# Syllable frequency effects in immediate but not delayed syllable naming in English

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## Abstract

Syllable frequency effects in production tasks are interpreted as evidence that speakers retrieve precompiled articulatory programs for high frequency syllables from a mental syllabary. They have not been found reliably in English, nor isolated to the phonetic encoding processes during which the syllabary is thought to be accessed. In this experiment, 48 participants produced matched high- and novel/low-frequency syllables in a near-replication of Laganaro and Alario's [(2006) On the locus of the syllable frequency effect in speech production. Journal of Memory and Language, 55(2), 198-196, http://dx.doi.org/10.1016/j.jml.2006.05.001] production conditions: immediate naming, naming following an unfilled delay, and naming after delay filled by concurrent articulation. Immediate naming was faster for high frequency syllables, demonstrating a robust syllable frequency effect in English. There was no high frequency advantage in either delayed naming condition, leaving open the question of whether syllable frequency effects arise during phonological or phonetic encoding.

**Keywords:** syllable frequency, prepared naming, speech motor control, articulatory suppression, motor program

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The *syllabary* is a hypothesised store of articulatory programs for spoken syllables (Crompton, 1982) at the interface between linguistic and motor levels of processing in models of speech production (Levelt, 1989; Levelt, Roelofs & Meyer, 1999). Evidence for spoken syllabic units has been reported for a number of European languages (Dutch: Cholin, Levelt, & Schiller, 2006; Cholin & Levelt, 2009; Levelt & Wheeldon, 1994; French: Alario, Ferrand, Laganaro, New, Frauenfelder, & Segui, 2004; Alario, Goslin, Michel, & Laganaro, 2010; Brand, Rey, Peereman, & Spieler, 2002; Laganaro & Alario, 2006; Perret, Schneider, Dayer & Laganaro, 2014); German: Aichert & Ziegler, 2004; Conrad & Jacobs, 2004; Staiger & Ziegler, 2008; Spanish: Alario, Goslin, Michel, & Laganaro, 2010; Álvarez, Carreiras, & Taft, 2001; Carreiras & Perea, 2004; Perea & Carreiras 1998) as well as Korean (Simpson & Kang, 2004), with participants producing high frequency syllables faster than low frequency syllables in a range of production tasks. Further studies in these languages have shown that this *syllable frequency effect* disappears in delayed syllable naming tasks (Dutch: Cholin & Levelt, 2009; French: Laganaro & Alario, 2006), suggesting that the effect arises at a post-lexical level of speech production. Evidence for syllable frequency effects in English has been inconsistent, however.

In the present study, we sought further evidence for the syllabary in English by investigating whether a syllable frequency effect would appear in a more rigorously designed immediate syllable naming task than has previously been reported in English. We further asked whether the effect would disappear in delayed naming, and re-appear in delayed naming with concurrent articulation, localising the effect to the phonetic encoding level of speech production following the logic of Laganaro and Alario (2006). Below, we summarise previous attempts to demonstrate syllable frequency effects in English speech production experiments and describe the experimental work that has been argued to localise the effects to the level of phonetic encoding, before reporting on the present study.

**Previous investigations of syllable frequency in English**

Varley, Whiteside and Luff (1999) predicted that frequently-used syllables would be characterized by faster response latencies and greater coarticulation (manifested in shorter syllable durations and faster transitions from consonant-to-vowel place of articulation), indexing the retrieval of stored plans for frequently-used syllables during speech production. By contrast, the need to compute plans for less-frequently used syllables was predicted to result in slower latencies, and longer syllables produced with less coarticulation. They reported finding a high frequency advantage in response latencies, but there was insufficient control for confounds between syllable and word frequency, receptive processing and production, and intrinsic articulatory factors. Varley et al.'s hypotheses and approach stimulated a high level of debate, however (see Varley & Whiteside, 2001a and 2001b, and commentaries), as well as further attempts to measure syllable frequency effects in English.

In a series of studies with greater experimental control, Monsell, Van der Lugt and Jessiman (2002) re-paired the onset and coda of regularly-spelled pairs of existing English syllables (e.g. BREK KEL, BREL KEK), to form pairs of existing versus novel syllables, where the frequency of the existing syllables is by definition higher than that of the novel syllables. These materials controlled for segmental and orthographic factors, but not for the time required to compute phonology from orthography. The syllables were elicited in an immediate naming task, in which participants read the orthographic stimuli aloud as quickly as possible upon presentation. Monsell and colleagues found a statistically reliable 5.4 ms advantage for existing syllables in mean response latencies, and a reliable 5.8 ms effect of syllable frequency on the mean durations, but not median durations, with shorter durations in existing syllables potentially associated with greater co-articulation, and fewer errors on the existing syllables. There was no effect of syllable frequency in a delayed naming task conducted in the same series of experiments, and the researchers interpreted this as evidence that high frequency syllable programs were not being retrieved during the execution of a prepared articulatory program.

Croot and Rastle (2004) investigated coarticulation, syllable durations and response latencies in three experiments eliciting high frequency and novel syllables in syllable naming tasks (see description of materials below, in Method). They found formant changes consistent with increased coarticulation in high frequency syllables in some phonetic contexts but not others in one experiment, effects of syllable frequency on rime durations that were confounded with number of phonemes in a second experiment, and an advantage of 6 ms for high-frequency syllables that did not reach statistical significance in a third experiment. This non-significant effect may have been due to a lack of statistical power, if syllable frequency effects in English are as small as reported by Cholin et al. (2011) and Monsell et al. (2002), both of which were higher-powered studies.

Macizo and Van Petten (2007) reported an analysis of word naming response latencies for 3,029 visually presented English monomorphemic disyllabic words (e.g., lady, spinach, bottom etc.) from the corpus of Balota, Cortese, Hutchison, Neely, Nelson, Simpson, & Treiman (2002), and also found that phonological syllable frequency contributed to faster naming. The effects were also small in this study ($R^2$ of .017 for the second syllable and .002 for the first), there was no within-participants or within-items control, and no analysis of the extent to which syllable frequency was confounded with lexical frequency.

In the most recent study of the syllable frequency effect in English, Cholin, Dell and Levelt (2011) found significant effects of syllable frequency using a symbol-association learning task that involved producing high- and low-frequency syllables as mono- and disyllabic pseudo-words. The construction of the base material set was restrictive because four syllables were required to form a syllabic quartet thereby controlling for syllable onsets, codas and other potentially confounding factors within syllables as described in more detail below (see Method). In total, 8 quartets served as the basic syllable material. As the syllabic stimuli were presented auditorially during the symbol-association learning phase, orthographic effects on response latencies could be ruled out. In the experiment, participants learned and practised the association between an auditory syllable and a symbol appearing on a computer screen. In test phases, the presentation of this symbol cued production of the associated target. Syllables were presented multiple times per condition, increasing statistical power.

