i>dis-/mis-</i> <i>re-/ex-</i>	within subjects between items
Group	M1: match on session 1/mismatch session 2 M2: mismatch on session 1/match on session 2	between subjects within items
TrialNumber	continuous variable from 1 to 99	within subjects and items ²
PrefixStatus	true: critical syllable spliced from a true prefixed word pseudo: critical syllable spliced from a pseudo prefixed word	within subjects and items

288

289 Creating matched and mismatched stimuli is crucial to our experimental
 290 manipulation. However, it also disrupts the natural systematic association
 291 between the acoustic information in any given critical syllable and its function as
 292 a true or pseudo prefix in the word. The fine phonetic detail of interest thus
 293 becomes uninformative within the context of the experiment. Because we were
 294 worried about the effects of this disruption on the listeners, we presented the
 295 matched and mismatched sentences in separate sessions on separate days. In our
 296 analyses we tested if our effect of Match depended on whether participants heard
 297 all the matches on Day 1 (M1) or on Day 2 (M2) (factor Group, see
 298 Counterbalancing section for more details). Furthermore, we tested whether the
 299 effect of Match changed over the time course of the experiment (factor
 300 TrialNumber—the order that each trial occurred in the experiment for each
 301 participant).

302 Finally, exploratory analyses also considered if the effect of Match depended on
 303 whether the acoustics of the critical syllable were from a word that had a true
 304 prefix or a pseudo prefix (PrefixStatus). For example, sentences in Figure 1 with a
 305 subscript_{T1} for the critical syllable *dis* have a PrefixStatus of true and those with a
 306 subscript_{P1} for the critical syllable have a PrefixStatus of pseudo (an example is
 307 also illustrated in Figure 3).

308 2.2 Participants

309 Participants were 34 native English speakers at the University of York (mean age
 310 21 years, range 18-32, 24 women), with normal or corrected-to-normal vision and
 311 no history of speech or hearing problems. Each participated in two sessions on
 312 different days at least one week apart. Each session took approximately 45-50

² By-item random slopes were not fit due to sparsity of item data for any given TrialNum.

313 minutes. Two additional participants were discarded due to errors in data
314 collection.

315 2.3 Auditory Stimuli

316 All stimuli can be found in the Open Science Framework repository
317 (<https://osf.io/dsyxu/> DOI 10.17605/OSF.IO/DSYXU). Sentences were constructed
318 for 32 pairs of target words differing in true vs. pseudo prefix status of their first
319 syllable (e.g. *displaces/displays*). As explained in the Introduction, these comprised
320 two types (factor PhonemeChange). In the *dis-mis-* type (e.g., *dis-*
321 *discolour/discover* [N = 7]; *mis-*: *mistypes/mistakes* [N = 4]), at least the first four
322 phonemes of each true-pseudo pair were identical. The *re-ex-* type followed the
323 same principle of having identical phonemes into at least the beginning of the
324 second syllable, except that for these words the first syllable's vowel phoneme
325 differed with prefix status (e.g., *re-*: [ri:] *re-strings/* [rə] *restricts* [N = 16]; *ex-*: [ɛks]
326 *ex-trampoliner/* [əks] *extravagance* [N = 5]). Primary lexical stress was on the
327 second syllable of each critical word. Each word was placed in a sentence which
328 was identical to that of its pair before the target word, and in some cases after it,
329 and could be illustrated by a picture (e.g. *It was difficult because Sam*
330 *distrusted/distracted him*).

331 Sentence pairs that differed after the target word had the same intonational and
332 foot structure, and hence number and stress-pattern of syllables, though not
333 necessarily the same word boundaries within a foot. In one *dis-* and one *ex-* case
334 identical foot structure was achieved by adding an extra syllable because one
335 target word had one less syllable than its pair: *A swan displaces water when it lands*
336 *and A swan displays its plumage to its mate; It's a perfect example of ex-*
337 *trampoliners' sense of balance* and *It's a perfect example of extravagance in public*
338 *spending*. These additions were made immediately after the target word so as to
339 match the foot structure created by the longer target word, the particular words
340 being chosen to be similar to the longer member of the pair in connected speech
341 e.g. *displays its* vs. *displaces*. All syllable counts were as standardly pronounced in
342 SSBE, as well as in the particular stimuli (e.g. *discourteous* had three syllables, not
343 four: /,dɪs'kɜːtjəs/). Appendix B shows the complete list.

344 Because our focus was on matching the phonetic structure of the stems while
345 using word pairs that could occur in sentences that were identical before the
346 critical word and had identical prosodic structure throughout, we could not match
347 target words on frequency. However, this should not bias the results, since over
348 and above the fact that word frequency is not a primary determinant of the
349 morphological distinction itself (Smith et al., 2012, Hay et al., in prep), the key
350 comparisons were to be between cross-spliced stimuli in which the lexical item
351 was the same, the only difference being in the acoustic signal in its first syllable, as
352 described below.

353 These 32 pairs of sentences were recorded in 6 random orders by a male SSBE
354 speaker. Quality was controlled as follows. To minimize reading effects, the
355 speaker had familiarized himself with the sentences and pictures for some days
356 before the recording, and was encouraged to look at the picture rather than the
357 text while recording. Contrastive stress on the critical words was avoided in that

358 only one picture was displayed at a time, and at least two other sentences
359 separated recording of the two members of each sentence pair. Trained
360 phoneticians checked the stimuli both at the time of recording and afterwards.
361 Errors (utterances that contained disfluencies or that sounded unnatural, unclear,
362 or inappropriate for the intended meaning), including borderline cases, were re-
363 recorded. Two recordings of each sentence were chosen for cross-splicing to
364 create a 'match' and a 'mismatch' version of each member of the pair. Sentences
365 were initially chosen for naturalness and the best impressionistic match of f0,
366 rhythm and loudness. Following this, the chosen pairs of stimuli were inspected
367 acoustically to ensure that they not only sounded acceptable in their original
368 contexts, but that, relative to each other, the internal acoustic structure of each
369 critical syllable conformed to expectations derived from Smith, Baker and
370 Hawkins (2012), primarily using durational criteria. This was necessary in order
371 that any observed behavioural differences could be interpreted in terms of
372 differences in internal acoustic structure. [See Section 2.7 for acoustic analyses of](#)
373 [the stimuli.](#)

374 Stimulus construction involved two types of cross-splicing, according to whether
375 the resultant token was a 'match' or 'mismatch' stimulus. Sentences were cut at
376 the end of the critical (target) syllable (just before the burst of the next stop if there
377 was one, as in *mistimes*) and cross-spliced either with the end of an identical
378 sentence for 'match' stimuli or with the end of its pair for 'mismatch' stimuli. Thus
379 each stimulus was constructed from two separate recorded tokens, spliced just
380 after the critical prefix/pseudo-prefix syllable: separate recordings of the same
381 sentence for 'match' stimuli and recordings of different sentences for 'mismatch'
382 stimuli.

383 Thus, as [Figure 1](#) shows, four versions were created from each sentence pair
384 corresponding to the four combinations of true and pseudo prefixes and
385 continuations: the matches true-true and pseudo-pseudo, and the mismatches
386 true-pseudo and pseudo-true, for a total of 128 test stimuli (32 pairs x 4
387 conditions). These procedures meant that no perceptually significant acoustic
388 information about the second syllable of the word was present in the first syllable:
389 second syllables all had identical or very similar vowel qualities (see Appendix B),
390 and for *mis-* and *dis-* syllables followed by a stop, Baker (2008) showed that
391 listeners could not predict the following vowel unless they heard the burst and
392 following VOT.

393 An additional 67 filler sentence pairs were constructed. Of these, 30 pairs had been
394 recorded by the same speaker and used in a previous experiment; in the present
395 study they comprised an independent experiment run at the same time. These 30
396 consisted of pairs of sentences identical except for one word, differing only in
397 whether it contained an /r/ or /l/ (e.g. *rams* vs. *lambs*), hereafter r-l sentences.
398 Matches and mismatches were created as described above, except that critical
399 words were spliced into the sentences, rather than abutting the first part of one
400 sentence with the second part of another (see Heinrich, Flory, & Hawkins, 2010
401 for details, and the list of words and sentences). Of the other 37 filler pairs (listed
402 in Appendix C), all but four were designed to mimic the prefix ones in that they
403 contained a word with a true or pseudo morpheme either before or after the
404 target/disambiguating words. For example *You purify water/whisky by distilling it.*

1 405 The remaining four fillers followed the same semantic and prosodic principles as
2 406 the others; three of them contained a word beginning *re-* paired in the other
3 407 sentence with a non-*re-* word. These 37 fillers were recorded twice; the most
4 408 natural of each was chosen, and not spliced. Six additional filler trials were created
5 409 in the same way and used in practice blocks.

6 7 410 **2.4 Visual Stimuli**

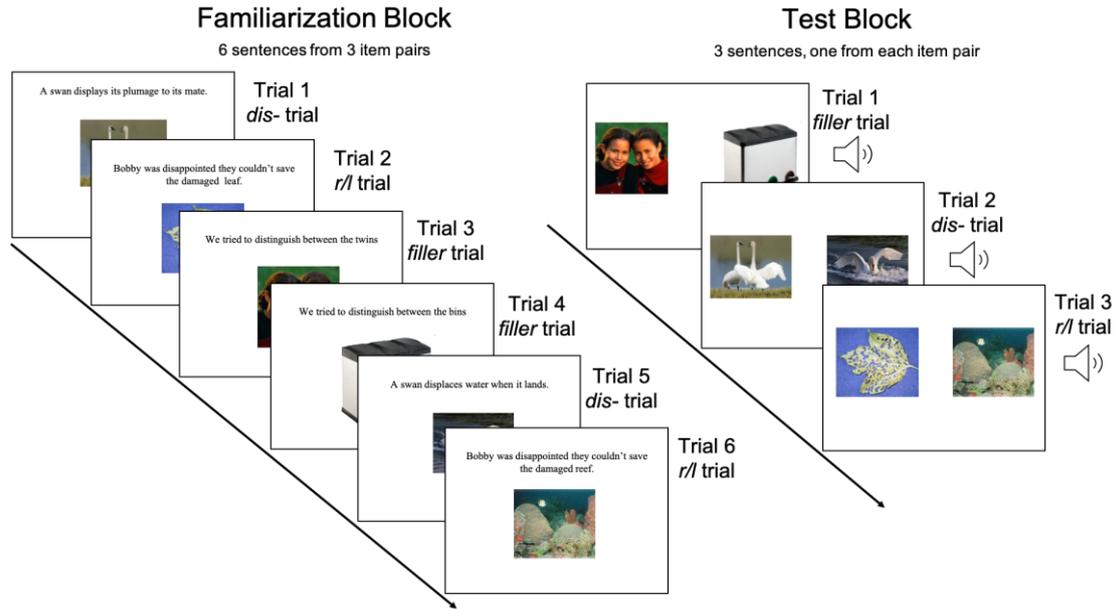
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9 411 A photograph was chosen to represent each sentence from images publicly
10 412 available on the web, and photographs we took ourselves. Care was taken to
11 413 ensure that pairs of images were similar in complexity and colourfulness, as
12 414 judged by six people, the four authors and two research assistants. See the
13 415 examples in Figure 1. The largest dimension of each image was 600 pixels. As
14 416 noted in the Results (Section 3), baseline measures of looking preference taken at
15 417 the moment the auditory stimulus was presented and at the onset of the critical
16 418 word revealed no systematic preferences for the pictures depicting true versus
17 419 pseudo prefixes.

