Exploring Universal Phonological Preferences: Beyond Articulation

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Abstract of Dissertation

Across languages, certain syllable types (e.g., *black*) are systematically preferred to others (e.g., *lback*). Specifically, syllables like *blif* are preferred to *bnif*, which, in turn, are preferred to *bdif*; least preferred are syllables like *lbif*. Such preferences have been documented experimentally among speakers of English, Korean, Spanish, French, Hebrew, Mandarin, even when none of these syllable types exists in their language. Previous research demonstrated that these preferences are unlikely due to the auditory/phonetic demands of auditory materials, as they obtain even when items are presented in print. However, it remains possible that they might be informed by articulatory demands.

According to the *motor embodiment* view, the perception of a linguistic stimulus entails the motor simulation of its production. The dispreference for items such as *lbif* could thus reflect the demands associated with their production—the harder a syllable is to articulate, even potentially, the more motor demands it requires, thus the less preferred it is. To address this possibility, we assessed participants’ syllable preferences while their articulation was mechanically suppressed. To the extent that suppression effects were found, we next examined whether suppression attenuates participants’ sensitivity to the syllable hierarchy (*blif>**bnif>*bdif>*lbif*). According to the *grammatical* account, a grammatical ban on clusters like *lb* will prevent speakers from encoding them correctly. As a result, ill-formed monosyllables such as *lbif* will be repaired as better-formed structures (e.g., as *lebif*)—the worse-formed the cluster, the more likely its repair, hence, its misidentification as a disyllable (e.g., *lebif*). Crucially, this account predicts that these
effects should be obtained irrespective of suppression. In contrast, if the syllable preference is due to articulatory simulation (as suggested by the motor embodiment account), then articulatory suppression should attenuate or even eliminate people’s sensitivity to the syllable hierarchy.

Our four experiments each found significant effects of suppression. Remarkably, people remained sensitive to the syllable hierarchy regardless of suppression. Specifically, the results from auditory materials (Experiments 1-2) yielded strong effects of syllable structure, and these effects obtained irrespective of suppression—the worse-formed the syllable, the more likely its misidentification. Moreover, syllable structure uniquely accounted for listeners’ behavior even when some of the phonetic cues of our auditory materials were controlled for. Results with printed stimuli (Experiments 3-4) were more complex, as participants in these experiments appeared to verify their perception by a spelling strategy. Nonetheless, readers were sensitive to most of the syllable hierarchy (e.g., blif-bnif-bdif). Furthermore, these preferences emerged even under articulatory suppression, and they were found even when the statistical properties of our materials were controlled via a regression analysis.

Together, these findings indicate that speakers possess broad grammatical preferences that are irreducible to either sensory or motor factors.
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Chapter 1. Introduction

Different languages of the world vary in many ways, but they nonetheless tend to converge on certain aspects of their design. Consider, for example, the regularities concerning the structure of onset clusters (i.e., initial consonant sequence of a syllable, e.g., \textit{black}). Across languages, onsets like \textit{bl} are more preferred than \textit{lb} (i.e., $\textit{blif} \succ \textit{lbif}$, “$\succ$” indicates preference; Berent, Steriade, Lennertz, & Vaknin, 2007). Moreover, if the less favored \textit{lb} onset is tolerated, it is likely that the more preferred structure \textit{bl} is legal in this language (e.g., Russian; Greenberg, 1978). Such observations indicate that speakers of different languages might share common restrictions on language structure.

The nature of these constraints, however, remains unclear. One explanation attributes these regularities to the language system, more specifically, to the grammar—a set of abstract linguistic principles. One theory of the grammar—Optimality Theory—asserts that all grammars share linguistic constraints on onset structure. According to this theory, such constraints are active in all speakers, irrespective of whether these onsets are present (i.e., attested) or absent (i.e., unattested) in their language (e.g., Prince & Smolensky, 1993/2004). Structures that abide by these constraints (e.g., \textit{blif}) are well-formed, hence, they are preferred to those that violate them (e.g., \textit{lbif}).

The above-mentioned preference for \textit{blif} over \textit{lbif} is captured by sonority (s)—an abstract phonological property of segments that correlates with acoustic intensity (Clements, 2005; Parker, 2008). Least sonorous are stops (e.g., \textit{b,p}, s=1), followed by fricatives (e.g., \textit{f,v}, s=2), nasals (e.g., \textit{m,n}, s=3), liquids (e.g., \textit{l,r}, s=4), and glides (e.g., \textit{w,y}, s=5).
Accordingly, onsets such as $bl$ exhibit a large rise in sonority ($\Delta s=s(l)–s(b)=3$), $bn$ manifests a small rise ($\Delta s=2$), $bd$ levels in sonority ($\Delta s=0$) and $lb$ falls in sonority ($\Delta s=-3$).

These sonority profiles could then provide a grammatical explanation for cross-linguistic preferences (e.g., $blif > lbif$). According to this account, the well-formedness of the onset is determined by the grammatical phonological constraints on sonority distance—the smaller the sonority distance, the worse-formed the onset. Consequently, onsets with large sonority rises are preferred to small rises, which, in turn, are favored to plateaus; least preferred are onsets falling in sonority (e.g., $bl>bn>bd>lb$). But on an alternative nongrammatical explanation, the onset hierarchy emanates only from more general sources—either shared lexical experience (i.e., a lexical account) and/or general auditory and articulatory demands associated with processing the stimuli (Blevins, 2004; Bybee, 2008; Evans & Levinson, 2009).

To adjudicate between the grammatical account and the role of shared lexical experience, previous studies investigated people’s sensitivity to onset clusters that are unattested in their language. Of interest is whether people are sensitive to the grammatical structure of the onset even when relevant statistical lexical information is minimal or absent altogether. The grammatical account predicts that the sonority restrictions on onset structure are active universally, even in languages that lack onset clusters entirely. If these grammatical constraints ban small sonority distances in the onset position, then such ill-formed syllables (e.g., $bnif$, $bdif$, $lbif$) will not be encoded faithfully by the grammar. Instead, these ill-formed syllables will be repaired, and consequently, systematically misidentified as better-formed structures (e.g., by inserting a schwa in between the consonants of the onset cluster, $lbif \rightarrow lebif$, etc.). As a result, speakers
should be more likely to misidentify ill-formed syllables (e.g., *lbif*) compared to well-formed ones (e.g., *blif*)—the worse formed a syllable, the more likely its misidentification. Misidentification, then, would suggest that onsets with small sonority distances are systematically dispreferred.

Consistent with the *grammatical* explanation, past results showed that speakers of different languages are sensitive to onset structures they have never heard before (e.g., English: Berent et al., 2007; Spanish: Berent, Lennertz, & Rosselli, 2012b; French: Maïonchi-Pino, de Cara, Ecalle, & Magnan, 2012; Hebrew: Berent et al., 2013), and even when their language does not allow any onset clusters at all (e.g., Korean: Berent, Lennertz, Jun, Moreno, & Smolensky, 2008; Mandarin Chinese: Zhao & Berent, 2015).

Indeed, misidentification of unattested onsets is monotonically related to their sonority distance—the smaller the distance, the more likely its misidentification. More specifically, participants were more prone to misidentify syllables with ill-formed onsets (e.g., *lbif* $\rightarrow$ *lebif*) despite having very limited experience with these onsets. Therefore, such findings are inexplicable by the lexical account.

Additional results suggest that onset preference is not solely due to auditory/phonetic failures to encode the acoustic input either (Berent et al., 2007; Berent, Lennertz, & Balaban, 2012a). Indeed, the misidentification of ill-formed structures has been found even when the materials were presented visually (Berent, 2008; Berent, Lennertz, Smolensky, & Vaknin-Nusbaum, 2009; Berent & Lennertz, 2010; Tamási & Berent, 2014). All these results show that people converge on onset preference despite minimal linguistic experience with these onsets, and irrespective of the input modality of these
stimuli (i.e., auditory or visual). This convergence suggests the possibility that people share universal grammatical constraints on language structure.