The faster production times for high-frequency syllables compared to low-frequency syllables in this experiment provided support for the retrieval of stored units during speech planning, presumably from the hypothesized syllabary. However, faster reaction times for high-frequency syllables in this task may have been the result of faster retrieval of a phonologically-based association, not faster retrieval of a phonetic syllable program. Further, to isolate syllable frequency effects to post-lexical phonetic levels, it is critical that syllable and lexical frequency are not confounded (i.e. the syllables are not also words, as occurred in the materials of Varley et al., 1999 and Marcizo & Van Petten, 2007, and for a small number of items in the Cholin et al. (2011) study, see below). In summary, previous investigations of syllable frequency effects in English have used a variety of production tasks (word repetition, word naming, immediate and delayed nonword syllable naming, symbol-association learning task with nonword syllables), only some of have yielded the predicted effects, and methodological confounds limit interpretation of some results. Further, and more importantly, the syllable frequency effect in English has not yet been reliably shown to arise at the level of phonetic encoding.

**Localising syllable frequency effects to phonetic encoding**

Laganaro and Alario (2006) argued that an effect of syllable frequency in spoken language production could be localised at the level of phonetic encoding if such an effect could (i) be demonstrated in an immediate syllable naming task, (ii) disappear when the same items were named after an unfilled delay, and (iii) re-appear for those items in delayed naming when participants were carrying out a concurrent articulation task during the delay. Their rationale was as follows. First, the syllable frequency effect in immediate syllable naming provides evidence for stored syllable representations as functional units in speech production, with more frequently-accessed syllables retrieved faster. The effect is assumed to be post-lexical because it has been demonstrated for syllables that do not also exist as words in the language investigated (Laganaro & Alario, 2006; Monsell et al., 2002). Second, the disappearance of the effect in naming after a delay suggests that stored articulatory programs for target syllables are retrieved from the syllabary and buffered (in an "articulatory" or "phonetic" buffer) until the signal to respond, neutralising the difference in retrieval times for higher versus lower frequency syllables. Word and syllable naming after a delay in tasks of this type is also known as "prepared naming", under the assumption that the word or syllable is fully "prepared" for the final motor execution stage of production by the time it is stored in the phonetic buffer, and that the signal to respond initiates motor execution (Monsell, 1986; Rastle, Croot, Harrington & Coltheart, 2005). The absence of syllable frequency effects in a delayed naming condition is interpreted to mean the effects do not arise during motor execution (Cholin & Levelt, 2009; Laganaro & Alario, 2006).

Finally, in Laganaro and Alario's account of their results, a concurrent articulation task is hypothesised to impede the buffering of the syllable at the phonetic level (Monsell, 1987). As the name suggests, concurrent articulation requires the production of irrelevant spoken material while carrying out a second task. In Laganaro and Alario's study, participants repeated the syllable [ba] while waiting to produce the target syllable as quickly as possible at the signal to respond. Laganaro and Alario reasoned that concurrent articulation during delayed naming occupies the phonetic buffer such that articulatory programs cannot be buffered after retrieval from the syllabary. These articulatory programs can therefore only be retrieved after the signal to respond, allowing syllable frequency effects to emerge in delayed naming with concurrent articulation as in immediate naming.

Laganaro and Alario (2006) demonstrated the series of effects described above in two pairs of experiments eliciting pseudoword naming and picture naming in immediate and delayed naming and delayed naming with concurrent articulation. They found a reliable 46ms advantage for pseudowords composed of high frequency compared with low frequency syllables in immediate naming, and a reliable 20ms advantage eliciting the same items in delayed naming with concurrent articulation, with no reliable difference in naming following an unfilled delay. There is support for the disappearance of the syllable frequency effect in naming following an unfilled delay in English. In the series of experiments by Monsell et al. (2002), the advantage for existing over novel syllables disappeared for both latency and duration measures in prepared production of utterances composed of one, two or three nonword syllables. Cholin and Levelt (2009) also found that syllable frequency effects seen in unprepared utterances in an implicit priming task were not evident in a prepared production task. There are, however, no English studies to date that demonstrate all three of the effects reported for French by Laganaro and Alario (2006). The locus of the syllable frequency effect in English, if it can be reliably demonstrated, remains controversial (Buchwald, Ferreira, Goldrick, & Miozzo, 2014).

## The present study

This study investigates syllable frequency effects in (Australian) English with a more rigorous and powerful design than previously reported for immediate syllable naming experiments in English. Standard Australian English uses the same set of phonemic contrasts as Southern British English, with phonetic differences primarily carried in the vowels (Cox, 2012). We utilised a syllable naming task because a clear demonstration of these effects in English would replicate the immediate naming results of Monsell et al. (2002), validate the English syllable frequency effects reported by Cholin et al. (2011) in the symbol-association learning task, and allow us to replicate the procedure of Laganaro and Alario (2006) investigating the locus of the effect. To increase the likelihood of observing a syllable frequency effect in immediate naming, we combined the non-word materials used in the Croot and Rastle (2004) syllable naming study and the Cholin et al. (2011) study, and we elicited them from a relatively large number of participants compared with previous studies of syllable frequency in English, increasing the statistical power relative to our previous (Cholin et al., 2011; Croot & Rastle, 2004) studies. Further, we carefully reviewed our previous materials and omitted items in both sets of stimuli that may be represented lexically to exclude the possibility of confounding lexical frequency effects (see below). We matched the high and low frequency materials on reading time by the DRC Model (Coltheart, Rastle, Perry, Ziegler & Langdon, 2001) to ensure that latency differences in naming high versus low frequency nonword syllables were not due to latency differences in calculating a phonological representation from the orthographic stimulus. We also elicited the syllables in immediate and delayed naming and delayed naming with concurrent articulation in a within-participants design, increasing the sensitivity of the design over between-participants studies (e.g. Laganaro & Alario, 2006). All three conditions had to be run in the one session to maximise testing efficiency, therefore we elicited the Immediate Naming Condition first for all participants to ensure any syllable frequency effect was unconfounded with any practice effects, then used the same order for the other tasks (Delayed Naming followed by Delayed Naming with Concurrent Articulation) to match naming condition order across participants.