20 21 420 **2.5 Procedure**

22
23 421 Participants were seated in front of a desktop-mounted remote Eyelink 2000 (SR
24 422 Research) to monitor eye-movements while they performed the task. Auditory
25 423 stimuli were presented over headphones at a comfortable listening level. Visual
26 424 stimuli were displayed on a 16"x12" monitor. Each session began with set up and
27 425 calibration of the eye-tracker followed by two practice blocks of trials, whose
28 426 structure was identical to the rest of the experiment .

29
30
31 427 Testing took place on two days (Section 2.6). Each day, participants heard one
32 428 trial for each of the 99 pairs (32 prefix pairs, 30 r-l pairs and 37 filler pairs). Stimuli
33 429 were grouped into 33 presentation sets, each containing three pairs of sentences,
34 430 generally one prefix pair, one r-l pair and one filler pair. Participants were first
35 431 presented with a block of six familiarization trials in which each of the six
36 432 sentences from a presentation set appeared, along with its accompanying picture,
37 433 one at a time, in random order. The sentence was not spoken, but instead printed
38 434 at the top of the screen. The picture was centered in the middle of the screen, as
39 435 shown in the left portion of Figure 2. Participants were instructed to read the
40 436 sentence silently and familiarize themselves with the picture, then click on the
41 437 picture to continue (the trial did not end before at least 2.5 seconds of viewing).

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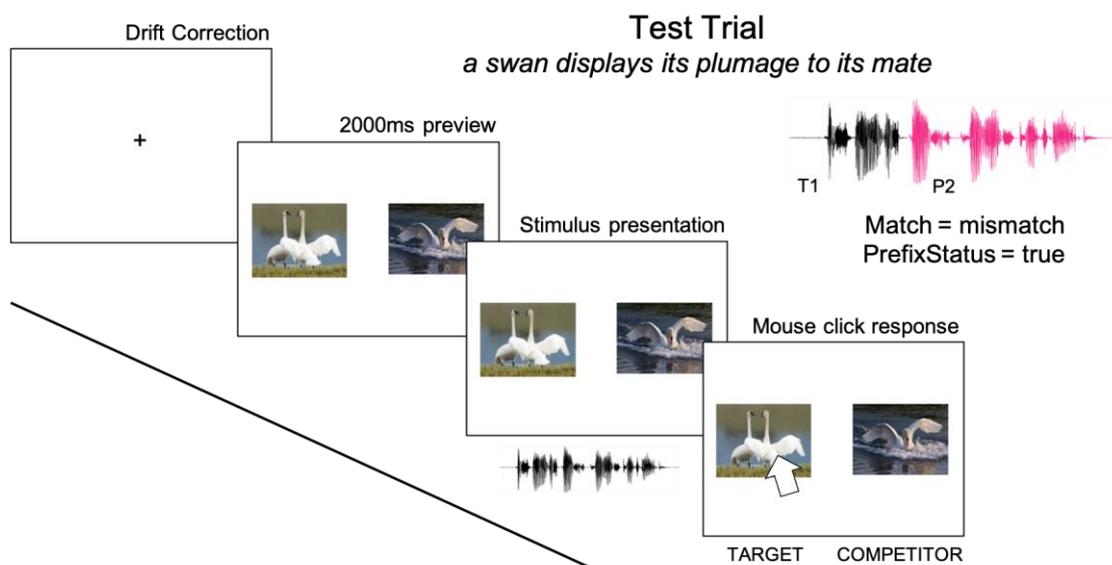


438

439 Figure 2: Example of a familiarization block and corresponding test block. Left:
440 Familiarization block, 6 written sentences from each of 3 item pairs. Right: Test
441 block, 3 spoken sentences, one from each of the same 3 item pairs. Colour online.

442 After the familiarization block came a corresponding block of three test trials
443 (shown in the right half of Figure 2), one from each pair in the 6-item presentation
444 set shown in the left half of Figure 2. Figure 3 shows the structure of an example
445 test trial. Each test trial began with a drift correction for the eye-tracker. One pair
446 of pictures was then presented, one centered in the left half of the screen, the other
447 in the right half. No text was displayed. The side on which the true prefix image
448 was displayed was randomized across trials. After two seconds of preview time,
449 one of the sentences was played. Participants were instructed to click on the
450 picture that matched the sentence as quickly and accurately as possible. Once the
451 participant responded, the pictures stayed onscreen for an additional 0.5 seconds;
452 they were then replaced briefly by a blank screen, after which the next trial began.

453



454

455 Figure 3: Structure of a single test trial. As this example trial shows, the
 456 PrefixStatus of the critical syllable can mismatch the Target sentence. In this
 457 example, the acoustics of the critical syllable are from a true prefixed word
 458 (*displaces*) but the target word and sentence continuation are the corresponding
 459 pseudo prefixed word (*displays (its)*). Colour online.

460

461 2.6 Counterbalancing

462 As discussed above, we were concerned that if the matched and mismatched trials
 463 were all presented in the same session, the fine phonetic detail of interest would
 464 thus be uninformative within the context of the experiment, and listeners could be
 465 expected to quickly learn to ignore it as they have for similarly subtle phonetic
 466 information (e.g. Hawkins & Nguyen, 2001, Experiments 2, 3a and 3b). The chosen
 467 blocked and counterbalanced design was intended to allow us to assess two
 468 things: how the critical phonetic information is used in real time when heard with
 469 its normal systematic distribution reflecting morphological status; and to what
 470 extent atypical distributions influence recognition behaviour in the shorter term.
 471 We thus used a blocked design in which all matched stimuli (r-l and prefix) were
 472 presented on one day, and all mismatched stimuli were presented on another, the
 473 two sessions being separated by at least a week. The order of match and mismatch
 474 was counterbalanced (factor Group): 18 participants heard all matches on Day 1
 475 (M1) and all mismatches on Day 2, while the other 16 heard all mismatches on Day
 476 1, and only matches on Day 2 (M2). Two additional participants were recruited for
 477 group M2 but it was later discovered that they had to be excluded due to
 478 experimenter error in data collection.

479 Because the participants would be seeing each pair of images (and hearing one of
 480 them described) on Day 1 and again on Day 2, it was important that they not be
 481 able to predict which image would be described on the second day. For this reason,
 482 a second counterbalancing factor was added. The stimulus pairs were divided into
 483 two sets such that for each participant, on one half of trials the same image was
 484 described on Days 1 and 2, and on the other half of trials, the opposite image was

485 described on Days 1 and 2. Thus, it was impossible for the participants to predict
486 which picture would be described on any trial. Practice blocks also illustrated this
487 pattern. In all cases (except the 37 unspliced fillers) the stimulus each participant
488 heard was different on the two days, either matching or mismatching depending
489 on the day and the group.

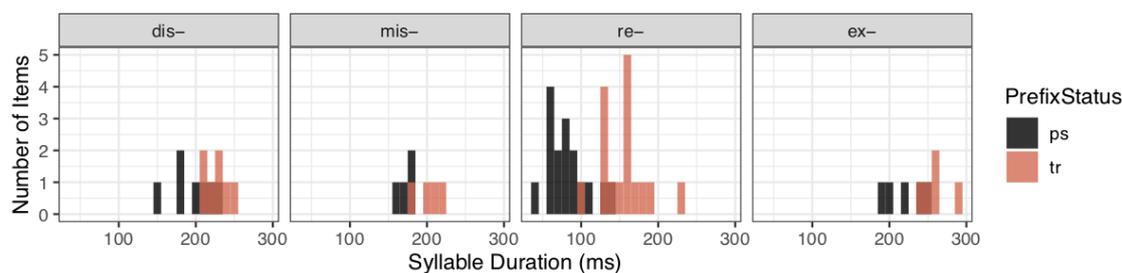
490 In summary, for critical test trials, each participant heard one of the four stimuli
491 describing each pair on each day; matches and mismatches were never mixed in
492 one session (order was counterbalanced between Groups M1 and M2); and the
493 presentation of spoken sentences within Day 1 and Day 2 was such that predicting
494 which of the two images would be described in the experimental trials should have
495 been at chance. There were four groups created by counterbalancing these
496 conditions. Four additional conditions were created with a different random
497 grouping of stimulus pairs. Trials from the *dis-mis-* and *re-ex-* sets of sentences
498 were evenly distributed throughout all these conditions.

499 2.7 Acoustics of critical syllables

500 We extensively analysed the acoustic properties of our stimuli to ensure that they
501 conformed to expectations from the previous phonetic literature and also to
502 ensure that they did not contain unwanted biases. A full report of these analyses
503 is available in the supplemental materials
504 (<https://osf.io/dsyxu/DOI.10.17605/OSF.IO/DSYXU>). We found that the critical
505 syllables varied according to prefix status as we would expect. We also found no
506 evidence for systematic acoustic differences before those syllables that might bias
507 the interpretation of the critical syllables. Here we briefly report on the duration
508 of the critical syllables themselves.

509 Figure 4 shows the distribution of syllable durations for each of the prefixes. True
510 prefixes were on average 54 ms longer than pseudo prefixes, with *dis-mis-*
511 syllables 55 ms longer on average than *re-ex-* syllables. However, as Figure 4
512 shows, these overall observations mask differences within the syllable types that
513 are important for interpreting the eye tracking results. While *mis-* and *dis-* mean
514 durations and standard deviations are similar enough that the two subtypes can
515 be regarded as a roughly homogeneous group, this is not the case for the *re-ex-* set:
516 there are large differences between *re-* and *ex-* syllable durations, with absolute
517 and relative values for *ex-* patterning more like those for *dis-* and *mis-* than those
518 for *re-*. These large differences within the *re-ex-* set are due to the phonetic makeup
519 of the syllables and the consequent degree to which each can be reduced. Whereas
520 *re-* can be severely reduced, inherent durational constraints on English /k/ and
521 particularly /s/ mean that *ex-* is much less open to reduction. Furthermore, *ex-*
522 syllables are the longest, and *re-* syllables the shortest of all four syllable types.
523 Because of this great heterogeneity, it was decided that *re-* and *ex-* should not be
524 treated as a single group; and because there were so few *ex-* tokens it was
525 necessary to exclude the *ex-* stimuli from the analysis.