However, it is still possible that the onset preference might be informed by articulatory demands. On this account, the harder an onset is to articulate, the less preferred it is. And if onsets with small sonority distances are universally harder to articulate, then the onset hierarchy could be due to their articulatory demands alone. More generally, according to the motor embodiment account\(^1\), speech perception requires listeners to simulate its production by means of sub-vocal articulation (e.g., Lakoff & Johnson, 1999; MacNeilage, 2008). In other words, speech perception is embodied in the motor speech production system. Accordingly, people’s sensitivity to onset structure reflects not universal linguistic bans, but rather their shared general articulatory/motor restrictions on speech production.

Indeed, articulatory actions have been shown to contribute to speech perception. Sato and colleagues (2011) reported that articulator-specific motor training could bias towards the categorization of speech sounds. During the motor training phase, one group of participants was instructed to either raise their tongue repeatedly with the mouth closed (tongue motor training), or protrude the lips (lip motor training). Another control group did not undergo such training. Both groups were then presented with speech syllables and were asked to indicate whether the syllable they heard was /pa/ or /ta/, either with or without background white noise. Regardless of background noise, participants in the

\(^1\) We are only testing a strong version of the embodied motor theory of speech perception. According to this view, it is the actual articulatory actions that mediate speech perception (e.g., Schwartz, Abry, Boé, & Cathiard, 2002). Other motor theories do exist (e.g., Motor Theory by Liberman and Mattingly (1985) and the Direct Realist Theory (Fowler, 1986)), but these theories claim at least some abstraction of the motor gestures (for reviews, see Diehl, Lotto, & Holt, 2004; Galantucci, Fowler, & Turvey, 2006; Samuel, 2011; Schwartz et al., 2002).
tongue motor training condition were more biased towards a syllable produced by the tongue (i.e. /ta/) relative to that produced by the lips (i.e., /pa/) than the control group. The opposite pattern was observed among those who went through lip motor training—

their bias towards /pa/ was pronounced (i.e., less likely to identify a syllable as /ta/), relative to the controls. These findings indicated that articulatory motor processes might affect responses to auditory speech sounds.

Further support for the embodiment account has come from neurophysiological studies. Using fMRI, Pulvermüller & Fadiga (2010) have shown that articulation and auditory perception of speech are interdependent. More precisely, participants’ articulator-specific motor representations were selectively engaged during passive listening to speech sounds compared to nonspeech noise. Pulvermüller et al. (2006) found that listening to labial sounds (e.g., /p/) triggered activation in lip motor sites (left precentral gyrus, as well as the corresponding muscle activity). Similarly, Fadiga, Craighero, Buccino, & Rizzolatti (2002) showed that passive listening to coronal sounds (e.g., /t/) engaged the tongue-related motor centers and induced motor-evoked potentials in the tongue muscle.

Further neurophysiological evidence has shown that the articulatory motor system contributes to speech perception by using transcranial magnetic stimulation (TMS) methodology. TMS is a noninvasive method that temporarily disrupts or induces activity of targeted brain regions by sending electromagnetic pulses from a stimulating coil to cortical surface (O’Shea & Walsh, 2007). In their study, Meister and colleagues (2007) first localized two cortical regions—the left premotor cortical region (PMC) and the left superior temporal gyrus (STG)—that were activated both during participants’ speech production and perception. They then used TMS to temporarily disrupt participants’ PMC
and STG during the performance of phonetic discrimination in an auditory task and color discrimination in a matched visual task. Results showed that TMS disruption of these two regions impaired participants’ ability to correctly identify consonant-vowel syllables (as /pa/, /ta/ or /ka/) in the auditory task, but not their ability to distinguish between different colors in the matched visual task (Meister, Wilson, Deblieck, Wu, & Iacoboni, 2007). In another study, selective impairment was found in speech sounds discrimination when corresponding articulatory motor sites were disrupted by TMS—TMS disruption of the lip representation in the motor area impaired categorization of labial sounds like /p/, relative to coronal sounds like /t/ (Möttönen & Watkins, 2009). Likewise, disruption of the laryngeal motor representation (a region that controls the laryngeal functions, which are essential in determining vocal pitch), elicited significantly slower discrimination of small vocal pitch shifts (F0-shifted vocal utterance /a/), compared to disruption of the tongue and lip motor region (D’Ausilio, Bufalari, Salmas, Busan, & Fadiga, 2011).

The findings reported so far showed that when imposing disruptive electromagnetic pulses\(^2\) to the articulator-specific motor representations, the perception of corresponding speech sounds were impaired. Additional results suggest facilitative TMS stimulation can improve speech perception. For example, stimulating the tongue motor region improved accuracy in the perception of concordant phonemes (e.g., /t/ and /d/) but inhibited that of discordant phonemes (e.g., /p/ and /b/) (D’Ausilio et al., 2009; D’Ausilio, Bufalari, Salmas, & Fadiga, 2012). These results suggest that activation in the articulatory motor network might be critical to speech perception.

\(^2\) The effect of TMS stimulation can be either inhibitory or excitatory, depending on parameters such as the frequency of stimulation, number and duration of the pulses, and time between each pulses (O’Shea & Walsh, 2007).
While these studies suggest the essential role of articulatory motor actions in *phonetic* categorization (e.g., /p/ vs. /t/), they do not speak to whether the motor system is linked to the *phonological* patterning of these sounds into syllables (e.g., /p/+l/+a/ vs. /l/+p/+a/).

Additional questions concern the precise nature of such link. Even if the motor system had been shown to contribute to phonological patterning, it is still unclear whether this link is causal—of interest is whether phonological computations require articulatory simulations (Berent et al., 2015).

A recent TMS study (Berent et al., 2015) addressed these questions. In this study, the researchers examined whether the universally observed onset hierarchy (i.e., \( bl > bn > bd > lb \)) reflects grammatical well-formedness or articulatory demands. To achieve this, they measured English speakers’ sensitivity to syllables with unattested onsets in a syllable-count task. During task performance, participants’ motor representation of the lip muscles (OO, i.e., left orbicularis oris) was disrupted by TMS pulses. Sensitivity to unattested syllable structure under TMS was compared to the Sham condition (no TMS stimulation). According to the *embodiment* account, the worst-formed onsets like \( lb \) should impose the greatest articulatory demands. Consequently, identification of \( lb \)-type onsets should be impaired the most by TMS, and speakers’ sensitivity to the onset hierarchy should be attenuated.

Results showed otherwise. TMS did not impair the perception of ill-formed onsets (e.g., \( lb \)). Instead, only identification of the best-formed onsets was impaired (e.g., \( bl \) and \( bn \)). Critically, participants remained sensitive to the onset hierarchy (i.e., \( bl > bn > bd > lb \)) even when OO was disrupted by TMS. Further contradicting the *embodiment* account, results from subsequent fMRI experiments (Experiment 3, Berent et al., 2015; see also Berent et
al., 2014) showed that the processing of *lb*-type onsets disengaged, rather than engaged the sensorimotor lip regions. Moreover, the traditional language region—Broca’s area was found automatically activated when ill-formed structures were presented (Berent et al., 2014). Together, these findings challenge the causal role of articulatory system in the computations of sound structures.