In a final aspect of the design, the prosody used in the concurrent articulation condition was manipulated between participants. We considered the possibility that effects of concurrent articulation may vary according to the nature of the irrelevant material articulated, and therefore introduced small variations in the prosody of the repeated syllables to allow for this possibility. In our first concurrent articulation condition, participants repeated the monosyllabic phonological word [‘da, ‘da, ‘da][1]. In the second prosodic condition, participants repeated the trochaic phonological word [‘dadə, ‘dadə, ‘dadə], and in the third condition, they repeated the iambic phonological word [də’da, də’da, də’da]. In the first condition, the metrical frame in the concurrent articulation task matched that of the target monosyllable. In the second and third concurrent articulation conditions, the metrical frames did not match those of the target monosyllables, varying from the target on the number of syllables, and from each other on the location of the prominent syllable in the frame. Jones and Macken (1995) reported that repeating what they called a “changing state” sequence of letters (e.g. “ABCDEFG”) in their study during concurrent articulation in an immediate memory task was more disruptive than repeating the same monosyllable (the letter name “A”). We anticipated that the first concurrent articulation condition might not sufficiently occupy the phonetic output buffer to restore the syllable frequency effect after the delay, whereas the second and third concurrent articulation conditions might constitute changing-state material that would be more disruptive and thereby more sensitive to a syllable frequency effect. To briefly anticipate our discussion of the present study, although our results in delayed naming with concurrent articulation condition differed from those of

[1] In this notation, the ‘ before a syllable indicates it is metrically prominent, thus [‘da-də] is trochaic and [də‘da] is iambic.

Laganaro and Alario (2006), the pattern of response latencies across our different concurrent articulation conditions in fact support the claim that syllable frequency effects originate from the level of phonetic encoding, consistent with Laganaro and Alario's claim.

The first aim of our experiment, therefore, was to establish whether a syllable frequency effect would be evident in immediate naming in English. The second was to determine whether such a frequency effect would disappear in delayed naming, and re-appear when the naming followed a delay filled with a concurrent articulation task. This would replicate in English the series of results found by Laganaro and Alario (2006) in French, and localise the effect to the phonetic planning level of speech production. A more exploratory aim was to investigate whether the prosody used in the concurrent articulation task would influence response latencies in the delayed naming with concurrent articulation condition.

Our three primary hypotheses were that we would see faster naming of high versus low frequency syllables in immediate naming and in naming following a delay filled by concurrent articulation, but that the advantage for high frequency syllables would not be apparent after an unfilled delay. We further hypothesised that we would see an interaction between syllable frequency and the concurrent articulation condition within delayed naming with concurrent articulation, such that the syllable frequency effect may not be apparent when the metrical frame of the concurrently articulated syllables matched that of the target syllables, but may appear in the more demanding conditions when the metrical frames in the concurrent articulation syllables and target syllables did not match.

## Method

### Participants

Participants were 48 first-year psychology students at the University of Sydney who participated for optional course credit. They were native Australian English speakers with an average age of 19 years (*SD* = 1). This study was conducted under approved by the University of Sydney Human Research Ethics Committee.

**Materials**

We used stimuli created for two previous investigations of syllable frequency in English (Cholin et al., 2011; Croot, & Rastle, 2004). Croot and Rastle's stimuli were 24 high-frequency English monosyllabic non-word syllables from the CELEX (Baayen et al., 1993) database occurring in 40 or more independent word-forms and in the top 20% of syllable token frequencies. Each syllable in that study was paired with a matched monosyllable that does not occur as a syllable in English (thereby low-frequency). Twenty-five syllable pairs were available due to strict matching on initial phoneme, number of phonemes, CV-structure, vowel length, and vowel height and backness, but one of these pairs was omitted in the current study, leaving 24 pairs.[2] No syllable ended with a lax vowel because such syllables cannot be produced in isolation in Australian English phonology. The orthographic representations of each pair member were matched to control for reading time in the syllable naming task on number of letters, orthographic body friends, enemies and neighbours, neighbourhood size, and reading aloud latency generated by the DRC Model (Coltheart et al., 2001).

Cholin et al.'s (2011) high- and low-frequency syllable pairs, also from the CELEX (Baayen et al., 1993) database, were selected on the basis of the summed frequency of occurrence of each syllable in CELEX and the number of times the syllable occurred in the lexicon. Cholin et al.'s syllable stimuli were limited to CVC-structured (i.e. consonant-vowel-consonant) syllables such that sets of four syllables could be paired into "quartets". In each quartet, the same onset and vowel e.g. /zɪ/, appeared once in a high-frequency syllable

[2] A previously novel syllable in this pair, /rʌd/, has become high-frequency in Australian English as the surname of Kevin Rudd, Prime Minister 2007-2010, 2013

/zɪz/ and once in a low-frequency syllable /zɪn/ to form a syllable pair, and the vowels and codas of those syllables also appeared in a high- and low-syllable frequency pair with a new onset: /gɪz / and /gɪn/. Number of syllable phonemes, phoneme frequency, initial phoneme, CV-structure, bigram/biphone frequency, and neighbourhood density were thereby controlled within quartets, as each high-low pair has the same syllabic neighbours. Sixteen English syllable pairs were created meeting these constraints for that study. For the current study, two quartets were removed, to remove syllables that exist as words, and their matched counterparts[3]. A further quartet was removed because it was constructed around the neutral vowel schwa /ə/, which cannot be transcribed for reliable reading aloud in Australian English nonword monosyllables. Removing these items left ten pairs of high- and low-frequency syllables. As Cholin et al.'s stimuli had been designed for auditory presentation, orthographic representations of the ten pairs were then created for visual presentation in the current experiment. These orthographic representations were matched across frequency condition on number of letters, number of neighbours, body neighbours, body friends and body enemies, summed frequency of body neighbours, friends and enemies, and reading aloud latency as based on the DRC Model (Coltheart et al., 2001).

A final consideration in selecting the current materials was that there were three high-frequency syllables that appeared in both Cholin et al.'s and Croot and Rastle's study, paired with a different low-frequency syllable in each. The closest match on manner and place of articulation (which both influence response preparation time; Rastle et al., 2005) was chosen for use here: KAL with KAV rather than KACK, FAKK with FAPP rather than FAL and SIG

[3] The following syllables were removed for the reasons indicated: BEN and BESS are English proper nouns, YES is a frequently used English word, the YEN is the Japanese currency, and the syllable KONG occurs in the proper nouns Hong Kong, King Kong and Donkey Kong.

with SIFF not SUG. In total, 31 high and low frequency syllable pairs were available for the present study.

**Apparatus.** The stimuli were visually presented on a Dell Optiplex 745 PC (Intel Core 2, 1.86GHz CPU; Windows XP Service Pack 2) with an Acer AC713 16-inch monitor running *DMDX* (Forster & Forster, 2003) to participants who sat approximately 40cm from the monitor. The response signal was played through the Dell external speakers and participants were wearing a Logitech Premium USB Microphone Headset 350 that detected the onset of verbal responses to trigger the DMDX voice-key. As voice-key measures can be unreliable (Rastle et al., 2005; Rastle & Davis, 2002), we also recorded response signals and verbal responses using *Audacity 1.2.5* to allow hand-labeling of the onset of the response signal and onset of acoustic energy of each response from the waveforms and spectrograms. Hand-labeling was carried out by the second author (GL) using *PRAAT* (Boersma & Weenink, 2015) after training by the first author (KC) in the criteria used to hand-label the Australian National Database of Spoken Language (ANDOSL) database. Application of the labeling criteria was checked over serial labeling sessions until high agreement was reached between the GL and KC about the location of the RT boundaries, the same process used to train labelers of the ANDOSL database by the first author (Croot, Fletcher & Harrington, 1992; Croot & Taylor, 1995).