526



527

528 Figure 4: Histograms of critical syllable durations for experimental stimuli. Colour
 529 online.

530 2.8 Eye-tracking data: analysis principles

531 Responses to filler stimuli were not analyzed. Trials in which the participant
 532 clicked on the incorrect image (did not match the continuation of the sentence)
 533 were removed (a total of 151 trials or 6% of the data). Eye-movements from all
 534 remaining trials were then time-aligned to the start of the critical word.

535 Because our visual stimuli and sentences were relatively complex, we first
 536 established that listeners had no overall preference for the images corresponding
 537 to one set of words or the other (true or pseudo prefixed words). The mean
 538 proportion of looks to the two types of image was almost identical at the onset of
 539 the critical word (plus the expected 200 ms oculomotor delay; Matin, Shao, & Boff,
 540 1993): pseudo = 0.46, true = 0.47; paired sample t-tests $p = 0.63$ by subjects, $p =$
 541 0.65 by items. There was likewise no difference at sentence onset ($p = 0.98$ by
 542 subjects, $p = 0.94$ by items).

543 For all analyses, proportion of fixations to the target image (as defined by the
 544 continuation of the sentence) were computed over a specific time window and
 545 these proportions were transformed to log odds for analysis with linear
 546 regression. Linear regression with log-odds-transformed proportional data is
 547 comparable to logistic regression on data in which each observation is either
 548 target or not, but allows for aggregation of data over a given time window.

549 All statistical analyses were done using mixed model linear regression using the
 550 *lmer()* function from the *lme4* package (Bates, Maechler & Bolker, 2015) in R (R
 551 Development Core Team). Significance was assessed using the Satterthwaite
 552 approximation of degrees of freedom as implemented in the *lmerTest* package
 553 (Kuznetsova, Brockhoff & Christensen, 2017) in R. All factors (binary categorical
 554 variables) were centered by using contrast coding (0.5 vs. -0.5) and continuous
 555 variables were centered and scaled. Centering the variables avoids any co-
 556 linearity between the effects and their interactions. Factors were Match (match =
 557 0.5, mismatch = -0.5), PhonemeChange (*dis-mis-* = 0.5, *re-* = -0.5), Group (M1 = 0.5,
 558 M2 = -0.5), and TrialNumber (continuous, scaled).

559 Random intercepts for subjects and items (each item was a sentence pair) were
 560 included in all models. Random slopes were included wherever the design and the
 561 data allowed (see below for details).

562

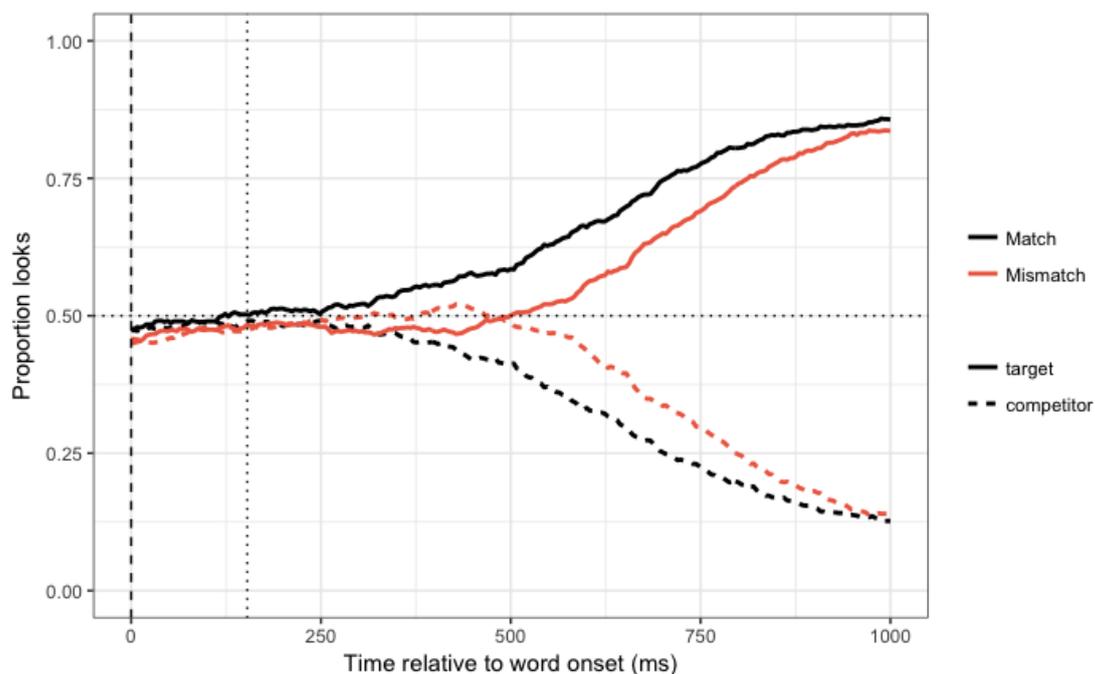
563 3 Results

564 The goal of the first analysis was to determine whether listeners were more likely
 565 to look at the target image when the acoustics of the critical syllable matched the
 566 morphemic structure of the target word, than when the acoustics mismatched.

567 3.1 200-800 ms window

568 3.1.1 Main analysis

569 Our first analysis aggregated looks within a window from 200 to 800 ms after the
 570 onset of the critical word. This window was chosen because it is generally
 571 assumed that it takes roughly 200 ms to plan and launch an eye movement (Matin,
 572 Shao, & Boff, 1993). Thus the window begins when we would expect to see looks
 573 influenced by the onset of the critical target word. The window continues until
 574 looks to the target start to asymptote (at which point we expect any effects to
 575 disappear). Thus any delay in identifying the target should be seen in this window.



576

577 Figure 5. Fixation proportions to the target and competitor image aligned to the
 578 word onset for the matching (black lines) and mismatching (red lines) conditions.
 579 Solid curves: looks to target image. Dotted curves: looks to competitor image. The
 580 dashed vertical line at time = 0 is the alignment point, the beginning of the word.
 581 The dotted vertical line indicates average splice point across all stimuli. 'Target' is
 582 defined as the part of the sentence following the splice point.

583 Figure 5 shows target and competitor fixations over time for trials in which the
 584 critical syllable either matched or mismatched the continuation of the sentence
 585 (i.e. the target), aligned at the word onset. Over the course of the trial, participants
 586 looked more at the target and less at the competitor and this difference is bigger
 587 for matching trials as predicted. We tested the difference in looks to the target by
 588 examining the effect of Match in a model that also included PhonemeChange and
 589 its interaction with Match to test whether the effect of Match was different for the

590 *dis-mis-* and the *re-* stimuli. This model included random slopes for Match by
 591 subject and item as well as random slopes for PhonemeChange and its interaction
 592 with Match by subject (i.e. the maximal model). The output of this model is
 593 summarized in **Error! Reference source not found.** Table 2. There was a higher
 594 proportion of looks to matched targets than to mismatched targets. Neither
 595 PhonemeChange nor the interaction of Match with PhonemeChange significantly
 596 affected responses however. See supplemental materials for item and participant
 597 variability in effect of Match.

598 Table 2: Model summary for 200-800ms window.

599

	Estimate	Std. Error	t	p
Match	0.57	0.21	2.73	0.01
PhonemeChange	0.15	0.30	0.48	0.63
Match:PhonemeChange	-0.01	0.41	0.03	0.97

600

601 **3.1.2 TrialNumber and Group (200-800 ms window)**

602 We also considered a model that included TrialNumber³ and Group as well as all
 603 the two and three-way interactions with Match and PhonemeChange. These
 604 models were considered because, as discussed in the Method (Section **Error!**
 605 **Reference source not found.**, Design), we hypothesized that being exposed to
 606 both matching and mismatching stimuli might weaken the relationship between
 607 the acoustics and the morphological status. This might lead to a decrease in the
 608 Match effect over the course of the experiment, or a decrease in the Match effect
 609 just for listeners exposed to mismatches on the first day (Group M2). Furthermore,
 610 it may be that only Group M2 would change behavior over the course of the
 611 experiment (an interaction between Group and TrialNumber). The model again
 612 found a robust effect of Match and no interaction between Match and
 613 PhonemeChange. Group was not significant and did not interact with any other
 614 effect. TrialNumber, which only approached significance as a main effect ($\beta = -0.17$,
 615 $SE = 0.09$, $t = 1.91$, $p = 0.06$), interacted significantly with PhonemeChange ($\beta =$
 616 0.43 , $SE = 0.18$, $t = 2.36$, $p = 0.02$) but not with Match ($\beta = -2.6$, $SE = 0.18$, $t = 1.43$, p
 617 $= 0.15$). This pattern indicates that looks to the target decreased over the course
 618 of the experiment, in particular for *dis-mis-* trials. There was also a trend in the
 619 data that indicated the effect of Match lessened over the course of the experiment
 620 for those *dis-mis-* trials. Analyses including Group and TrialNumber can be found
 621 in the supplemental materials.

622 **3.1.3 PrefixStatus (200-800 ms window)**

³ The models reported here did not include any random slopes for TrialNumber as this led to convergence problems, likely due to the sparsity of the data on an individual or item level.

623 A final set of exploratory analyses examined whether there were any asymmetries
624 in the effects of Match due to PrefixStatus rather than PhonemeChange. Visual
625 inspection of the data suggested asymmetries (as shown in the supplemental
626 materials) with a bigger effect of Match when the critical syllable was taken from
627 true prefixes, especially for group M1 and especially for trials in the first half of
628 the experiment. A model including PrefixStatus, TrialNumber and Group found an
629 interaction between Match, PrefixStatus and TrialNumber ($\beta = 0.93$, $SE = 0.36$, $t =$
630 2.56 , $p = 0.01$) which indicated that the effect of Match was greater when the
631 critical syllable was taken from a true prefix than when it was taken from a pseudo
632 prefix, especially in the beginning of the experiment. Interactions with Group were
633 not significant though numerically the effect of Match was greatest for the true
634 prefixes for group M1.