The TMS results, however, have several limitations (Berent et al, 2015). One of the limitations concerns the magnitude of disruption. Since TMS pulses could only reach the surface cortical regions\(^\text{3}\) (Bolognini and Ro, 2010), it is possible that motor simulation in the lip area (including those generated in subcortical regions) was not blocked entirely. In addition, TMS typically targets only a single articulator at a time—either the lip (e.g., Pulvermüller et al., 2006) or the tongue (e.g., Fadiga et al., 2002). Therefore, suppression is incomplete. Another limitation is that these electromagnetic pulses can also affect connected regions adjacent to the target site (O’Shea & Walsh, 2007). This could compromise the selectivity of TMS. For example, selective impairment in identifying labial sounds like /p/ might be due to TMS disruption of both the lip region and its adjacent regions, rather than disruption of the lip motor representation alone. As a result, other motor-irrelevant functions might also be disrupted, including ones that are language related. Therefore, it is difficult to gauge the role of the motor system in speech perception from these findings.

\(^{3}\) This could be resolved by increasing the intensity of the TMS stimulation, however, higher intensity may not be tolerated by participants.
To overcome these limitations, the current study utilizes a mechanical method of articulatory suppression. Mechanical methods interfere with articulatory suppression in one of the two ways: dynamic or static suppression.

In the dynamic suppression paradigm, articulation is disrupted by irrelevant vocalization. Usually, participants are instructed to repeatedly produce out aloud some irrelevant sounds (hereafter, interfering sounds) concurrently with the presentation of a target stimulus (either visually or aurally). For example, in Saito (1998), participants were required to continuously whistle while performing a serial recall on letter sequences. In another study, participants repeated digits 1,2,3,4 overtly during a spoken word recall task (Experiment 1, Baddeley, Lewis and Vallar, 1984). This type of suppression has been widely utilized in research on phonological working memory (e.g., Baddeley et al., 1984) as well as in studies concerning phonology assembly in reading (e.g., McCutchen & Perfetti, 1982; Paap & Noel, 1991).

Despite its prevalence, the effectiveness of dynamic suppression is unclear. First, it is difficult to ensure that the suppression is enforced consistently and continuously. Any pauses in the concurrent articulation would result in ineffective interference, and such pauses cannot be readily detected or controlled by the experimenter. In addition, it is difficult to ensure that the degree of suppression is equated for the different types of target stimuli (e.g., ta vs. pa). Finally, dynamic suppression is incomplete, as it typically affects only one articulator at a time (e.g., lip vs. tongue).

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4 Target-specific interfering sounds could be used to overcome this, for example, instructing participants to articulate /ba/ when blif is presented but to vocalize /la/ when they hear bif. However, because the instructions are target-specific, such instruction might prepare, instead of suppress, the articulators to
In light of these limitations, here, we employ a static method of articulatory suppression. This type of suppression could be used to disrupt articulation in various ways. The conventional way is to insert a bite block inside the participant’s mouth during task performance (e.g., Baum, McFarland, & Diab, 1996). However, a bite block only suppresses tongue movements—it does not fully disrupt the lips. Therefore, suppression is incomplete.

In order to suppress articulation by both the lips and the tongue, the current research utilizes a relatively novel manipulation with two tongue depressors. During the task, participants were instructed to accommodate two tongue depressors in their mouth, one above and another below the tongue and then close their mouth—this should have suppressed all tongue movements. In addition, they were asked to point the two tongue depressors at the same direction; doing so requires the use of both lips, and so prevents lip movements. This manipulation overcame the problems induced by dynamic suppression. First, it targeted two articulators—the tongue and the lips - simultaneously. Moreover, the effect of suppression was stable throughout the entire course of task performance, irrespective of the phonemic content of target stimuli.

According to the motor embodiment account, suppressing speech-motor articulators should impair speech processing. In line with this prediction, previous research has demonstrated that the perception of linguistic stimuli is modulated by articulatory actions. For example, when holding a pen sideways in their teeth, engaging the muscles that control a partial smile, participants read pleasant sentences significantly faster than

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simulate the target stimulus. In this case, the dynamic suppression might facilitate the articulatory motor actions.
unpleasant ones. In contrast, when holding a pen between their nose and upper lip, engaging muscles that control a frown, the reverse pattern was found (Glenberg, Havas, Becker, & Rinck, 2005). Another more recent study provides additional evidence for this static suppression method (Bruderer, Danielson, Kandhadai, & Werker, 2015). Bruderer and colleagues investigated the capacity of 6-month olds to discriminate two non-native sounds that contrast on the placement of the tongue tip. Results showed that, when the relevant articulator (i.e., tongue) was selectively suppressed (by a teething toy that blocked the tongue’s movement), infants were no longer able to discriminate these two sounds. These results suggest this new suppression manipulation could be effective. Accordingly, the following experiments opt for a static method of articulatory suppression.

This dissertation examines the relationship between phonological computation and speech simulation. Specifically, we ask whether the onset hierarchy (i.e., $bl > bn > bd > lb$) is due to grammatical principles or articulatory demands. To address this question, we examine whether people’s sensitivity to the syllable hierarchy is maintained when their articulatory actions are suppressed mechanically.

This research addresses two questions. First, we investigate whether there is an effect of articulatory suppression, more precisely, whether suppression affects participant’s overall ability to differentiate monosyllables from their disyllabic counterparts. Insofar as suppression effects are found, we next ask whether participants respect the full onset hierarchy ($bl > bn > bd > lb$) despite articulatory suppression. Of interest is whether suppression will attenuate, or even eliminate, participants’ sensitivity to the onset hierarchy.
If the onset hierarchy is due to grammatical constraints, as predicted by the grammatical account, participants’ sensitivity to the onset hierarchy should obtain regardless of whether they are able to articulate the stimuli. According to this account, the smaller the sonority distance, the less favored the onset structure, hence, the more likely it is to be repaired and misidentified. So \( lb \) should be the most likely to be misidentified, followed by \( bd \) and \( bn \), with \( bl \) the least likely to be misidentified overall (e.g., \( bl > bn > bd > lb \)).

By contrast, the motor embodiment account predicts that speakers’ sensitivity to onset structure depends on articulatory simulations—the harder the simulation, the more likely its misidentification (e.g., \( lbif \) is more likely to be misidentified compared to \( blif \)), hence the worse the performance. Accordingly, articulatory suppression should attenuate speakers’ overall sensitivity to onset structure. In addition, the harder an onset is to articulate, the higher its articulatory demands, thus the more susceptible it is to suppression. Since suppression alleviates the articulatory demands associated with ill-formed onsets, it should potentially improve their identification. As a result, articulatory suppression should attenuate participants’ overall sensitivity to the onset hierarchy.

To adjudicate between these possibilities, four experiments were conducted: Experiment 1 used a syllable count task, and Experiment 2 used an identity discrimination paradigm (e.g., is “blif” identical to “belif”? ) with auditory materials. To address the possibility that the findings with auditory materials only reflect auditory/phonetic factors, Experiments 3-4 extend our investigation to printed materials, either with the absence or presence of background visual noise, respectively.
Chapter 2. Experimental examinations

2.1 Experiment 1: Syllable count

Experiment 1 examined the effect of articulatory suppression in the syllable count task.

On each trial, participants heard a single nonword stimulus (either monosyllabic or disyllabic) and they were instructed to indicate whether this item had one syllable or two.

Our investigation proceeded in two steps. First, we examined whether syllable count is disrupted by suppression. Inasmuch as such effect is found, we can next ask whether suppression attenuates speakers’ sensitivity to onset structure.

In this and all subsequent experiments, each participant completed two experimental blocks. Half of the participants received the control condition (no articulatory suppression) in the first block, followed by articulatory suppression in the second block (they completed Experiment List 1); and the other half were assigned to the reversed order of conditions (i.e., List 2; see Table 1). Accordingly, the list factor forms part of our analyses.