**Elicitation procedure.** Participants named each syllable once in each of three conditions carried out in the following order for all participants: Immediate Naming, Delayed Naming and Delayed Naming with Concurrent Articulation. Each Immediate Naming trial began when a “+” sign appeared for 500ms to allow participants to focus on the screen, followed by the simultaneous presentation of a brief auditory cue (bell) and a target syllable that remained on screen for 2000ms or until the voice-key was triggered when participants read the syllable aloud.

Each Delayed Naming trial began with the "+" sign for 500ms followed by the presentation of the target syllable for 1000ms and a blank delay screen that appeared for 1000ms or 2000ms, randomly assigned across trials so participants could not predict the length of the delay, as in Laganaro and Alario (2006). Laganaro and Alario argued that 1000ms was enough time to allow for the preparation of a response (Savage, Bradley & Forster, 1990) while 2000ms was sufficiently long for the response to decay in the phonological store without articulatory rehearsal (Baddeley, 2003). After the delay, two simultaneous response cues signaled the participant to say the target syllable – the auditory cue and a visually-presented "?" sign that remained on the screen for 2000ms or until the voice-key was triggered.

The procedure in the Delayed Naming with Concurrent Articulation condition was identical to the procedure in Delayed Naming, except that during the delay each participant produced the phonological syllable /da/ in one of three conditions that varied the metrical frame used in the concurrent articulation task. Concurrent Articulation Prosody condition was manipulated between participants so that each participant only had to master one prosodic structure when repeating the syllables. The first concurrent articulation condition was similar to that of Laganaro and Alario (2006), except our participants said [‘da] rather than [‘ba]. Participants saw DA-DA-DA-DA… on the screen for the duration of the delay and were instructed to begin repeating [‘da] rapidly and regularly until the signals to respond with the target syllable. In the second concurrent articulation condition, participants saw DA-da-DA-da… on the screen during the delay and repeated [‘dadə] until the signal to respond. In the third concurrent articulation condition, participants saw da-DA-da-DA… on the screen and repeated [də’da] during the delay.

**Procedure**

Each naming condition began with two sets of practice trials utilising six five-letter non-word syllables selected from the ARC Nonword Database (Rastle, Harrington & Coltheart, 2002) that were not among Croot and Rastle's (2004) or Cholin et al.'s (2011) stimuli. The first practice set consisted of three trials in which the experimenter performed the task along with the participant. He demonstrated responses in each condition, including modeling the concurrent articulation prosody, and gave feedback, correcting the participant as required. The second practice set consisted of six trials that the participant performed independently. After each set of practice trials, participants could ask questions or re-take the practice trials before the experimental trials began. Participants took a short break between conditions as needed and were debriefed at the end of the experiment.

In many trials the highly sensitive DMDX voice-key was activated by environmental noises rather than by articulation of the syllable, and in the Delayed Naming with Concurrent Articulation conditions, the key was triggered if participants were still articulating a concurrent articulation syllable after the response signal was given. Therefore, the voice-key data were not used, and response times were instead hand-labeled from the acoustic signal as described above.

**Analysis**

All analyses were carried out by participants and by items, with the dependent variable being response latency in milliseconds. In the first set of analyses, we carried out a fully within-participants and a fully within-items two-way analysis of variance (ANOVAs) on the independent variables Syllable Frequency (High, Low) and Naming Condition (Immediate Naming, Delayed Naming, Delayed Naming with Concurrent Articulation). Post-hoc comparisons of latencies for high versus low frequency syllables within each naming condition used paired t-tests. In a second set of analyses, we investigated the effects of Syllable Frequency (High, Low/Non-exisiting) and Concurrent Articulation Prosody

(Monosyllable, Trochee, Iamb) on response latencies elicited within the Delayed Naming with Concurrent Articulation condition only. For this analysis by participants we conducted a mixed model two-way ANOVA (with Syllable Frequency manipulated within participants and Concurrent Articulation Prosody manipulated between participants), and by items we conducted a fully within-items two way ANOVA. Post-hoc comparisons of the significant main effects in these analyses were conducted using mixed model and fully repeated 2 x 2 ANOVAs by participants and by items, respectively.

## Results

Trials yielding the following non-systematic incorrect or invalid responses were removed from the analysis: non-responses (0.38% of all items), pronunciations of the syllable that differed from the target pronunciation (9.7%), audio recording insufficiently clear to allow hand-labeling of reaction times (12.59% of all items), and not following instructions in the concurrent articulation condition (i.e. continuing with concurrent articulation task after signal to respond, stopping concurrent articulation before signal to respond, failing to start concurrent articulation task etc., 1.72% of all items)[4]. Next we examined the distributions of the data in each cell of the Frequency by Naming Condition analysis by participants using stem-and-whisker plots and observed two extreme outlying participants[5] whose response latencies suggested they had difficulty carrying out the syllable naming task in the Delayed Naming with Concurrent Articulation condition. We replaced their means for the High and Low Frequency conditions with the overall means for these conditions, to maximize power in the other conditions of the repeated measures analyses, an important consideration given that

[4] Highly similar rates of these response types were produced across frequency conditions within each of the three syllable naming conditions and overall.

[5] Participants with means more than three interquartile ranges higher than the 75$^{th}$ %ile.

lack of power has been a key weakness of previous syllable frequency studies in English. During this latter analysis we also discovered that one item (FLOU, target pronunciation /flau/) had been incorrectly or invalidly produced by all participants in one of the concurrent articulation conditions (see above for description of incorrect and invalid responses), so we replaced the latencies for these trials with the mean for this condition, again to maximize power in the repeated measures analyses involving this item. Finally, reaction times more than 3 standard deviations above or below each participant's mean in each cell of the design were considered invalid and were also omitted from the analyses. In the analysis by participants 118 values were excluded on this basis, constituting 1.87% of the data, and by items, 58 values were excluded; 0.92% of the data.