635

636 3.2 Time course of effects

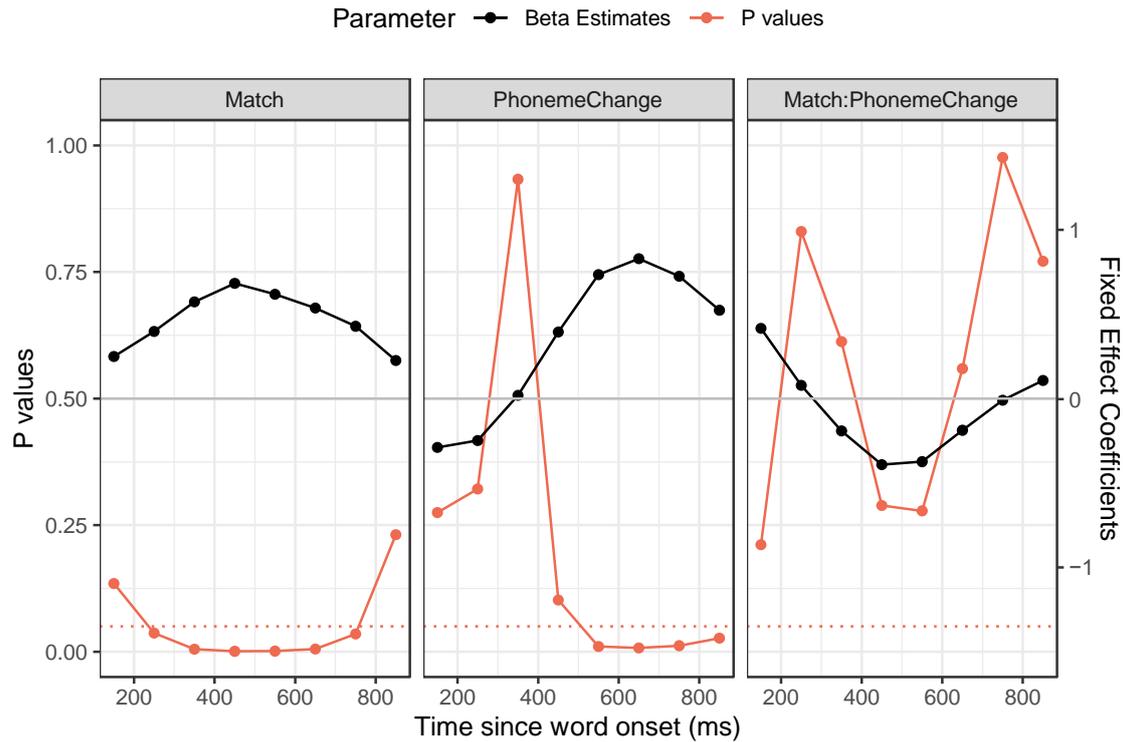
637 3.2.1 Main analysis

638 The previous analyses established that listeners spent less time fixating the target
639 image when the acoustic information in the critical syllable mismatched the
640 morphological structure of the target. As noted in the Introduction, we were also
641 interested in how quickly the acoustic information influenced their looking
642 behaviour, i.e. whether listeners used the acoustic information to drive eye-
643 movements predictively, before they heard any disambiguating information. The
644 alternative explanation of the mismatch effect observed above would be that the
645 information is noted, but is not by itself sufficient to guide expectations and hence
646 influence behaviour. Rather it would presumably have a sort of cumulative
647 influence on perceptual decisions that depended on overall acoustic coherence
648 between the first and later syllables in the word, and as such would presumably
649 influence later and not earlier looks. Such a result would be interesting, but would
650 point to a role that is different from our hypothesis of a strong predictive influence
651 that is the main motivation for our work.

652 To address this issue, we examined the evolution of the effects examined in
653 previous sections over the course of the trial. Following Clayards, Niebuhr &
654 Gaskell (2015) and Kingston, Levy, Rysling & Staum (2016) we binned the eye
655 movements into 100 ms bins and performed the regression model on each bin.
656 We included the same fixed and random effects structure as the main model above
657 (Match, PhonemeChange, and their interaction) as well as TrialNumber and Group
658 and their interactions with the other fixed effects⁴. The estimates for Match,
659 PhonemeChange and their interaction (as well as TrialNumber discussed below)
660 are plotted in Figure 3 in terms of the estimates and p values of the fitted models.

⁴ Models run without Trial and Group had the same pattern of results for Match, PhonemeChange and their interaction, see supplemental materials.

661



662

663

664 Figure 6. Results of mixed effects regressions over time for Match,
 665 PhonemeChange, and their interaction. Shading is two standard errors of the
 666 coefficient estimates as calculated by the regression models. On each panel's y axis,
 667 p values are shown at the left and beta coefficients at the right. Black curves: beta
 668 coefficients; red curves: p values. The dotted red horizontal line indicates $p=0.05$.
 669 The thick grey solid horizontal line indicates Coefficient = 0. Colour online.

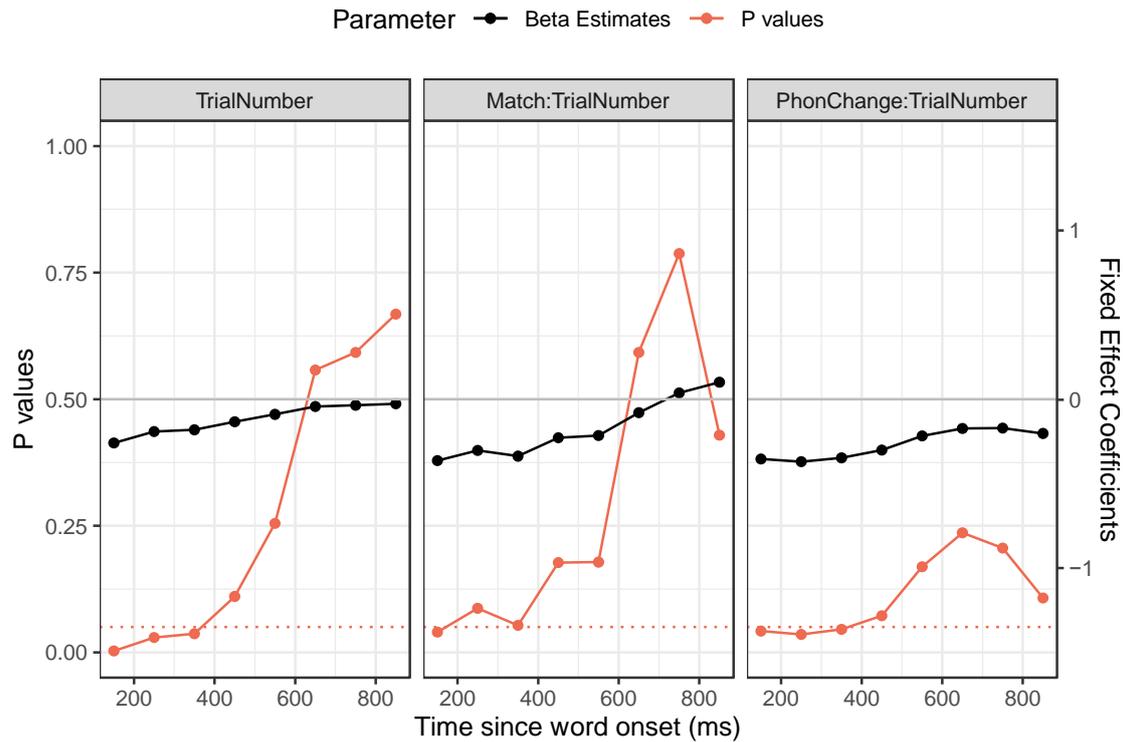
670 Figure 6 (left panel) shows that the beta values for Match increase and then
 671 decrease as the trial progresses, asymptoting around 450 ms after critical word
 672 onset. At the second time bin, between 200 and 300 ms from the onset of the word,
 673 the two-standard error bars just miss touching zero and the p value is 0.04. After
 674 that point the effect of Match is clearly below $p = 0.05$ until the last time bin, when
 675 it returns to > 0.05 . This indicates that the acoustic pattern of the critical syllable
 676 affects looks to the target from very early on in the syllable; Matches facilitate
 677 correct prediction of the sentence continuation (the target). Assuming the
 678 standard 200 ms lag between planning and executing an eye-movement, 200-300
 679 ms after word onset is the earliest possible window for which we might expect to
 680 see any effects. The results of that model indicate that at least for many
 681 participants and items, there is an effect of Match at this earliest time point. As
 682 Figure 4 shows, for most of the items, the critical syllable is longer than the length
 683 of this window (100 ms) so the disambiguating information at the splice point has
 684 not yet arrived. This strengthens our claim that the acoustic information in the
 685 critical syllable is being used to anticipate the target word and looks to the target
 686 are delayed when it mismatches.

687 Although the model on a single large window (Section 3.1) found no effect of
 688 PhonemeChange, this time-course analysis shows that PhonemeChange (shown in

689 Figure 6, middle panel) is significant in the second half of the 200 ms to 800 ms
690 window (from about 500 ms since word onset and after the end of the critical
691 syllable). The coefficient estimates indicate that this was due to more looks to the
692 target for *dis-mis-* items than for *re-* items later in the sentence. As before in the
693 model on a single large window, there is no interaction between Match and
694 PhonemeChange (Figure 6, right panel).

695 **3.2.2 Group and TrialNumber (Time course)**

696 As before, we also included Group (whether the participants heard all matches or
697 all mismatches on day 1) and TrialNumber (the trial order in the experiment) and
698 their interactions. As before we found that neither Group nor any of its
699 interactions had a significant effect at any time point. The model on a single large
700 window had found that looks to the target decreased over the course of the
701 experiment (effect of TrialNumber), especially for the *dis-mis-* stimuli
702 (TrialNumber by PhonemeChange interaction). The models fit every 100 ms found
703 that the effects of TrialNumber as well as its interaction with PhonemeChange
704 were limited to the first few hundred milliseconds after word onset ($p < 0.05$ for
705 the first three time bins, Figure 7). This seems to indicate that over the course of
706 the experiment, participants stopped making early looks to the target, i.e. they
707 stopped anticipating the target. As pointed out in the Introduction, this may be
708 because (within the context of the experiment) it was not essential to pay
709 attention to the early part of the word—the continuation of the sentence typically
710 disambiguated the two images. Participants may have learned this (implicitly or
711 explicitly) as the experiment progressed. There was also a trend for the early effect
712 of Match to get smaller over the course of the experiment (Match by TrialNumber
713 Figure 7). No other two or three-way interactions had any time points with a p -
714 value < 0.05 (see supplemental materials for full details).