*Table 1. General procedure of suppression manipulation in Experiments 1-4. All participants completed two experimental blocks; half followed the order specified in list 1 and the other half followed list 2.*

<table>
<thead>
<tr>
<th>Experimental block</th>
<th>List 1</th>
<th>List 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>First block</td>
<td>Second block</td>
</tr>
<tr>
<td></td>
<td>Control (No suppression)</td>
<td>Suppression</td>
</tr>
<tr>
<td></td>
<td>Suppression</td>
<td>Control (No suppression)</td>
</tr>
</tbody>
</table>
2.1.1 Method

Participants. Forty native English speakers, students of Northeastern University, took part in this experiment. In this and all subsequent experiments, each of the participants received course credit for their participation.

Materials. The materials consisted of pairs of monosyllabic nonwords and their matched disyllabic counterparts described in Berent et al. (2007). Briefly, monosyllables were arranged in quartets whose onsets exhibited either large sonority rises, small rises, plateaus or falls in sonority (e.g., blif, bnif, bdif, lbif, respectively, see Appendix A). Disyllables differed from monosyllables by a schwa (e.g., belif, benif, bedif, lebif). The materials included a total of 240 items (2 syllable: monosyllable/disyllable x 4 onset type: large rise/small rise/plateau/fall x 30 quartets), divided into two halves, matched for the number of onset type x syllable combination. These two halves were treated as two experimental sublists, and each such list was presented in a separate experimental block (with order counter-balanced), such that each participant completed all 240 trials (with 120 trials per block). All items were recorded by a native Russian speaker (Russian allows all these onset types, so these items can be all produced naturally by Russian speakers).

Procedure. In this and all subsequent experiments, participants were randomly assigned to one of two experimental lists that contained the order of the suppression condition (control-suppression vs. suppression-control, for lists 1 and 2, respectively). In the suppression condition, participants were instructed to safely accommodate two tongue depressors in their mouth—one above and the other beneath their tongue, pointing at the
same direction. In the control condition, participants performed the task normally, without tongue depressors. Trial order was randomized.

In all four experiments, participants were first familiarized with the task in a practice session with existing English words (e.g., sport, support), which preceded the experimental session. Slow responses (response time over 2500ms) triggered a computerized warning message (“Too Slow!”).

On each trial, participants were presented aurally with one nonword, and were asked to quickly indicate whether the stimulus they heard had one or two syllables by pressing the corresponding computer key (1=one-syllable; 2=two-syllable).

2.1.2 Results

d-prime analyses.

The effect of suppression on sensitivity (d’) was examined using 2 suppression (suppression/control) x 4 onset type (large rise/small rise/plateau/fall) x 2 list (control-suppression /suppression - control) ANOVAs, conducted using participants (F1) and items (F2) as random variables. The 3-way suppression x onset type x list interaction was marginally significant ($F1(3,114)=2.35, p=0.076; F2(3,174)=2.34, p=0.075$). This suggests that suppression modulated the various onset types differently, depending on the block order of the suppression manipulation in the experiment (block order is captured by experimental list, see Table 1 for details).

To further examine the effect of suppression, we next compared the suppression and control conditions in the first and second blocks of trials separately.
First, we evaluated whether there was an effect of suppression in each block. Figure 1 plots participants’ sensitivity to the different types of onsets in the first (Figure 1A) and second blocks (Figure 1B). An inspection of the means suggests that suppression affected participants’ sensitivity to onset structure only in the second block.

The 2 suppression x 4 onset type ANOVAs in the first block did not yield a significant interaction (both \(p>0.13\)), nor a significant main effect of suppression (both \(p>0.14\)). By contrast, in the second block, the suppression x onset type interaction was significant \((F1(3,114)=3.53, p<0.018; F2(3,174)=4.23, p<0.007)\). To interpret this effect of suppression, we next compared responses to the suppression and control conditions for each of the four types of onsets presented in the second block. Planned comparisons revealed that articulatory suppression *impaired* participants’ responses to onsets of level sonority (e.g., *bdif*; \(t1(20)=1.77, p=0.079\); \(t2(30)=2.11, p<0.036\)). In contrast, for onsets with large rises (e.g., *blif*), suppression tended to *improve* performance, and this effect was marginally significant \((t2(30)=2.12, p<0.04\); albeit not by participant, \(t1(20)=1.31, p=0.19\)). For the remaining two types of onsets (e.g., *bnif, lbif*), the effect of suppression was not significant (all \(p>0.13\)).

We next investigated whether the effect of onset type was maintained irrespective of articulatory suppression. An inspection of the means indicates that as the onset became worse formed, performance decreased, and this trend obtained regardless of whether suppression was present or absent (Figure 1).
The results of the statistical analyses were in line with this conclusion. Under the control condition, the simple main effect of onset type was found significant in both the first (F1(3, 57)=112.02, p<0.001; F2(3, 87)=48.67, p<0.001) and second block (F1(3, 57)=45.89, p<0.001; F2(3, 87)=37.85, p<0.001). Planned comparisons revealed that onsets with large rises (e.g., blif) elicited better performance than small rises (e.g., bnif) in both blocks (first block: t1(57)=8.52, p<0.001; t2(87)=5.43, p<0.001; second block: t1(57)=5.14, p<0.001; t2(87)=5.11, p<0.001). Small rises, in turn, produced better sensitivity than plateaus (e.g., bdif; first block: t1(57)=6.57, p<0.001; t2(87)=4.61, p<0.001; second block: t1(57)=4.65, p<0.001; t2(87)=3.75, p<0.001). Identification of sonority plateaus and falling onsets (e.g., bdif vs. lbif) did not differ significantly (first block: t1(57)=1.23, p=0.22; t2(87)=0.59, p=0.55; second block: t1(57)=0.45, p=0.65; t2(87)=0.57, p=0.57). Thus, as sonority distance decreased, participants in the control condition became less sensitive to the onset structure (i.e., blif>bnif>{bdif,lbif}).
Crucially, the effect of onset type remained significant even when articulation was suppressed. Specifically, the simple main effect of onset type was significant in both the first ($F_1(3,57)=39.19, p<0.001$; $F_2(3,87)=40.01, p<0.001$) and second block ($F_1(3,57)=146.87, p<0.001$; $F_2(3,87)=66.74, p<0.001$). Planned comparisons showed that as sonority distance decreased, so did participants’ sensitivity. Specifically, identification of onsets with large rises (e.g., $blif$) was reliably better than that of small rises (e.g., $bnif$) (first block: $t_1(57)=4.47, p<0.001$; $t_2(87)=4.85, p<0.001$; second block: $t_1(57)=8.66, p<0.001$; $t_2(87)=5.92, p<0.001$). Small rises, in turn, elicited better performance than plateaus (e.g., $bdif$) (first block: $t_1(57)=3.33, p<0.002$; $t_2(87)=2.70, p<0.009$; second block: $t_1(57)=9.16, p<0.001$; $t_2(87)=6.17, p<0.001$). Finally, the worst-formed onsets of falling sonority (e.g., $lbif$) produced even worse sensitivity compared to onsets with level sonority (e.g., $bdif$) in the first block of trials ($t_1(57)=2.43, p<0.02$; $t_2(87)=2.98, p<0.005$), albeit not in the second block ($t_1(57)=0.04, p=0.96$; $t_2(87)=0.10, p=0.93$). Thus, regardless of suppression, the effect of sonority distance emerged—as the onset became worse-formed, sensitivity decreased (i.e., $blif>bnif>bdif>lbif$).

**Response time analyses.**

In this and all subsequent experiments, correct responses that fall 2.5 SD above the mean and faster than 200ms were excluded from the analyses.