In the first set of analyses examining effects of Syllable Frequency and Naming Condition on response latencies, Mauchly's test showed that the assumption of sphericity approached significance for the Naming Condition main effect by participants, $\chi^2(2) = 5.30$, $p = 0.071$, and was violated for the Frequency by Naming Condition interaction by participants, $\chi^2(2) = 8.16$, $p = 0.017$, so degrees of freedom for these effects were corrected using the Greenhouse-Geisser method. There was no significant effect of Syllable Frequency by participants, $F(1, 47) = 2.36$, $p = .13$ or by items, $F(1, 28) = 1.79$, $p = .19$. There was a significant main effect of Naming Condition by participants, $F(1.804, 84.77) = 48.54$, $p < .001$, and by items, $F(2, 56) = 224.84$, $p < .001$, such that responses were slower in the Immediate Naming condition than the other two conditions, which did not differ significantly from each other. This was overshadowed by a significant interaction between Naming Condition and Frequency, by participants, $F(1.72, 80.86) = 3.37$, $p = .046$, and by items, $F(2, 56) = 3.42$, $p < .040$, illustrated in Figure 1. High frequency syllables were produced faster than low frequency syllables in the Immediate Naming Condition only, confirmed by a series of paired t-tests comparing latencies for high versus low frequency syllables in each naming condition, significant in Immediate Naming by participants, $t(47) = 4.06$, $p < .001$ and by items, $t(28) = 2.36$, $p = .025$, but not in Delayed Naming by participants, $t(47) = 0.36$, $p = .72$ or by items, $t(28) = 1.19$, $p = .24$, nor in Delayed Naming with Concurrent Articulation by participants, $t(47) = 0.21$, $p = .84$, or by items, $t(28) = 0.27$, $p = .77$.

INSERT FIGURE 1 HERE

In the second set of analyses examining the effects of Syllable Frequency and Concurrent Articulation Prosody on response latencies within the Delayed Naming with Concurrent Articulation condition only, Mauchly's test showed that the assumption of sphericity was violated for the Concurrent Articulation Prosody main effect by items, $\chi^2(2) = 11.06$, p = 0.004 and the Frequency by Concurrent Articulation Prosody interaction by items, $\chi^2(2) = 10.47$, p = 0.005, so degrees of freedom for these effects were corrected using the Greenhouse-Geisser method. There was no effect of Frequency by participants, $F(1,45) = .04$, $p = .84$, or by items, $F(1, 28) = 1.31$, $p = .26$. There was a significant main effect of Concurrent Articulation Prosody by participants $F(2, 45) = 3.91$, $p = .027$, and by items $F(1.50, 41.92) = 20.92$, $p < .001$, with no significant interaction between Frequency and Concurrent Articulation Prosody by participants $F(2, 45) = .10$, $p = .90$, or by items $F(1.51, 42.38) = .542$, $p < .537$. Figure 2 shows that responses were faster in the Delayed Naming with Concurrent Articulation of monosyllables than in the other two Concurrent Articulation Prosody conditions. This was supported by significant post hoc comparisons between Monosyllables and Trochees by participants $F(1, 30) = 5.176$, $p = .03$ and by items $F(1, 28) = 86.78$, $p < .001$, and between Monosyllables and Iambs by participants $F(1, 30) = 6.94$, $p = .013$ and by items $F(1, 28) = 19.63$, $p < .001$, whereas the comparison between Trochees and

Iambs was not significant by participants $F(1, 30) = 0.02$, $p = .89$ or by items $F(1,28) = 0.80$, $p = .38$.

INSERT FIGURE 2 HERE

## Discussion

The twin aims of this experiment were to strengthen the evidence for a syllable frequency effect in English, and to demonstrate in English the sequence of effects reported by Laganaro and Alario (2006) for French that would localise the syllable frequency effect to the level of phonetic encoding in speech production. We clearly met our first aim, with higher frequency syllables produced faster than low frequency syllables in an immediate naming task. This provides the most robust evidence for syllable frequency effects in English to date, when previous results have been inconsistent and their interpretation constrained by methodological considerations. Our observed syllable frequency effect was in the order of 11ms in immediate naming. Across different languages and tasks, significant syllable frequency effects have been reported to be rather small: Dutch: 9-19ms in pseudoword/syllable symbol association tasks, Cholin et al., 2006; Levelt & Wheeldon, 1994 and pseudoword reading, Cholin & Levelt, 2009; Spanish: 8-14ms in word and pseudoword reading tasks, Carreiras & Perea, 2004; Perea & Carreiras, 1998; French: 17-46ms in immediate and delayed pseudoword and picture naming tasks, Lagnaro & Alario, 2006; English: 5-14ms in pseudoword/syllable symbol association tasks Cholin et al., 2011, and immediate naming, Monsell et al. 2002). Taken together, most of these studies consistently show RT differences for high- and low frequency syllable productions between 5-19ms; the outlier in this list is the difference of 46ms in Experiment 1 in the French study by Laganaro and Alario, 2006 using pseudo-word naming. The differences in effect sizes across these studies may be due to differing experimental designs, materials, procedures, and language inherent differences (for discussion see Cholin et al., 2011).

We used latencies to read our nonword syllables aloud as generated by the DRC model to control for orthographic effects in our syllable naming latencies. However, although the DRC latencies are conceptualised as the time taken to generate a phonological representation from an orthographic string (Coltheart et al., 2001), the DRC latencies are in fact evaluated against word and nonword naming (reading aloud) latencies as well as accuracy data, that is, against latencies that include the process of phonetic encoding in word production. By matching our high and low frequency syllable materials on DRC naming latency, we may inadvertently have made our task of finding a difference in naming latency for these materials more difficult, albeit running a more rigorous experiment.

Our second aim was to replicate in English the findings by Laganaro and Alario (2006) in their delayed syllable naming and delayed syllable naming with concurrent articulation conditions that would localise the syllable frequency effect to the phonetic encoding level of speech production. We found the first of these additional effects: the syllable frequency effect disappeared in delayed naming, consistent with the findings of Laganaro and Alario in French, Cholin and Levelt (2009) in Dutch, and Monsell et al. (2002) in English. This has previously been argued to localise the syllable frequency effect in immediate naming prior to the motor execution stage of production, indicating that retrieving "prepared" syllables from the buffer and executing them (e.g. as per the subprogram model of motor execution) is not a syllable-frequency-dependent process.

We failed, however, to replicate the third of Laganaro and Alario's effects, as we did not find the predicted syllable frequency effect in the delayed naming with concurrent articulation condition. Further, there was no indication that the syllable frequency effect was modulated by the metrical frame of the syllables produced during concurrent articulation, as there was no interaction between syllable frequency and concurrent articulation prosody. Thus, the effect was not seen in the monosyllable condition that best matched Laganaro and Alario's concurrent articulation condition, nor in the iambic or trocaic "changing state" conditions that we had introduced in attempt to increase the sensitivity of the concurrent articulation task. Instead, we found a novel main effect of concurrent articulation prosody such that both high- and low-frequency syllables were produced more quickly after a delay filled by concurrent articulation of monosyllabic phonological word syllables [ʻda] than trochaic [ʻdadə] or iambic [də'da] phonological word syllables. The situation remains, therefore, that all three of the effects that would together localise the syllable frequency effect to phonetic encoding have still not been demonstrated in English. We consider three possible accounts of this outcome below.