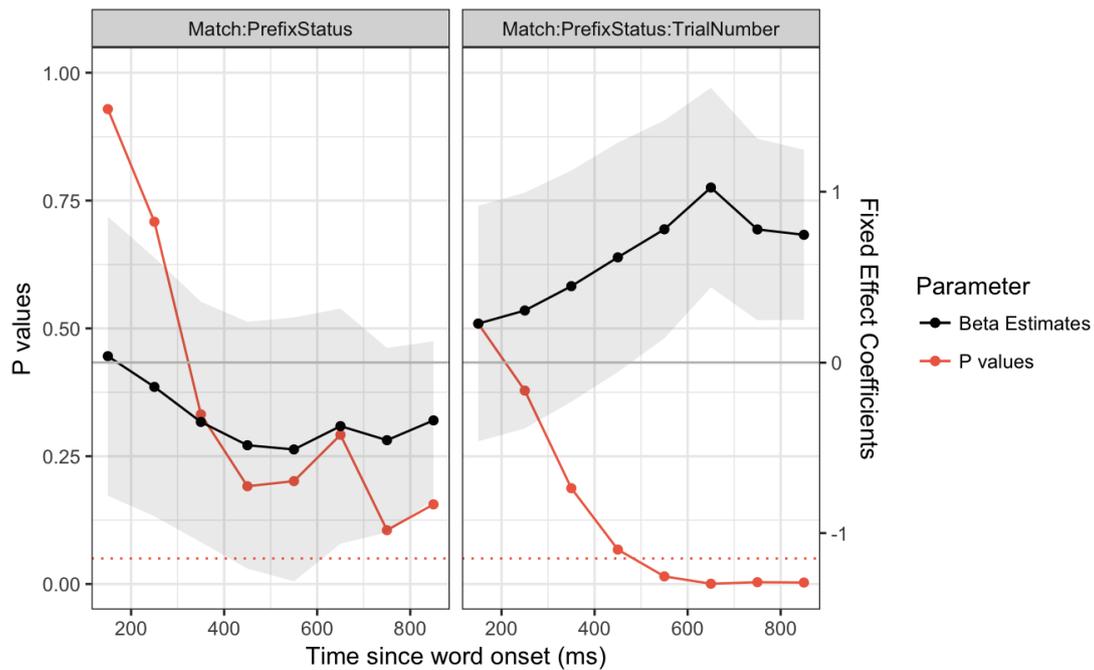
715

716 Figure 7: Results of mixed effects regressions over time for TrialNumber and its
 717 interactions with Match and PhonemeChange. Shading is two standard errors of
 718 the coefficient estimates as calculated by the regression models. On each panel's y
 719 axis, p values are shown at the left and beta coefficients at the right. Black curves:
 720 beta coefficients; red curves: p values. The dotted red horizontal line indicates
 721 $p=0.05$. The thick grey solid horizontal line indicates Coefficient = 0. Colour online.

722 **3.2.3 Prefix Status (Time course)**

723 A final analysis considered models that included PrefixStatus instead of
 724 PhonemeChange and its interactions with Match and Group as well as Match and
 725 TrialNumber. Figure 8 (left panel) shows that there was a non-significant trend
 726 for an interaction between PrefixStatus and Match in the second half of the 200-
 727 800 ms window (after 500 ms from word onset) that indicated that the effect of
 728 Match may have been greater for true prefixes, consistent with the numeric trend
 729 from the single large-window model. There were also significant interactions
 730 between PrefixStatus, Match and TrialNumber during this same later part of the
 731 200-800 ms window, as shown in the right panel of Figure 8. This indicates that
 732 the Match x PrefixStatus interaction influenced eye-movements at the beginning
 733 of the experiment but became weaker over the course of the experiment, which is
 734 probably why it was not statistically significant when aggregated over the whole
 735 time-course of the experiment.

736



737

738 Figure 8: Results of mixed effects regressions over time for the interactions Match
 739 x PrefixStatus and Match x PrefixStatus x TrialNumber. Shading is two standard
 740 errors of the coefficient estimates as calculated by the regression models. On each
 741 panel's y axis, p values are shown at the left and beta coefficients at the right. Black
 742 curves: beta coefficients; red curves: p values. The dotted red horizontal line
 743 indicates p=0.05. The thick grey solid horizontal line indicates Coefficient = 0.
 744 Colour online.

745

746 3.3 Summary of results

747 Overall, listeners spent more time looking at the target image (the one consistent
 748 with the sentence continuation) when the acoustic properties of the critical
 749 syllable matched those expected for the target word in the associated image (main
 750 effect of Match in all models), thus supporting the main hypothesis. This was true
 751 both when the phoneme changed (*re-* stimuli) and when only the acoustical
 752 pattern within the syllables changed (*dis-mis-* stimuli) (i.e. no interaction with
 753 PhonemeChange in the model on a single window from 200 ms to 800 ms).

754 We also examined patterns over the course of the sentence (successive 100 ms
 755 windows between 200 to 800 ms from word onset) and over the course of trials
 756 in the experiment (from the first to the last trial for each participant). When we
 757 examined the time-course of the sentence, we found that listeners looked to the
 758 correct critical syllable from the earliest moments of its being heard. This use of
 759 the acoustic-phonetic detail of the critical syllable is reflected in the effect of Match
 760 being significant from the 200-300 ms bin. It indicates that the acoustic
 761 information was immediately taken up and used predictively by listeners. We also
 762 found that a few hundred milliseconds later, listeners had mostly converged on
 763 the target for *dis-mis-* stimuli but were looking less consistently at the target for
 764 *re-* stimuli (i.e. effect of PhonemeChange starting at the 500-600ms bin). This may

765 be because many of the *re-* stimuli were globally ambiguous, or possibly because
766 the greater acoustic complexity of *dis-mis-* syllables compared with *re-* ones
767 (including the presence of abrupt acoustic boundaries within *dis-mis-* syllables)
768 makes them more auditorily distinctive. Examining the time-course of the
769 experiment, we found that as the experiment progressed, the early looks to the
770 target decreased, especially for the *dis-mis-* stimuli (i.e. PhonemeChange by
771 TrialNumber interaction up to the 300-400 ms bin). This indicates that listeners
772 began to respond differently to (especially) *dis-mis-* critical syllables as they
773 became familiar with the structure of the stimuli. Finally, we found that after about
774 500 ms from the word onset, effects of Match were greatest when listeners heard
775 a true prefix, though, consistent with the way responses changed as the
776 experiment progressed, this benefit for matched prefixes was only at the
777 beginning of the experiment.

778

779 4 Discussion

780 4.1 The main findings

781 At a general level, we asked whether listeners are sensitive to phonetic detail –
782 both segmental and rhythmic information – that systematically reflects
783 morphological structure while involving no changes in number of syllables. We
784 further asked whether listeners are likely to use this phonetic detail predictively
785 (in order to help distinguish words that contain true prefixes from those that
786 contain pseudo prefixes) in ordinary listening conditions—that is, in an easy on-
787 line task under good listening conditions in which the aim is response accuracy
788 but not speed.

789 The three main questions specific to our experiment were whether there is a
790 mismatch effect overall, whether it is independent of the phonemic status of the
791 acoustic difference (i.e. with *dis-mis-* as well as *re-*), and in particular whether the
792 acoustic information within the critical syllable influences perceptual decisions in
793 real time, rather than only being influential in combination with the rest of the
794 word. All three questions are answered affirmatively. Listeners spent more time
795 fixating the target image when the critical syllable matched the continuation of the
796 sentence, whether or not there was a phoneme change, and in real time.
797 Furthermore, while prefix status did not affect the answers to the three main
798 questions, the results suggest that true prefixes may convey more reliable
799 information about their status than pseudo prefixes in some circumstances, as
800 discussed below.

801 We also made some additional observations. Foremost amongst these is the
802 evidence for rapid learning during the task. As expected, listeners used the
803 internal acoustic structure of the prefixed or non-prefixed syllable predictively.
804 However, as the experiment progressed this prediction effect weakened,
805 presumably as listeners learned that they could wait for the sentence continuation
806 to provide disambiguating information. That they did not wait for the continuation
807 during early trials means that the critical acoustic information is likely to be used
808 predictively in normal listening conditions. This finding has practical as well as
809 theoretical interest: the fact that listeners' behavior changed early in the

810 experiment suggests that future work on this type of distinction should consider
811 trial number as a predictor variable. Furthermore, prefix status (whether the
812 initial syllable came from a true or pseudo prefixed word) seems to affect eye
813 movements. The 200-800 ms single window analysis showed a stronger benefit of
814 Match when the critical syllable was a true prefix, and the interaction with
815 TrialNumber confirmed that this benefit was again especially obvious in the
816 beginning stages of the experiment. As noted in the Introduction, although both
817 prefixes and pseudo prefixes are weak syllables in that they do not carry primary
818 lexical stress and are not normally accented in utterances, prefixes are associated
819 with a degree of stress, or rhythmic prominence, that pseudo prefixes in
820 comparable word structures lack. The present results suggest that the rhythmic
821 emphasis that comes with a true prefix may be more perceptually compelling than
822 the absence of such a focus. This further encourages exploration of the hypothesis
823 that rhythmic properties of the signal are fundamental to speech processing in real
824 time. The next two sections discuss the nature of rhythm and metre, and outline
825 its relevance to a general model of perceptual processing.

826

827 **4.2 Rhythm and hierarchical metrical structure as organising principles** 828 **for speech perception**

829 It has been argued that the phonetic detail manipulated in our study is best
830 understood as reflecting differences in rhythmic or metrical structure between
831 prefixes and their equivalent phones in mono-morphemic words (e.g. Smith, 2012;
832 Hawkins, 2001; 2003; 2010). This argument, and our current results, support
833 other suggestions in the literature that rhythmic or metrical structure is an
834 important part of the representation used to recognize speech (cf. Salverda et al.,
835 2003; Brown et al., 2015; Breen et al., 2014). This section first outlines the useful
836 distinction between rhythm and metrical structure, and their interrelationship.
837 Then it explores how the metrical-rhythmic structure of speech might serve as a
838 fundamental organising principle for speech perception, melding multi-modal
839 properties of the physical signal with linguistic and social knowledge to achieve
840 communicative success.

841

842 **4.2.1 Metre and rhythm**

843 Musical analyses distinguish rhythm from metre. London (2012) expresses the
844 distinction as follows. Rhythm represents a series of physical events having
845 particular relationships with one another. In music, these are largely durational
846 (the inter-onset intervals of notes). Metre, in contrast, is a perceptual
847 phenomenon: an emergent organization involving a degree of periodicity that is
848 constructed by the brain in response to stimuli that are perceived as rhythmic
849 (Fujioka et al., 2012). In hearing metrically, the brain sets up a beat that
850 hierarchically structures the rhythm, focusses attention on the metrical beats, and
851 allows prediction of the time of occurrence of future events (see e.g. Calderone et
852 al., 2014; Lakatos et al., 2005; Lakatos et al., 2008).