A 2 suppression x 2 syllable x 4 onset type x 2 list ANOVA on correct response time (RT, see Table 2 for means) yielded a significant suppression x list interaction ($F_1(1,8)=5.57, p<0.05$; $F_2(1,22)=28.59, p<0.0001$). Post hoc tests (Tukey HSD) showed that in the first
block, suppression produced slower responses relative to the control condition; whereas in the second block, the effect of suppression reversed—participants responded faster under the suppression condition. These effects, however, were significant only by items (both \( p<0.02 \); by participants, both \( p>0.8 \)). The effect of suppression was also marginally modulated by the number of syllables, but this effect was significant only across participants \((F_{1}(1,8)=5.78, p<0.05)\); albeit not significant by item, \( F_{2}<1 \) and onset type \((F_{1}(3,24)=3.33, p<0.04)\); but not significant by item, \( F_{2}<1 \). All other effects involving suppression, either main effect (both \( p>0.16 \)) or interactions with suppression were not significant (all \( p>0.16 \)).

The 2 suppression x 2 syllable x 4 onset type x 2 list ANOVA also revealed a significant syllable x \textbf{onset type} interaction \((F_{1}(3,24)=4.65, p<0.02); F_{2}(3,66)=5.27, p<0.003\).

Planned comparisons showed that participants were reliably faster to identify \textit{blif}-type syllables than all other types of monosyllables (e.g., \textit{bnif}, \textit{bdif}, \textit{lbif}, \textit{all} \( p<0.005 \)). Likewise, \textit{blif}-type monosyllables elicited faster responses relative to their disyllabic counterparts (e.g., \textit{belif}, \textit{both} \( p<0.008 \)). However, this effect was not further modulated by suppression (for the suppression x syllable x onset type interaction, both \( p>0.16 \)), or list (for syllable x onset type x list interaction, \( F_{1}(3,24)=2.91, p=0.06; F_{2}<1, \text{n.s.} \)). The effect of onset type on RT across suppression conditions is provided in Figure 2.
Table 2. Mean response accuracy (ACC, proportion correct) and correct response time (RT) in Experiment 1.

<table>
<thead>
<tr>
<th></th>
<th>Monosyllabic items</th>
<th>Disyllabic items</th>
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<td></td>
<td>Large rise</td>
<td>Small rise</td>
<td>Plateau</td>
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<tr>
<td>ACC</td>
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<tr>
<td></td>
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<tr>
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<tr>
<td></td>
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Table 2: Mean response accuracy (ACC, proportion correct) and correct response time (RT) in Experiment 1.
Figure 2. The effect of onset type on correct response time (RT) across suppression conditions in Experiment 1. Note: error bars indicate 95% confidence intervals for the difference between the means.

2.1.3 Discussion

In Experiment 1, we asked two questions: 1) does articulatory suppression affect syllable identification; and 2) how does suppression alter participants’ sensitivity to the onset hierarchy. According to the grammatical account, participants’ sensitivity to onset structure should be spared under suppression. In contrast, the motor embodiment account predicts that suppression should attenuate the syllable hierarchy by potentially improving participants’ identification of ill-formed onsets.

Consistent with the motor embodiment hypothesis, results from this experiment suggest that articulatory suppression indeed affected participants’ sensitivity to syllable structure. The direction of this effect, however, stands in stark contrast to the motor embodiment hypothesis—suppression impaired, rather than improved, identification of ill-formed syllables (e.g., bdif). Moreover, this effect of suppression emerged only in the second
block of the experiment. Crucially, articulatory suppression did not attenuate speakers’
sensitivity to the onset hierarchy. Rather, when suppression was administered, well-
formed *blif*-type syllables still produced substantially better performance relative to the
worst-formed syllables like *lbif*. In fact, the overall effect of well-formedness, as
measured by the differential responses to the best- compared to the worst-formed onsets
(i.e., *blif-lbif*) was numerically *larger* in the suppression condition (\(\Delta d' = d'(blif) - d'(lbif) = 2.85 - 0.16 = 2.69\)) compared to the control condition (\(\Delta d' = 2.54 - 0.49 = 2.05\)). These
findings counter the *motor embodiment* account.

We next consider several alternative explanations for our findings. One possibility is that
the decrease of performance in the second block originates from non-articulatory reasons,
such as fatigue. According to this explanation, participants might gradually become tired,
resulting in performance decline in the second block of trials. Another non-articulatory
explanation could be that our suppression manipulation caused distraction—holding two
tongue depressors in the mouth might have distracted participants’ attention, hence,
impairing their performance.

These two accounts each lead to a different prediction. If the fatigue explanation is
correct, we should expect an overall increase in erroneous responses in the second
relative to the first block, regardless of 1) the suppression condition; 2) onset type; and 3)
experimental condition that was administered in the second block (i.e., suppression or
control). By contrast, the distraction account predicts a decrease in overall performance
under suppression condition, regardless of block order.
We evaluated these explanations by examining each experimental list separately. An inspection of the means (Figure 3) revealed that performance decreased in the second block of trials, but this was evident only when suppression was administered after control (i.e., list 1). Indeed, a 2 suppression x 4 onset type ANOVA in list 1 showed that suppression decreased participants’ performance in the second block \( (F1(1,19)=13.20, p<0.002; F2(1,29)=29.30, p<0.0001) \), and this effect was not further modulated by onset type (both \( p>0.08 \)). However, no effect of suppression was found in list 2 (main effect of suppression, both \( p>0.29 \); suppression x onset type interaction, both \( p>0.18 \)). Clearly, then, performance was not invariably worse in the second block (relative to the first), nor was it always affected by suppression. These results indicate that the effect of suppression cannot be explained by either fatigue or distraction.

*Figure 3. The effect of the suppression manipulation on the sensitivity (d’) to onset type in experiment List 1 (A) and List 2 (B) of Experiment 1. Note: error bars indicate 95% confidence intervals for the difference between the means.*

So far, we have considered three explanations for our findings: the *motor embodiment* account and the two non-articulatory reasons: fatigue and attention. None of these
explanations fully accounted for the results. To capture our findings, we thus propose a modified *embodiment* account. On this account, articulatory simulation presents a strategy that facilitates the identification of the spoken stimuli. Participants who were free to articulate the stimuli in the first block of trials developed this strategy, and consequently, when suppression was administered in the second block, their performance decreased. Critically, unlike the original *embodiment* account, in this strategic account, identification of various syllable types are likely to be affected equally by suppression regardless of their structural well-formedness. Consequently, while both accounts predict that suppression should attenuate overall performance, the original *embodiment* account expects suppression to eliminate participants’ sensitivity to onset hierarchy. By contrast, according to the modified *embodiment* account, articulatory suppression should spare participants’ sensitivity to onset structure, and this effect should be evident only when suppression was administered in the second block. If so, for participants who received suppression in the second block, suppression should result in an overall decrease in performance. Crucially, the effect of onset type should be maintained even under suppression. To assess this hypothesis, we compared these participants’ performance across two experimental blocks.

In line with the strategic hypothesis, earlier analyses revealed that participants’ performance indeed decreased in the second block (i.e., when suppression was administered) compared to the first block (Figure 3A). Crucially, articulatory suppression did not eliminate participants’ sensitivity to onset type. These findings suggest that articulatory simulation is not the source of the onset hierarchy. Rather, simulation is a strategy of syllable identification that is recruited when participants are first allowed to
engage in sub-vocal articulation. Consequently, articulatory suppression hinders the identification process, and this effect is only found when suppression is administered after the control condition.

Taken as a whole, the suppression manipulation did impair participants’ performance in syllable count, but this effect was only evident when suppression was administered in the second block. Moreover, participants’ sensitivity to onset type was maintained regardless of suppression. These results are inconsistent with the motor embodiment account. However, our findings are in line with the grammatical account, as long as the strategic role of motor simulation is recognized.