The first possibility is that the syllable frequency effect arises in phonological rather than phonetic encoding. We can assume the effect is post lexical, because the effect can be demonstrated for syllables that do not also exist as words in the language (and we were rigorous in excluding stimuli that were problematic in this regard). As discussed in the previous paragraph, we can also assume the effect occurs prior to motor execution. Under Laganaro and Alario's logic, however, our results do not rule out the possibility that the effect arises at a post-lexical, pre-phonetic level of phonological processing (see Goldrick, 2014, for a wide range of evidence for syllabic structure in phonological retrieval and encoding). While it is beyond the scope of this paper to discuss the range of phonological encoding mechanisms that are candidate loci for a syllable frequency effect, a possible basis for our results is that faster processing of high- than low- frequency syllables occurs prior to phonetic encoding.

The second possibility is that the syllable frequency effect does emerge in phonetic encoding, and our failure to detect the effect in delayed naming with concurrent articulation constitutes a Type II error. Syllable frequency effects previously reported in English (see above) are smaller than those reported by Laganaro and Alario (2006) for French, making them less robust against experimental noise. We have also already noted that matching our syllable frequency conditions on DRC nonword reading latencies may have removed some of the syllable-frequency-related variance in production times while controlling for orthographic factors. We were, however, careful to remove invalid latencies from our analyses as described above. We further chose a design in which each participant produced all syllables in all three conditions to reduce between-participants variance, but this choice, together with the decision to match task order across participants, meant that the concurrent articulation condition was always performed last. This raises the possibility that two prior productions of the low frequency syllables had primed their retrieval such that the high frequency advantage over low frequency syllables disappeared by the third production. Although Cholin and Levelt (2009), and Cholin, et al. (2011) found significant syllable frequency effects in Dutch and English in experiments that elicited each syllable multiple times, it remains to be seen whether counterbalancing the order of syllable naming condition in a sufficiently-powered replication of the current experiment would reveal the effect in delayed naming with concurrent articulation.

Another consideration is that the variable 1000ms or 2000ms delay in our experiment was the same as that used by Laganaro and Alario (2006), and our delayed naming results showed this delay was more than sufficient to absorb the different retrieval times for the high- versus low-frequency syllables. Our participants generally performed the concurrent articulation task as instructed, as described in many studies implementing concurrent articulation in the literature (e.g., Besner, 1987) where the concurrent articulation task is presumed to occupy the phonetic output buffer (Monsell, 1987). Participants may, however, have ceased the concurrent articulation task just sufficiently early before the signal to respond to allow them to retrieve the syllable plan from the syllabary to the buffer and therefore be ready to commence motor execution at the time of the signal. Even if this only occurred in the longer delays, where participants were better able to predict the signal to respond, this may have been sufficient to wash out the small syllable frequency effect. In this scenario, there would have been prepared articulation due to syllable program retrieval *after* concurrent articulation, and our concurrent articulation condition would not in fact have occupied the phonetic buffer. A number of these issues await clarification in future research.

A third possibility is that the syllable frequency effect does arise at the level of phonetic encoding, under a different account to that offered by Laganaro and Alario (2006). The target syllable programs may have been retrieved from the syllabary *before* the participant began concurrent articulation, then maintained in the buffer until the signal to respond. In this scenario, too, the syllables would be produced as prepared responses, rather than retrieved afresh from the syllabary, in our third naming condition. We make this suggestion on the basis of the clear effect of our concurrent articulation prosody manipulation – syllable naming faster after repeated articulation of monosyllable phonological words than bisyllabic phonological words. This can be explained by the *sub-program retrieval model* of motor execution (Monsell, 1986; Sternberg, Knoll, Monsell & Wright, 1988; Sternberg, Monsell, Knoll & Wright, 1978), as described below.

**The sub-program retrieval model of motor execution**

According to the sub-program retrieval model, speakers in a prepared production task (such as delayed naming) construct a *program* for the utterance and place it in a phonetic buffer until the signal to respond occurs (Monsell, 1986). At the signal, the first *sub-program* is retrieved, comprising the program components for the first stress group in the utterance, a spoken unit with one stressed syllable and associated unstressed syllables (Sternberg et al., 1988), equivalent to a phonological word (Levelt, 1989). The time taken to retrieve the first sub-program from the buffer depends on the number of phonological words in the utterance as a whole, which is the same as the number of subprograms in the buffer. The first sub-program is then *unpacked*, in a separate processing stage with a duration that reflects the composition of the sub-program (for example, the number of syllables in the program). Finally, completion of the unpacking stage results in a *command* that initiates motor activity in the speech articulators to produce the first phonological word. If there is a second phonological word in the utterance, this three-step cycle of retrieval, unpacking and command is repeated, and so on for any subsequent phonological words in the utterance.

In our delayed naming with concurrent articulation conditions, our assumption was that each participant would retrieve an articulatory program for the target syllable from the syllabary and place it in the phonetic buffer during the 1000ms presentation of the orthographic form of the target syllable on the screen. According to the sub-program retrieval model, when the target syllable disappeared, the participant would then construct a program for an utterance comprised of subprograms for [‘da], [‘dadə] or [də’da] phonological words, and place this in the buffer. This, we assumed, would over-write the program for the target syllable in the buffer. The participant would then retrieve the sub-program for the first phonological word in the concurrent articulation utterance from the phonetic buffer, unpack that program, and send the command to initiate motor activity, commencing concurrent articulation, repeating this cycle as many times as there were concurrent articulation sub-programs in the buffer, or until the signal to respond. On the basis of average diadochokinetic durations for young healthy speakers from a similar sample to our participants (Croot, Palethorpe, Tree, Rastle, Stephenson, Deacon, Brunsden & Bakker, 2006), we know that our participants could have produced concurrent articulation for the

1000 or 2000ms delay intervals as a single utterance, although this assumption is not critical to our account, as they could equally effectively have produced the concurrent articulation as two or more utterances, especially over the longer 2000ms delay. At the signal to respond, the articulatory program for the target syllable would then need to be retrieved again from the syllabary into the buffer, retrieved from the buffer, and unpacked to yield the command initiating motor activity. We predicted, however, that this would yield syllable frequency effects and it did not.

Syllable frequency effects in delayed naming with concurrent articulation rely on the assumption that the target (high or low frequency) syllable program is overwritten by the concurrent articulation program in the buffer. The absence of a syllable frequency effect in this condition in our experiment raises the question of whether the target syllable program was in fact overwritten in the buffer. If participants constructed concurrent articulation utterance programs that did not fully occupy the buffer, they would be able to maintain the target syllable program alongside the concurrent articulation program. The slower response latencies we observed in the two bisyllabic concurrent articulation conditions compared with the monosyllabic condition would then be expected under this account.