853

854 This distinction between rhythm and metre can be helpful for speech analysis too.
855 Speech rhythm can often be represented simply in terms of relative durations of

856 similar units in the utterance. Other parameters— f_0 , amplitude, and sometimes
1 857 timbre—may contribute to both rhythmic and metrical aspects of speech. In doing
2 858 so, they can override durational influences on perceived rhythmic and metrical
3 859 structure (e.g. Dilley, Mattys & Vinke, 2010, Experiment 3a). Thus metre, which is
4 860 inherently hierarchical, can be represented for speech as the mapping of auditory
5 861 patterns onto linguistic units, from segments (allophones, phonemes or their
6 862 psychological equivalents) through syllables to metrical feet and intonational
7 863 phrases.
8
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10 864
11 865 Metrical, or beat-based, structure, enables establishment of a metrical hierarchy
12 866 where faster rhythmic events can happen within slower ones. Faster rhythmic
13 867 events in speech presumably include syllables (or syllable-like units such as
14 868 Japanese morae, hereafter not distinguished from syllables). In linguistic terms
15 869 suitable for languages like English, a beat-based hierarchy of syllabic weight is
16 870 called stress, the main beats being accented syllables (sometimes called
17 871 prominence, or primary stress), while less important syllables take secondary
18 872 stress or are unstressed. Common to both speech and music is that perception of
19 873 a rhythmic group can change depending on the listener's construal of the wider
20 874 metrical (e.g. for speech, sentential) structure it occurs in. [For speech, preceding
21 875 meaning and/or rate of speech influence perception \(e.g. Pickett and Pollack,
22 876 1963; Ernestus, Baayen and Schreuder, 2002; Ernestus, 2014; Ernestus, Hanique
23 877 and Verboom, 2015; Dilley, Mattys & Vinke, 2010; Heffner, Dilley, McAuley and
24 878 Pitt, 2013; Morrill, Heffner and Dilley, 2014\), while explicit instructions to hear a
25 879 beat train in ternary or else in binary time can also influence listeners' metrical
26 880 response, as measured by EEG \(Nozaradan, Peretz, Missal and Mouraux, 2011;
27 881 Nozaradan, Peretz, and Mouraux, 2012\).](#)
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33 882
34 883 The experience of rhythm in complex auditory signals such as speech and most
35 884 music is learned (Mattys et al., 1999; Hannon & Trehub, 2005). Without such
36 885 (usually implicit) learning from exposure to the relevant signals, which amounts
37 886 to acculturation, complex sound sequences sound unstructured, even chaotic. For
38 887 speech, such learning is part of linguistic knowledge. With such knowledge, beat-
39 888 based listening facilitates prediction of upcoming events, a property increasingly
40 889 seen as essential to successful communication between individuals (Philips-Silver
41 890 & Trainor, 2005; Cirelli, Wan & Trainor, 2016).
42
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44 891
45 892 [The principles described here have been used to explore the relationship between
46 893 speech rhythm and the various frequencies of cortical neural oscillations in the
47 894 brain which entrain to external stimuli. One of the more complete models, Giraud
48 895 and Poeppel \(2012\), privileges rhythm in speech intelligibility. Amongst other
49 896 things, it identifies low gamma \(25-30 Hz, 33-40 ms\) and theta \(4-8 Hz, 125-250
50 897 ms\) frequencies as entraining to feature/phoneme-sized and syllable-sized
51 898 durations respectively. Delta frequencies \(1-3 or 4 Hz, 250-1000 ms\) are
52 899 implicated in prosodic processing. However, it seems mistaken to necessarily
53 900 associate shorter durations with phonological units and longer ones with prosody.
54 901 English has many instances of long phonological units and short prosodic ones
55 902 \(Hawkins, 2014:1-3\).](#)
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903 A stronger argument, relevant to the present study, comes from Mai, Minnett and
904 Wang's (2016) EEG study of Mandarin Chinese. They manipulated sentences of
905 meaningful vs. nonsense disyllabic words, and backwards vs. normal speech. Like
906 Giraud and Poeppel (2012), they concluded that phonological and syntactic-
907 semantic processing engage different neural networks, but identified quite
908 different frequencies: semantic/syntactic processing with fast gamma
909 frequencies, and phonological processing with slower theta and delta frequencies,
910 as well as beta (13-30 Hz, 33-77 ms). These patterns reflect that the syllable, not
911 the phoneme, is the important contrastive unit in Mandarin phonology:
912 consonants strongly determine vowel quality, f_0 operates over the entire syllable
913 to change word meaning, as well as in longer prosodies, and syllable stress is
914 relatively invariant.

915 In sum, perceived speech rhythm involves representation of sequences of
916 linguistic units of the size of syllables or longer. Metre is hierarchical and involves
917 representation of the entire spectrotemporal signal of a phrase or more. That is,
918 metrical structure is constructed or imposed by the listening brain, rather than
919 being a property inherent within the physical signal. So recognition of speech
920 rhythm and metre may entail recognition of entire complex auditory patterns,
921 within which subunits can be discerned. Expected attributes not clearly present in
922 the physical signal but whose presence is implied by and compatible with the
923 overall pattern can be adduced by neural pattern completion, a process attested
924 for both vision (e.g. Meng, Remus and Tong, 2005; Murray, Kersten, Olshausen,
925 Schrater and Woods, 2002) and speech (Shahin, Bishop and Miller, 2009; for a
926 review, see Hawkins, 2014). As such, rhythm and metre offer the possibility of
927 structuring the speech signal such that all its contrasting abstract units are
928 representable in a systematic and economical way that necessarily includes 'top-
929 down' knowledge of the language itself.

930 **4.2.2 Relevance to perception of affixed words**

931 Consistent with the arguments above, every utterance can be described by a
932 metrical (prosodic) hierarchy that partly governs the phonetic detail of segments
933 and syllables within its domain. Autosegmental-Metrical (AM) phonology (e.g.
934 Pierrehumbert & Beckman, 1988; Post, D'Imperio & Gussenhoven, 2007; Cho,
935 2016), and Firthian Prosodic Analysis (FPA, e.g. Ogden et al., 2000) exemplify two
936 theoretical frameworks based on this approach. In Cho's (2016, p136) words for
937 AM, "Prosodic structure provides a "frame" for articulation based on which
938 abstract phonological representations whose phonetic detail is rather coarsely
939 specified by the phonology of the language are fleshed out with fine-grained
940 phonetic content in both segmental and suprasegmental dimensions...this
941 assumption entails that the prosodic structure of an utterance is phonetically
942 "encoded" into the speech signal and the listener in turn decodes the structural
943 information from the signal and exploits it in speech comprehension." FPA
944 embodies similar principles, and in addition every metrical/prosodic hierarchical
945 structure describing an utterance is linked to its corresponding syntactic
946 hierarchical structure (Ogden et al., 2000). These metrical principles have been
947 extended to perception, particularly of prefixed vs non-prefixed words, with
948 discussion of links to grammar, morphological structure, and lexical items and
949 their associative networks (Hawkins, 2010; Hawkins and Smith, 2001; Hawkins,

950 2003). The results of the present experiment broadly support claims in the papers
951 cited, but some updating is warranted.

952 The present study supports four central tenets of Hawkins' theoretical position,
953 made in the papers cited above. The first tenet (which before the present study
954 was a hypothesis) is that the fine phonetic detail that distinguishes prefixes from
955 nonprefix syllables is used by listeners in real time—i.e. their behavior changes as
956 they hear it. This phonetic detail relates to meaning, and does not depend on there
957 being a phonemic contrast to relate it to meaning. By extension, all phonetic detail
958 seems likely to be related to meaning, with no intervening 'levels' of formal
959 linguistic structure likely to be obligatory in the process of relating sound to the
960 talker's meaning. This does not deny the psychological reality of intervening
961 structural 'levels'; it merely says that a given level of analysis does not always have
962 to be accessed for meaning to be understood from the spoken signal. Neuropsychological support for this claim comes from Krieger-Redwood *et al.* (2013), who used TMS to show that processes requiring semantic categorisation (i.e. understanding word meaning) are independent of judgments requiring phonological classification (i.e. phonemic content); semantic judgments can operate when phonological processes are unavailable. This has important consequences: it means that the perceptual system is probably more closely attuned to general, modality-free properties of pattern recognition than is normally assumed by perceptual theories based on the mutually exclusive categories and analytic levels of theoretical linguistics.

972 The second tenet is that every short pattern of sound (segment or several
973 segments) can only be described and hence perceptually interpreted in terms of
974 its context. The same sound in a different context may be interpreted entirely
975 differently. [Our experimental manipulation and analysis addressed this claim implicitly, especially by virtue of tracking decision changes \(e.g. to the critical syllable\) over time.](#) A listener can map sound directly to meaning, but only for the context in which it is heard. Context is broadly defined. It includes the immediate local context—that is, the prosodic/metrical structure of the utterance that the sound is part of—possibly one or more preceding phrases, and the listener's understanding of the entire communicative situation. Understanding speech is thus inherently situation-specific (see also Hawkins, 2011; Hawkins, 2014).

983 The third tenet that our results support is that fine phonetic detail will be used to
984 access meaning when it is relevant to the situation at hand. The reduction in early
985 looks to the target for *dis-* and *mis-* stimuli indicates that listeners used the
986 information in the critical syllable at the start of the experiment but quickly
987 adapted to the fact that the task did not demand it—they could wait until later in
988 the sentence for acoustically clearer disambiguation. This rapid adaptation to task
989 requirements is supported by the literature on perceptual learning and adaptation
990 to new accents etc. (e.g. Maye, Aslin & Tanenhaus, 2008; Bradlow & Bent, 2008;
991 Barden & Hawkins, 2013; Nguyen and Hawkins, 2001).

992 The fourth tenet is that "lack of clear evidence for a particular category, as with
993 the reduced first syllable in *mistakes*, can be informative" (Hawkins, 2010, p486).
994 That is, it was expected that the absence of a perceptual beat on unprefixed forms
995 of the critical syllables *mis-*, *dis-* and *re-* would help listeners predict

996 monomorphemic word identity. This was broadly the case. However, as noted
1 997 above, in the early part of the experiment and after about 500 ms from word onset,
2 998 true prefixes helped word identification more than nonprefixes did. Since the
3 999 prefix contains a heavier beat than the non-prefix, we interpret this last result as
4 1000 indicating that a perceptual beat is important in driving perceptual decisions,
5 1001 whereas its absence may be less influential. This is consistent with neuroscientific
6 1002 studies showing that a beat-based hierarchy is fundamental to selective attention
7 1003 (Lakatos et al., 2007; Lakatos et al., 2008; Lakatos et al., 2009; Arnal & Giraud,
8 1004 2012). An obvious inference is that the prefix is emphasized because it bears
9 1005 quasi-independent information about meaning that the phonemically-identical
10 1006 nonprefix does not.