To further investigate the effect of articulatory suppression, we next used the same materials in a harder task that potentially imposes greater articulatory demands—identity discrimination.

2.2 Experiment 2: Identity discrimination

In Experiment 2, participants heard a nonword (the prime, e.g., blif) followed (after 3000 ms) by another nonword (the target, e.g., belif). Their task was to indicate whether the two items were identical.

Due to the nature of the task, the prime must be maintained in (verbal) working memory for comparison to the target. And because working memory maintenance requires articulatory rehearsal (e.g., Levy, 1971), this task may impose greater articulatory demands compared to the syllable count task (in Experiment 1). If ill-formed onsets are harder to articulate, then articulatory demands should be greater for monosyllabic primes (e.g., lbif-lbif), as their articulatory demands are higher than disyllables (e.g., lebif-lebif).
Accordingly, the deleterious effect of suppression should be stronger for monosyllabic primes compared to disyllabic primes. To test this prediction, the number of syllables in the prime word (prime syllable) was also introduced to form our analyses. Our primary interest is in whether articulatory suppression would attenuate participants’ sensitivity to onset hierarchy.

2.2.1 Method

Participants. Another 56 native English speakers participated in this experiment. All of them were college students from Northeastern University.

Materials. The materials were the same as in Experiment 1, except that they were arranged in pairs. Half of the pairs were physically identical (e.g., monosyllabic: blif-blif; disyllabic: belif-belif), whereas the other half was nonidentical (e.g., blif-belif; belif-blif, with order counterbalanced). To counterbalance all the conditions, only 28 quartets (out of 30) were included in this experiment.

Procedure. On each trial, participants heard a pair of nonwords with an SOA of 3000 ms. They were instructed to indicate as fast and as accurately as possible whether the second stimulus they heard (the target) was identical to the first one (the prime) or not, by pressing the appropriate key (1=identical; 2=nonidentical).

2.2.2 Results

*d prime analyses.*

The effect of suppression on participants’ sensitivity (d’) was examined by 2 suppression (suppression/control) x 2 prime syllable (the number of syllables in the first stimulus:
one/two) x 4 onset type (large rise/small rise/plateau/fall) x 2 list (control - suppression/suppression - control) ANOVAs. The four-way interaction was significant ($F1(3,162)=2.96, p<0.04; F2(3,162)=2.39, p=0.071$). Since the list factor is directly linked to block order (i.e., whether the trial occurred in the first or second block of trials; see Table 1), this four-way interaction indicates that suppression modulated response to the various onset types differently, depending on block order and the number of syllables in the prime word.

To interpret this interaction, we next examined the first and second blocks of trials separately. Of interest is whether there is an effect of suppression and whether suppression attenuates the effect of onset type in the discrimination task. We evaluated these two effects in turn in the following analyses.

An inspection of the means (Figure 4) showed that suppression impaired participants’ performance. However, this effect was found only in the second block. In addition, in both blocks, participants’ sensitivity tended to decrease as the onset became worse formed.

1). Analyses of the first block

Consider first the first block of trials (Figure 4A and 4B). A 2 suppression x 2 prime syllable x 4 onset type ANOVA indeed showed that there was no reliable effect of suppression. The main effect of suppression was not significant (both $F<0.16$), nor did it interact with other factors (for the interactions, all $F<1.2$).
Figure 4. The effect of articulatory suppression on the sensitivity ($d'$) to onset type in the first (panel A and B) and the second block (panel C and D) of Experiment 2. Note: error bars indicate 95% confidence intervals for the difference between the means.

The main effect of onset type, however, was found significant ($F1(3,162)=74.48, p<0.0001; F2(3,162)=44, p<0.0001$), and it was not further modulated by suppression or prime syllable (for the interactions, all $F<1.2$). Planned comparisons revealed that sensitivity to blif-type syllables was significantly better than to bnif-type syllables ($t1(162)=5.90, p<0.0001; t2(162)=4.55, p<0.0001$). Bnif-type onsets, in turn, elicited reliably higher sensitivity than bdif-type ones ($t1(162)=6.63, p<0.0001; t2(162)=5.00, p<0.0001$). Responses to bdif- and lbif-type syllables did not differ significantly (both $p>0.72$).
Therefore, in the first block, suppression did not affect the discrimination task. Moreover, participants were sensitive to the onset hierarchy regardless of suppression (i.e., $blif > bnif > \{bdif, lbif\}$).

2). Analyses of the second block

An inspection of the means (Figure 4C and 4D) suggests that, unlike the first block of trials, in the second block, suppression impaired discrimination. However, this effect did not eliminate participants’ sensitivity to onset hierarchy—the worse formed the onset, the worse their performance.

Indeed, a 2 suppression x 2 prime syllable x 4 onset type ANOVA yielded a significant main effect of suppression ($F1(1,54)=2.97, p=0.09; F2(1,54)=7.62, p<0.008$). Results showed that suppression impaired participants’ performance, and this effect was not further modulated by onset type or the number of syllables in the prime (for the interactions, all $p>0.11$).

The ANOVA also yielded a significant main effect of onset type ($F1(3,162)=73.78, p<0.0001; F2(3,162)=60.82, p<0.0001$) as well as a prime syllable x onset type interaction ($F1(3,162)=3.48, p<0.02; F2(3,162)=2.87, p<0.04$). We thus inspected the effect of onset type on each level of prime syllable separately.

When prime was monosyllabic (Figure 4B), onsets with large sonority rises produced reliably better sensitivity than small rises (e.g., $blif$ vs. $bnif$, $t1(162)=3.92, p<0.0002$; $t2(162)=3.26, p<0.002$). Small rise onsets, in turn, elicited better sensitivity than onsets level in sonority (e.g., $bnif$ vs. $bdif$, $t1(162)=6.15, p<0.0001$; $t2(162)=5.59, p<0.0001$).
Sensitivity to sonority plateaus and falls did not differ significantly (e.g., bdif vs. lbif, both $p>0.33$).

Likewise, when prime was disyllabic, syllables with large rises (e.g., blif) produced significantly higher sensitivity than those with small rises (e.g., bnif) ($t1(162)=3.34, p<0.002$, $t2(162)=2.92, p<0.005$), which, in turn, elicited significantly better responses than syllables with sonority plateaus (e.g., bdif; $t1(162)=4.71, p<0.0001$, $t2(162)=4.11, p<0.0001$). Unlike monosyllabic primes, in the case of disyllabic primes, sensitivity to syllables with sonority plateaus (e.g., bdif) was also significantly better than those with sonority falls (e.g., lbif; $t1(162)=3.22, p<0.002$; $t2(162)=2.78, p>0.007$).

To sum up, results from d-prime data showed that suppression impaired participants’ overall performance in the discrimination task. Crucially, this effect did not attenuate participants’ sensitivity to onset hierarchy. As the syllables became worse formed, sensitivity declined, regardless of suppression.

**Response time analyses.**

We next examined the effects of suppression and onset type on correct response time (RT) to identical and nonidentical trials.

**Identical trials.**

Consider first responses to identical trials (Figure 5A and 5B; for means, see Table 3). A 2 suppression x 2 prime syllable x 4 onset type x 2 list ANOVA revealed a significant suppression x list interaction ($F1(1,54)=16.0, p<0.0002$; $F2(1,54)=17.07, p<0.0002$).
However, post hoc tests (Tukey HSD) yielded no reliable differences between the suppression and control conditions in either of the two blocks (all $p>0.23$). Likewise, none of the effects involving suppression—either main effect (both $F<1$) or interactions (all $p>0.32$)—were significant. These findings indicate that suppression did not affect RT to identical trials.