The relevant step in the sub-program retrieval model is the unpacking step, thought to depend on the composition of the sub-program, including the number of syllables in the program. A participant concurrently articulating monosyllabic phonological words (our [‘da, ‘da, ‘da] condition), would spend less time unpacking each sub-program on each repetition than a participant concurrently articulating bisyllabic phonological words (our trochaic [‘dadə, ‘dadə, ‘dadə], and iambic [də’da, də’da, də’da] conditions). Here we need to make the further, reasonable assumption, that participants who detect the signal to respond during the unpacking step complete that step before switching to the retrieval of the target syllable from the buffer – on at least some occasions. Participants in the bisyllabic concurrent articulation conditions would then take longer on average to switch to producing the target syllable than participants in the monosyllabic condition, which would be reflected in the overall response latencies for each concurrent articulation group. Under this account, the complete absence of any effect of syllable frequency in any of our delayed naming with concurrent articulation conditions argues for the articulatory syllable program for the target syllable *already having been delivered to the buffer*.

Our results in this condition also imply caution is needed in comparing results across prepared naming experiments with varying concurrent articulation material. Different concurrent articulation conditions have rarely been compared within the same experiment in the immediate memory literature, and there have been failures to replicate effects of varying content in the concurrent articulation task (for example, compare Larsen & Baddeley, 2003 with Macken & Jones, 2003). It is generally assumed that concurrent articulation of any irrelevant material (c.f. "1,2,3,4"; "hiya, hiya, hiya"; "besner, besner, besner", Besner, 1987, p. 468) occupies the phonetic buffer or short term phonological store (Monsell, 1987). Response latencies may, however, depend on the content of the material, specifically the phonological, metrical or phonetic factors that influence retrieval from the phonetic buffer and the unpacking stage of motor execution (Monsell, 1986; Sternberg et al., 1978, 1988). This further underscores the need to understand motor execution processes in order to interpret production latencies in tasks addressing earlier processes in speech production, as we have argued previously (Rastle et al., 2005).

The fact that delayed naming latencies varied with the metrical properties of the concurrent articulation material in our experiment may therefore also help explain why we found different results in this condition to those found by Laganaro and Alario (2006) in delayed naming with concurrent articulation. English and French metrical properties differ, the French results may not generalise to a comparable English task, and phonological and/or phonetic encoding processes may not be the same in both languages (compare O'Seaghdha, Chen & Chen, 2010, who demonstrate that phonological encoding units differ in English and Mandarin Chinese).

**How do people produce novel syllables?**

An unresolved issue in accounts of the syllabary is determining which items are of sufficiently high frequency to be represented there, and the corollary problem of how exactly speakers generate articulatory programs for items not represented in the syllabary. Levelt et al. (1999) motivated their support for the syllabary on the basis that speakers of languages such as English, Dutch or German do 80-85% of their talking with approximately 6% their language's syllable, such that storing articulatory programs for the high frequency items in a syllabary would be computationally efficient (Schiller, Meyer, Baayen, & Levelt, 1996). It was proposed that plans for other (lower frequency) syllables were computed as required using online assembly of segments (Cholin et al., 2011). In our experiment, the materials were high frequency syllables in English (Cholin et al. 2011; Croot & Rastle, 2004), compared with low frequency syllables in English from the materials of Cholin et al. and phonotactically legal syllables that do not exist in English from the materials of Croot and Rastle. These materials were not designed to allow a comparison of retrieval times for low frequency versus novel syllables, but such a comparison in future work would indicate whether the plans for low frequency syllables are indeed being assembled afresh on each production (if production latencies for low frequency and novel syllables are similar), or whether articulatory programs are stored for both high and low frequency syllables, with the higher frequency syllables more accessible (if production latencies are faster for low frequency than novel syllables) . There are accounts of how articulatory programs are learned for newly-encountered syllables (e.g. during language acquisition and second language acquisition, Callan, 2006; Guenther, 2006), but these assume multiple presentations of a target item, and a more precise account of the processing involved in computing one-off productions of rarely- or not-previously-used items is still required.

**Concluding Remarks**

The current experiment found robust syllable frequency effects in immediate naming of non-lexical syllables in English, which were not evident in delayed naming of the same syllables, with or without concurrent articulation. Under the logic of Laganaro and Alario (2006), our results do not rule out a locus for syllable frequency effects during phonological encoding. Alternatively, our failure to detect a syllable frequency effect in delayed naming with concurrent articulation may constitute a Type II error. Because we manipulated the metrical frame used in the concurrent articulation condition, we were also able to demonstrate the novel finding that delayed naming with concurrent articulation of monosyllables (‘da) was faster than with concurrent articulation of bisyllables (‘dadə , də’da). A principled account of this finding based on the subprogram retrieval model of motor execution allows that the target syllable programs produced under concurrent articulation conditions were stored in the phonetic buffer while concurrent articulation was carried out, then produced as prepared responses when required. This account is consistent with the claim that articulatory programs for high frequency syllables are retrieved from a mental syllabary during phonetic encoding processes in English speech production. Finally, the theoretical consideration of how the sequence of syllable retrieval (as described by Levelt-type accounts), buffering, and motor execution processes (as per the subprogram retrieval model) might be investigated on the basis of latency data across our syllable naming and concurrent articulation prosody conditions is an important contribution of this study. Since few studies of word production investigate factors (syllable frequency, prosodic structure) potentially influencing processing in the Levelt-type and the subprogram retrieval accounts, we hope this integrated theoretical account may advance our understanding of the later stages of word production.

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**FIGURE CAPTIONS**

Figure 1. Mean response latencies for high frequency versus low frequency/novel syllables in the three syllable naming conditions. Bars indicate standard errors.

Figure 2. Mean response latencies for high frequency versus low frequency/novel syllables produced in the three prosodic conditions in Delayed Naming with Concurrent Articulation. Bars indicate standard errors.