14 1007 If prefixes carry secondary stress to draw attention to them and their meaning,
15 1008 why are suffixes not similarly stressed? One possibility takes us again to the role
16 1009 of prediction in understanding speech. Understood within the natural context of
17 1010 their metrical structure, prefixes herald the beginning of a new lexical item that
18 1011 will be a polysyllabic word with a main lexical stress later than the prefix, and the
19 1012 prefix will change the meaning of the stem. There are numerous subtle changes to
20 1013 segmental durations in polysyllabic words that depend on the word's phonological
21 1014 and acoustic structure (see Hay et al. (in prep.) for information pertinent to
22 1015 prefixes). Suffixes make the word phonologically longer, by adding either a
23 1016 syllable or else a segment that makes the final coda more complex. Word stems
24 1017 are likewise subtly modified by the addition of one or more suffixes, and there are
25 1018 differences between words with different types of suffix, compared with
26 1019 monomorphemic words. For example, Plag, Homann, and Kunter (2015/2017)
27 1020 discuss complexities of regularities found for the various morphemes represented
28 1021 by English /s/ and /z/ (plural, genitive, 3rd person singular, etc).

34 1022 If the stress on a prefix heralds a polymorphemic word, it seems reasonable that
35 1023 the changes that a suffixed word stem undergo could raise the probability of an
36 1024 upcoming suffix. Perceptual experiments described in Section 1.2 show that they
37 1025 do for both English and Dutch (Blazej & Cohen-Goldberg, 2014; Kemps et al.,
38 1026 2005a; Kemps et al., 2005b). However, as noted there, given that these studies
39 1027 contrasted monosyllabic, mono-morphemic words with polysyllabic,
40 1028 polymorphemic words, it is impossible to tell whether their listeners were simply
41 1029 anticipating a longer word, or anticipating the polymorphemic structure of the
42 1030 longer word, or both.

46 1031 What is clear, however, is that the suffix itself does not “need” to receive secondary
47 1032 stress because its presence is predictable from the internal acoustic structure of
48 1033 its stem, which would typically take strongest stress in the word. Together with a
49 1034 constraint against stressing word-final syllables of polysyllabic words in English
50 1035 and Dutch, and, presumably, usually some grammatical priming, this might be
51 1036 sufficient to reduce perceptual uncertainty.

54 1037 In sum, this study supports previous claims and hypotheses that listeners use fine
55 1038 phonetic detail in real time to efficiently access meaning, but only in its
56 1039 appropriate context and if the task makes it relevant and ‘cost-effective’ to do so.

1040 The previous section concluded by implying that rhythm and metre have the
1041 potential to provide the underlying ‘glue’ of speech communication by focusing
1042 attention onto critical events in the speech stream. Those critical events are
1043 associated with beats that allow a metrical structure to be created by the listening
1044 brain. The metrical structure facilitates prediction and allows meaning to be
1045 efficiently accessed. This section concludes by briefly adding two points to that
1046 claim. The first is that much of the speech signal is of course crucial to intelligibility
1047 but does not receive a metrical beat. How might that ‘non-beat’ information be
1048 processed? Hawkins (2010) suggested that phonetic detail in the entire speech
1049 signal is continuously monitored, for a variety of reasons including in order to
1050 learn about communicatively significant new patterns. This position is supported
1051 by neuroscientific evidence related to that cited above demonstrating creation of
1052 beat-based metrical structure. For example, Schroeder and Lakatos (2009)
1053 propose that when a stimulus lacks rhythm, lower-frequency neuroelectric
1054 oscillations entrained to metrical structure are suppressed and replaced by
1055 continuous monitoring (vigilance) that uses higher-frequency oscillations. These
1056 systems can operate simultaneously, differing in balance depending on the
1057 rhythmicity of the stimulus. This claim is also consistent with experiments that
1058 show that lexical activation varies continuously in a way which reflects variation
1059 in the acoustic signal as it unfolds over time (e.g. Allopenna, Magnuson, &
1060 Tanenhaus, 1998; Gow & McMurray, 2007; McMurray et al., 2003; Warren &
1061 Marslen-Wilson, 1987).

1062
1063 The second concluding point is that speech normally takes place as part of
1064 meaningful communication between people. Any hypothesis concerning the role
1065 of rhythm and metre in understanding speech needs to encompass the interactive
1066 and multimodal properties typical of most human communication. The power of
1067 multimodal sensory information in facilitating speech intelligibility and spoken
1068 communication is well known. The strong correlation between the auditory signal
1069 and visual input from the gestural code and facial expression is equally well
1070 known. There is ample evidence that rhythm and metrical structure play a crucial
1071 role in both multimodal integration of a message from a single talker (e.g.
1072 Schroeder et al., 2008) and in the entrainment that occurs during communication
1073 between talkers (e.g. Hasson et al., 2012). Detailed discussion goes beyond the
1074 scope of this paper, but a general review relevant to rhythm in both spoken and
1075 musical interaction can be found in Hawkins, Cross and Ogden (2013).

1076 **4.3 Strengths, limitations and extensions of the study**

1077 *We achieved our aim of demonstrating that a rhythmic distinction of fine phonetic*
1078 *detail, with no phonemic contrast involved, can be used to access meaning and*
1079 *predict lexical identity in real time. We used the morphological prefix distinction*
1080 *because it suited our aims well, since there is relatively good consensus about the*
1081 *meaning of a prefix. Other contrasts could have been used, but few lend*
1082 *themselves as well to our primary question.*

1083 *Unlike previous studies, we controlled for confounding factors like the number of*
1084 *syllables in the mono-morphemic vs. prefixed words, and prosodic structure of*
1085 *pairs of stimuli. We put much effort into ensuring that our stimuli described and*

1086 illustrated plausible visual scenes. By tracking our results over the course of the
1 1087 experiment we were also able to show that the experiment itself changed
2 1088 participants' behaviour. This points to an important methodological consideration
3 1089 for future studies. Adaptation to experimental conditions can occur with just a few
4 1090 trials. Researchers should consider this possibility in their analyses before
5 1091 concluding that a manipulation did not affect participants' behaviour, since a
6 1092 weakening of the effect over the course of the experiment can obscure important
7 1093 results relevant to understanding speech in normal, everyday situations. It should
8 1094 also be noted that we found our effect weakened over the course of the
9 1095 experiment, even though the stimuli included a high proportion of filler trials, a
10 1096 subset of which were designed to counteract effects of cross-spliced critical
11 1097 syllables.

15 1098 We expect these results to generalize to most if not all English prefixes. The
16 1099 phonetic detail will be specific to the prefix, and some words and contexts may
17 1100 differ from the usual pattern. Word-specific influences could include
18 1101 decomposability, and the relative frequency of the prefixed and unprefixed word.
19 1102 But the principle of more vs. less stress (or less vs. more syllable reduction) is
20 1103 expected to be true for all prefixes and pseudo prefixes. We expect some dialect
21 1104 differences in the exact acoustic details: work in progress supports this prediction
22 1105 while confirming that the general patterns hold across dialects of English (Hay et
23 1106 al., in prep). In terms of wider theoretical implications, the same type of reasoning
24 1107 can presumably be generalized to perception of any other audible contrast based
25 1108 on non-phonemic phonetic detail, as long as the auditory contrast has a systematic
26 1109 relationship with distinctions of meaning, broadly defined.

31 1110 A question for future research is whether the multiple acoustic cues we and others
32 1111 have identified as contributing to the prefix-nonprefix distinction work together
33 1112 in concert, or whether any dominate perceptual responses. Perhaps the most
34 1113 valuable question we can ask pertains to the role of duration in the syllables *dis-*
35 1114 and *mis-*. Syllable duration is often shown to be an over-riding perceptual cue (e.g.
36 1115 Salverda, Dahan & McQueen (2003) Experiment 2). But for distinguishing prefix
37 1116 and non-prefix forms of *dis-* and *mis-*, is what matters the duration of the whole
38 1117 syllable, regardless of its internal acoustic structure (e.g. the s:i ratio), or is it the
39 1118 internal acoustic structure regardless (within limits) of the overall syllable
40 1119 duration? We hypothesize that for SSBE, it is likely to be the internal acoustic
41 1120 structure, as carried by the s:i ratio, since that ratio is distinctive in production
42 1121 (Smith, Baker and Hawkins 2012). We suggest this because there is more scope
43 1122 for a relatively long vowel to convey a stronger rhythmic beat (indicative of the
44 1123 prefix form), by virtue of amplitude, f₀ and formant spacing, than for the short
45 1124 vowel that tends to accompany the non-prefix form. In sum, the rhythmic
46 1125 hypothesis would be supported if the internal acoustic structure proved more
47 1126 decisive in indicating prefix status than overall syllable duration alone, without
48 1127 any change in s:i ratio. This experiment is planned.

54 1128

57 1129 **4.4 Concluding summary**

59 1130 This study confirms that phonetic detail associated with prefixes and pseudo
60 1131 prefixes can aid prediction of the upcoming word's identity. Our results, especially

1132 from early trials, indicate that such phonetic detail will typically be used
1133 predictively in real-world listening conditions. However, we have also shown that
1134 over the course of our experiment many of the effects weakened, indicating
1135 relatively fast adaptation to the experimental conditions. There was also some
1136 evidence that prefixes influence predictive behavior more strongly than pseudo
1137 prefixes do. We suggest that our findings support the hypothesis that speech
1138 rhythm (more properly, the metre of speech) provides a fundamental binding
1139 principle of speech processing, enabling linguistic structures to be created and
1140 matched with similar structures in memory to allow rapid matching of complex
1141 sound patterns to meaning.

1142 **Supplementary Materials**

1143 Stimuli, original data, supplementary figures, R code for the analyses, and
1144 additional acoustic analyses of the stimuli not reported in the manuscript are
1145 available at <https://osf.io/dsyxu>. DOI 10.17605/OSF.IO/DSYXU.