Figure 5. The effect of suppression on correct response time (RT) to identical (panel A and B) and nonidentical trials (panel C and D) of Experiment 2. Note: error bars indicate 95% confidence intervals for the difference between the means.
Table 3. Mean response accuracy (ACC, proportion correct) and correct response time (RT) of both identical and nonidentical trials in Experiment 2.
However, the 2 suppression x 2 prime syllable x 4 onset type x 2 list ANOVA yielded a significant main effect of **onset type** \( (F_1(3, 162) = 13.58, p < 0.0001; F_2(3, 162) = 8.81, p < 0.0001) \), and it was not further modulated by other factors (all \( p > 0.32 \)). The effect of onset type, however, applied to both monosyllabic and disyllabic items (i.e., there was no prime syllable x onset type interaction), so it is unlikely due to the syllable hierarchy *per se*.

**Nonidentical trials.**

An inspection of the means (Figure 5C and 5D, see Table 3 for means) suggests a pattern that mirrors the d-prime results. There was a very limited effect of suppression, and it was evident only when prime was disyllabic. Moreover, participants’ performance declined as the onsets’ well-formedness decreased.

The effect of **suppression** on response time to *nonidentical* trials was evaluated by a 2 suppression x 2 prime syllable x 4 onset type x 2 list ANOVA (see Table 3 for means). Results showed that the four-way interaction was marginally significant \( (F_1(3, 90) = 1.77, p = 0.16; F_2(3, 93) = 2.72, p < 0.05) \). In addition, there was a significant suppression x list interaction \( (F_1(1, 30) = 18.74, p < 0.0002, F_2(1, 31) = 5.27, p < 0.03) \), suggesting suppression affected each experimental block differently. Tukey HSD tests suggested that responses to the control and suppression manipulation did not differ significantly in either of the blocks (all \( p > 0.11 \)). Similarly, neither the main effect of suppression (both \( p > 0.28 \)) nor its interactions with other factors (all \( p > 0.12 \)) were significant. Thus, suppression did not affect participants’ RT in the nonidentical trials.
By contrast, a significant main effect of **onset type** was found ($F1(3,90)=32.75, p<0.0001; F2(3,93)=29.71, p<0.0001$). Planned comparisons showed that *blif*-type syllables produced faster responses than *bnif*-type ones ($t1(90)=1.89, p=0.06; t2(93)=2.66, p<0.01$). *Bnif*-type syllables, in turn, elicited significantly faster responses than *bdif*-type ones ($t1(90)=3.97, p<0.0005; t2(93)=3.47, p<0.0008$). Finally, *lbif*-type syllables generated reliably slower responses compared to *bdif*-type ones ($t1(90)=3.27, p<0.002; t2(93)=2.75, p<0.008$). Thus, as the syllables became worse formed, participants’ performance decreased (i.e., $blif\succ bnif\succ bdif\succ lbif$).

Taken together, the findings from d-prime and RT data converged—suppression impaired participants’ performance in the identity discrimination task, but its effect was very limited. Crucially, suppression did not diminish participants’ sensitivity to the onset hierarchy. These results stood in stark contrast to the predictions from the *motor embodiment* account. We discuss this further in the next section.

2.2.3 Discussion

Experiment 2 extended the investigation of articulatory suppression to an identity discrimination task. First, we examined whether suppression affected syllable discrimination. Second, we asked whether suppression eliminates participants’ sensitivity to the onset hierarchy. The *grammatical* account predicts that participants should be sensitive to onset structure irrespective of whether suppression is present or absent. The *motor embodiment* account asserts otherwise—suppression should decrease **overall** performance but it could potentially **improve** the identification of ill-formed syllables,
especially when those syllables are presented first (as the prime). Consequently, participants’ sensitivity to onset hierarchy should be attenuated.

Our results showed that suppression indeed impaired participants’ performance. When suppression was administered, responses were reliably slower and more error-prone. These findings partly agree with the motor embodiment account. Contrary to the motor embodiment account, however, the effect of suppression was not larger for monosyllabic primes. Furthermore, rather than improving performance on ill-formed syllables (e.g., \textit{lbif}), suppression impaired the discrimination of better-formed ones (e.g., \textit{blif} and \textit{bnif}). Crucially, suppression did not attenuate participants’ sensitivity to onset structure. Therefore, these findings are inexplicable by the motor embodiment account.

So, what is the source of the suppression effect? As discussed in the last experiment, these effects are consistent with three sources. One concerns fatigue—participants might have become tired towards the end of the experiment, hence the decrease in performance in the second block. Another non-articulatory explanation attributes this suppression effect to distraction. It is possible that biting on the two tongue depressors attracted participants’ attention, and distracted them from the syllable discrimination task. A third explanation appeals to strategic control. According to this hypothesis, participants in the control condition could actively simulate the articulation of the stimulus, and this activity aids performance. Accordingly, when suppression is administered second (after the control condition), they are unable to utilize this strategy, and their performance declines.

Each account predicts distinct result patterns. The fatigue account predicts a decrease in performance in the second compared to the first block, regardless of the suppression
condition—whether suppression or control is administered in the second block. In contrast, the distraction account predicts that there should be a decline in performance under articulatory suppression, irrespective of block order. Unlike the two non-articulatory accounts, the strategic account asserts that sensitivity should decrease only when suppression is administered after the control (i.e., when they are able to articulate).

To distinguish among these three possibilities, we compared participants’ sensitivity (d’) under the control and suppression conditions in each block order (i.e., control followed by suppression condition, and suppression followed by control condition) separately. Of interest is whether the observed suppression effect is associated with the suppression manipulation or block order.

An inspection of the means suggests that when suppression manipulation was administered after the control condition (Figure 6A), performance decreased. However, a similar decrease was also present when block order was reversed (i.e., when suppression was administered before the control condition, Figure 6B).

Indeed, a 2 suppression x 2 prime syllable ANOVA yielded a marginal main effect of suppression, irrespective of block order (control-suppression: $F1(1,27)=3.49$, $p=0.07$; $F2(1,27)=5.15$, $p<0.04$; suppression-control: $F1(1,27)=4.85$, $p<0.04$; $F2(1,27)=3.72$, $p=0.06$). In both orders, participants were better at discrimination under the control condition.
Figure 6. The effect of the suppression manipulation on the sensitivity (d’) to onset type in Experiment 2. Note: error bars indicate 95% confidence intervals for the difference between the means. In list 1 (panel A), suppression was administered in the second block; list 2 reversed the block order (panel B).

Therefore, regardless of block order, suppression impaired performance relative to the control condition. These findings are consistent with the predictions of both the distraction and the strategic account. Remarkably, participants remained sensitive to onset hierarchy regardless of whether articulatory suppression was present or absent. These findings, again, are inconsistent with the motor embodiment account. However, they are in line with the grammatical hypothesis, provided that the role of articulatory simulation is recognized.

2.3 Experiment 3: Identity discrimination with printed materials

Results from Experiments 1 and 2 suggest that people might possess broad preferences concerning syllable structure, and these preferences are inexplicable by articulatory factors. However, both of these experiments used auditory materials. Accordingly, one might worry that the effect of syllable structure might reflect auditory failure—
difficulties in extracting auditory/phonetic representations, rather than grammatical restrictions.

Previous research addressed this possibility by using printed materials. These materials were used because extensive research has suggested that readers assemble phonological representations from print in silent reading (e.g., Berent & Perfetti, 1995; van Orden, Pennington, & Stone, 1990). If readers’ sensitivity to onset hierarchy obtains with printed materials, then it is unlikely that their performance is solely due to auditory failure. Previous findings showed that, contrary to the auditory account, participants were nonetheless sensitive to onset structure even when the nonword stimuli were presented visually (Berent, 2008; Berent et al., 2009; Berent & Lennertz, 2010; Tamási & Berent, 2014).