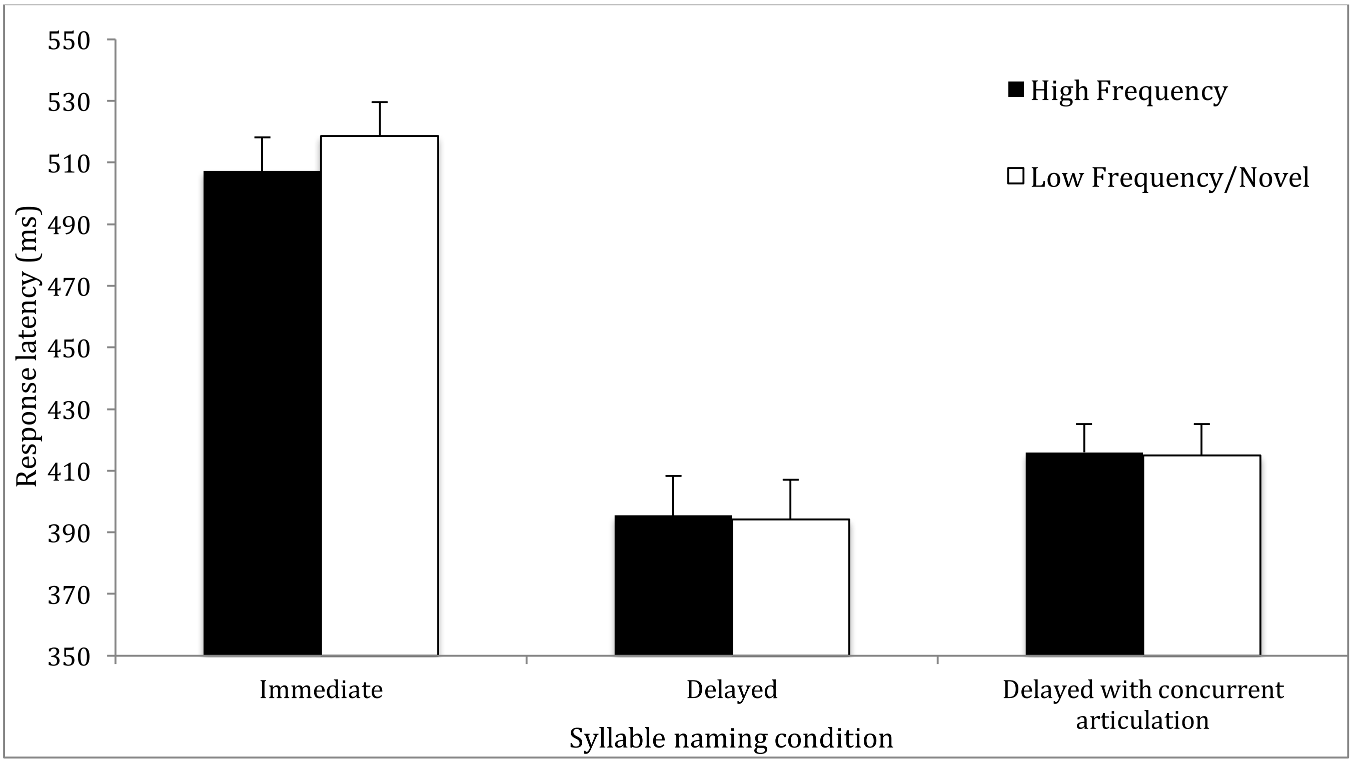
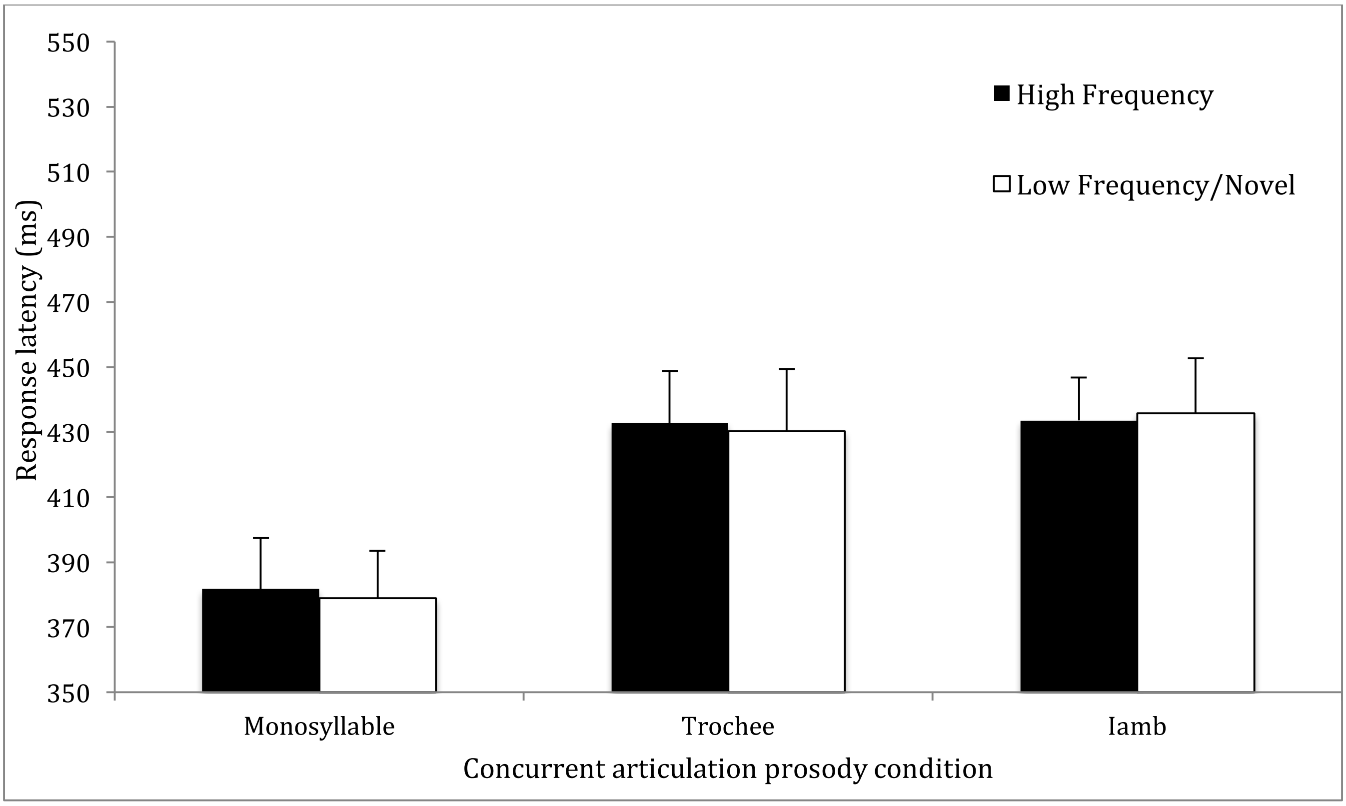

550
530
510
490
470
450
430
410
390
370
350
Response latency (ms)
High Frequency
Low Frequency/Novel
Immediate
Delayed
Delayed with concurrent articulation
Syllable naming condition

Figure 1.


550
530
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410
390
370
350
Response latency (ms)
High Frequency
Low Frequency/Novel
Monosyllable
Trochee
Iamb
Concurrent articulation prosody condition

Figure 2.