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1148

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1159 **Appendix A**

1
2 1160 The term ‘phonetic detail’ as used in this paper has a very particular meaning . It
3 1161 refers to acoustic-phonetic properties that are systematically distributed and
4 1162 communicatively significant but that are not essential to differentiate phonemes,
5 1163 and hence to distinguish the phonological form of words. This definition hides a
6 1164 number of complexities, discussed for example by Carlson and Hawkins (2007)
7 1165 and Hawkins and Local (2007), but the main points for present purposes are (1)
8 1166 that speech sounds can systematically distinguish meanings and communicative
9 1167 functions without there being a difference in phonemic structure; and (2) that the
10 1168 perceptual significance and hence meaning of any single part of the speech signal
11 1169 depends on the situational and phonetic context in which it is heard. The first
12 1170 claim is widely accepted, although the meanings concerned (e.g. question vs.
13 1171 statement intonation, expressions of doubt) were traditionally designated
14 1172 ‘paralinguistic’ and treated separately both from the types of lexical meaning
15 1173 distinguished in phonemic analysis, and from mainstream psycholinguistic
16 1174 theories of spoken word recognition; the account proposed here makes no such
17 1175 restriction, as exemplified by our focus on grammatical (specifically
18 1176 morphological) linguistic structure. The second claim is likewise widely accepted,
19 1177 but its implications do not always drive the theoretical interpretation of
20 1178 experimental results, nor the design of experiments testing the role of phonetic
21 1179 detail in speech perception.

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1184 **Appendix B**

1
2 1185 *Sentence pairs used in the experiment. The first sentence of each pair contains the*
3 1186 *pseudo prefix and the second sentence of each pair contains the true prefix.*

4
5 1187 I wouldn't be surprised if the boys **discover** them.

6 1188 I wouldn't be surprised if the boys **discolour** them.

7 1189

8 1190 He fell asleep despite all the **discussion**.

9 1191 He fell asleep despite all the **discomfort**.

10 1192

11 1193 The teacher has a very **discursive** style.

12 1194 The teacher has a very **discourteous** style. (3-syllable pronunciation of target word)

13 1195

14 1196 Her paintings are so **distinctive**.

15 1197 Her paintings are so **distasteful**.

16 1198

17 1199 It was difficult because Sam **distracted** him.

18 1200 It was difficult because Sam **distrusted** him.

19 1201

20 1202 A swan **displays** its plumage to its mate.

21 1203 A swan **displaces** water when it lands.

22 1204

23 1205 Alex typically **discards** the fruit.

24 1206 Alex typically **discounts** the risk.

25 1207

26 1208 I'd be surprised if Tess **mistakes** the letters.

27 1209 I'd be surprised if Tess **mistypes** the letters.

28 1210

29 1211 We felt uncomfortable about his **mysterious** demeanour. (3-syllable pronunciation)

30 1212 We felt uncomfortable about his **mistreatment** of Amina.

31 1213

32 1214 The girls were spellbound by tales of Jo's **mystique**.

33 1215 The girls were spellbound by tales of Jo's **misdeeds**.

34 1216

35 1217 We think Jeff **mistook** the tree for a person.

36 1218 We think Jeff **mistimed** the turning on purpose.

37 1219

38 1220 Jo struggled to **recover** her balance.

39 1221 Joe struggled to **re-cover** the sofa.

40 1222

41 1223 They agreed they should **repeal** the verdict.

42 1224 They agreed they should **re-peel** the carrots.

43 1225

44 1226 That's Oscar Wilde. He loved **reposing** quietly.

45 1227 That's Oscar Wilde. He loved **re-posing** questions.

46 1228

47 1229 After the massacre, the armed forces **reformed** their procedures.

48 1230 After the massacre, the armed forces **re-formed** on the hillside.

49 1231

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- 1 1232 After the noisy lawn party, Josh **receded** behind the shed.
2 1233 After the noisy lawn party, Josh **re-seeded** the trampled lawn.
3 1234
4 1235 Everyone was happier after Geoff **restrained** the brute.
5 1236 Everyone was happier after Geoff **re-strained** the fruit.
6 1237
7 1238 He hurried to **relay** the message.
8 1239 He hurried to **re-lay** the carpet.
9 1240
10 1241 They're starting to **redress** the wrong.
11 1242 They're starting to **re-dress** the wound.
12 1243
13 1244 We hoped he'd **release** the catch soon.
14 1245 We hoped he'd **re-lease** the house soon.
15 1246
16 1247 The next job was to **repair** the socks.
17 1248 They next job was to **re-pair** the socks.
18 1249
19 1250 We watched Jess **restore** them.
20 1251 We watched Jess **re-store** them.
21 1252
22 1253 He was punished for **refusing** so rudely.
23 1254 He was punished for **re-fuelling** so slowly.
24 1255
25 1256 The man **rejoiced** as he finished the race.
26 1257 The man **re-joined** the ends of the rope.
27 1258
28 1259 Todd **rebutted** the argument successfully.
29 1260 Todd **re-baited** the fishing line successfully.
30 1261
31 1262 Harry's parents **revoked** his privileges.
32 1263 Harry's parents **revoiced** his worries again.
33 1264
34 1265 We know that Dave **restricts** his arm movements when necessary.
35 1266 We know that Dave **re-strings** his instrument when necessary.
36 1267
37 1268 It's a perfect example of **extravagance** in public spending.
38 1269 It's a perfect example of **ex-trampoliners'** sense of balance.
39 1270
40 1271 We were amused to hear those **expletives** had been censored.
41 1272 We were amused to hear those **ex-policemen** had been honoured.
42 1273
43 1274 There are conflicting views about these **expanders'** roles in orthodontistry.
44 1275 There are conflicting views about these **expatriates'** roles in this society.
45 1276 (3-syllable pronunciation of target word)
46 1277
47 1278 They didn't understand why these **exponency** terms were important.
48 1279 They didn't understand why these **ex-pony club** girls were important.
49 1280
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- 1281 The judge decided he'd **expatiate** at some length.
1 1282 The judge decided he'd **expatriate** the poor kids.
2 1283
3 1284
4 1285 **Appendix C**
5 1286 *37 pairs of Filler items specific to this experiment (For the other 30 pairs of filler*
6 1287 *items, see Heinrich, Flory and Hawkins, 2010.) Words in bold contain either a true*
7 1288 *(tr) or a pseudo (ps) prefix*
8 1289
9 1290 We tried to **distinguish** between the twins (ps)
10 1291 We tried to **distinguish** between the bins
11 1292
12 1293 You purify water by **distilling** it (ps)
13 1294 You purify whisky by **distilling** it
14 1295
15 1296 We liked the **description** of the balloons over mountains (ps)
16 1297 We liked the **description** of the fantastical dragon
17 1298
18 1299 The conductor loves his job **despite** being prone to backache (ps)
19 1300 The conductor likes his job **despite** being prone to motion sickness
20 1301
21 1302 We could just **discern** the bridges in the fog (ps)
22 1303 We could just **discern** the ridges in the fog
23 1304
24 1305 Sue **disturbed** the cows (ps)
25 1306 Sue **disturbed** the sheep
26 1307
27 1308 He began to **destroy** the door (ps)
28 1309 He began to **destroy** the cube
29 1310
30 1311 The vandals **distorted** the frame to get revenge (ps)
31 1312 The vandals **distorted** the wheel to get revenge
32 1313
33 1314 They were all impressed with the **disabled** girl's spirit (ambiguously tr)
34 1315 They were all impressed with the **disabled** boy's spirit
35 1316
36 1317 Sugar **dissolves** faster in hot liquids (ps + pronunciation change)
37 1318 Sugar **dissolves** faster when you stir it
38 1319
39 1320 The man had seriously **mistreated** the donkey (tr)
40 1321 The man had seriously **mistreated** the dog
41 1322
42 1323 The drawer was **misaligned** (tr)
43 1324 The door was **misaligned**
44 1325
45 1326 The Lord of **Misrule** as a puppet (tr)
46 1327 The Lord of **Misrule** as a carving
47 1328
48 1329 A **mistrial** is a rollerblader's trick (tr)
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- 1330 A **mistrial** is a lawyer's last resort
1 1331
2 1332 Jody had **miscalculated** when to take the toast out (tr)
3 1333 Jody had **miscalculated** when to jump for the frisbee
4 1334
5 1335 The sheep did not **react** to the fox's presence (tr)
6 1336 The sheep did not **react** to the dog's presence
7 1337
8 1338 A **refectory's** where monks eat (ps)
9 1339 A **refectory's** where monks sleep
10 1340
11 1341 We were slow to **repack** because of the baby (tr)
12 1342 We were slow to **repack** because of the dog
13 1343
14 1344 The dog was reluctant to **relinquish** the ball (ps)
15 1345 The dog was reluctant to **relinquish** the ring
16 1346
17 1347 The class **redrew** classical cartoons (tr)
18 1348 The class **redrew** classical plans
19 1349
20 1350 Kate **refused** to buy the coat (ps)
21 1351 Kate **refused** to buy the dress
22 1352
23 1353 We'll **repaint** the dhow (tr)
24 1354 We'll **repaint** the bow
25 1355
26 1356 They did a good job of **re-creating** the original instruments (tr)
27 1357 They did a good job of **re-creating** the Victorian atmosphere
28 1358
29 1359 He **recited** the poem perfectly (ps)
30 1360 He **recited** the poem passionately
31 1361
32 1362 His favorite was this **repeating** rifle (ps)
33 1363 His favorite was this **repeating** pattern
34 1364
35 1365 They planned to **reheat** the risotto (tr)
36 1366 They planned to **reheat** the lasagna
37 1367
38 1368 Cameron **re-sets** the stone (tr)
39 1369 Cameron **re-sets** the bone
40 1370
41 1371 Ali **examined** the book intently (ps)
42 1372 Ali **examined** the paint intently
43 1373
44 1374 Her **ex-husband** is a diver (tr)
45 1375 Her **ex-husband** is a driver
46 1376
47 1377 The men **exchanged** looks (ps)
48 1378 The men **exchanged** books
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- 1379
1 1380 She's a really **excellent** musician (ps)
2 1381 She's a really **excellent** clinician
3 1382
4 1383 Nothing like **extorting** promises (ps)
5 1384 Nothing like **extorting** money
6 1385
7 1386 Geoff **extracted** the tooth (ps)
8 1387 Geoff **extracted** the juice
9 1388
10 1389 There was a mountain of plastic **recycling** (tr?)
11 1390 There was a mountain of plastic for playing in
12 1391
13 1392 Sally liked meeting all the **relations** (ps)
14 1393 Sally like seeing the celebrations
15 1394
16 1395 Eddie always takes **revising** seriously (ps)
17 1396 Eddie always takes his driving seriously
18 1397
19 1398 Luke tried hard not to eat the cake
20 1399 Luke tried hard not to eat the ice cream
21 1400
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S. Hawkins developed the study concept, designed, constructed and acoustically analysed the stimuli. All authors were involved in the design of the experiment. M. Clayards implemented the experiment, and conducted the statistical analyses in discussion with the other two authors. S. Hawkins and M. Clayards wrote the manuscript, with G. Gaskell providing critical feedback. All authors approved the final version of the manuscript for submission.