While auditory failure is unlikely the source of the previous findings with printed materials, it is possible that they could emanate from articulatory simulations. Past research has demonstrated that subvocal articulation plays an important role in silent reading—concurrent articulatory suppression has been found to interfere with visual word recognition (e.g., Lukatela, Eaton, Sabadini, & Turvey, 2004; Eiter & Inhoff, 2008). Specifically, suppression disrupted operations that are performed on phonological representations (Besner, 1987), such as assembling the pronunciation of *blif* by mapping its letters to corresponding phonemes (e.g., Baddeley, Thompson, and Buchanan, 1975; Besner & Davelaar, 1982; Hitch & Baddeley, 1976; Kleiman, 1975; Levy, 1975, 1978; Martin, 1978). For example, Baddeley and colleagues (1975) found that the effect of stimulus length effect of printed materials (i.e., items that are pronounced faster are better recalled) has been completely eliminated by irrelevant concurrent articulation. They
concluded that articulatory codes were created during reading, and suppression prevented the mapping of graphemes onto a phonemic code (i.e., letter-sound mapping). Likewise, numerous studies indicate that suppression impaired rhyming judgment with visually presented letter strings, be they words (e.g., heard-beard), or nonwords (e.g., kerm-curm; e.g., Besner, Davies, & Daniels, 1981; Johnston & McDermott, 1986; Kleiman, 1975; Wilding & White, 1985). In view of these findings, it is possible that readers’ sensitivity to the syllable hierarchy reflects articulatory simulation.

To further investigate the source of the syllable hierarchy, we examined participants’ ability to discriminate monosyllables from their disyllabic counterparts with printed materials under articulatory suppression. Because auditory/phonetic information is not available for printed items, any effects of onset structure cannot be explained by auditory or phonetic factors. Our experiments examine whether these effects could be due to subvocal articulatory simulation.

There are several reasons to expect subvocal articulation to facilitate performance in this task. First, subvocal articulation could facilitate phonological decoding. In addition, articulatory simulation could aid holding the prime in phonological working memory (e.g., Smith, Wilson, & Reisberg, 1995; Murray, 1967; Peterson & Johnson, 1971; Richardson, Greaves, & Smith 1980; Wilding & Mohindra, 1980). Thus, we should expect an even larger effect of articulatory suppression in the current experiment compared to the last one with auditory materials. Of interest is, whether readers are nonetheless able to compute phonological structure, even in the absence of auditory and articulatory information.
Unlike auditory items, however, visual stimuli offer additional orthographic information for syllable identification, and this fact might lead to a more complex result pattern. Specifically, readers could utilize a dual-route process to identify printed words—either through phonological decoding or an orthographic route (Figure 7). And the decision as to which route to take might depend on the accuracy of these two processes. The orthographic information can reliably distinguish monosyllables from disyllables, whereas phonological representations require elaborate decoding which is error-prone—the worse formed a monosyllable, the more likely its misidentification as a disyllable (e.g., lbif$\rightarrow$lebif). To avoid such errors, participants might strategically shift their attention to rely on graphemic verification (i.e., monitoring the letter e in the second letter-position). Such a shift is especially likely for sonority falls as these items are the most error-prone, and their graphemic structure is distinct (i.e., they begin with a sonorant consonant). As a result, sonority falls should yield relatively accurate responses.

By contrast, the identification accuracy of better-formed syllables should be mediated by phonology, hence, accuracy should decline as they become worse formed (i.e., $blif\succ bnif\succ bdif$). Experiment 3 tested these predictions.

2.3.1 Method

*Participants.* A new group of 48 native English speakers, students of Northeastern University, participated in this experiment.

*Materials.* A printed version of the same nonword stimuli from the previous experiments was included, arranged as explained in Experiment 2. To minimize the effect of visual overlap, prime and target were presented in different type cases, masked by a series of Xs.
Figure 7. A dual-route account for the identification of printed materials in Experiments 3-4. Printed stimuli offer two routes for identification—phonological and orthographic routes. The phonological route will often lead to misidentification (e.g., lbif→lebif). In contrast, the orthographic route is always accurate. Because the phonological processing of ill-formed syllables like lbif is erroneous, participants might strategically shift their processing to rely on the orthographic route. Note: font size of “e” in semi-product and output signifies the likelihood of misidentification—the bigger the font, the more likely its misidentification.

Procedure. After pressing the spacebar, participants saw one nonword (the prime) for 500ms, followed by a mask of “XXXXXXX”, presented on the screen for 2500ms. Then a second nonword (the target) appeared with a maximum duration of 2500ms. Participants were instructed to quickly indicate whether the prime and the target nonword were identical by pressing a computer key (1=identical, 2=nonidentical). Note that the SOA in this experiment (3000 ms) matched the SOA used in Experiment 2.
2.3.2 Results

d-prime analyses.

An inspection of the means (Figure 8) suggested that sensitivity (d’) declined when suppression was administered. Crucially, participants were still sensitive to onset structure even under suppression, although the effect of onset type appeared to be nonlinear. Specifically, when suppression was administered, participants’ sensitivity first dropped as the onset became worse formed. Notably, the worst-formed lbif-type syllables elicited better discrimination. We next evaluate the effects of suppression and onset type, in turn.

Figure 8. The effect of suppression and onset type on sensitivity (d’) in Experiment 3. Note: error bars indicate 95% confidence intervals for the difference between the means.

The effect of suppression was evaluated by a 2 suppression x 2 prime syllable x 4 onset type x 2 list ANOVA. Results yielded a significant main effect of suppression
These findings suggest that suppression manipulation impaired participants’ ability to discriminate monosyllables from their disyllabic counterparts.

In addition, there was a main effect of onset type \( F(3,138) = 7.73, p < 0.0001; \) \( F(3,162) = 7.77, p < 0.0001 \). The onset type x list interaction was significant only across participants, \( F(3,138) = 3.08, p < 0.03 \); but not by item, \( F(3,162) = 2.00, p > 0.11 \), and it was not further modulated by suppression (for the suppression x onset type interaction, \( F(3,138) = 2.23, p = 0.087; F(3,162) = 1.95, p > 0.12 \)), or any other factor (all \( p > 0.12 \)).

Planned comparisons showed that onsets with large sonority rises (e.g., blif) elicited significantly better sensitivity than those with small rises (e.g., bnif; \( t(138) = 3.26, p < 0.002; t(162) = 3.03, p < 0.003 \)). Likewise, onset with small rises (e.g., bnif) elicited numerically better sensitivity than those with sonority plateaus (e.g., bdif; both \( p > 0.32, n.s. \)). Notably, onsets with sonority plateaus (e.g., bdif), elicited significantly worse performance compared to sonority falls (e.g., lbif, \( t(138) = 3.27, p < 0.002; t(162) = 3.67, p < 0.0004 \)).

In summary, although suppression impaired readers’ ability to distinguish monosyllables from disyllables, participants were generally sensitive to onset hierarchy even when suppression was administered: as the onset became worse formed, discrimination generally decreased. The one notable exception was presented by the benefit of lbif-type onsets. We will address this finding in the discussion section.
**Response time analyses.**

We next evaluated the effects of suppression and onset type on correct response time (RT) to identical and nonidentical trials. Unlike the findings from d’, the results from the RT data did not reveal reliable effects of suppression or onset type. These results are plotted in Figure 9.

*Figure 9. The effect of suppression and onset type on correct response time (RT) to identical (panel A and B) and nonidentical trials (panel C and D) in Experiment 3. Note: error bars indicate 95% confidence intervals for the difference between the means.*
Identical trials.

The 2 suppression x 2 prime syllable x 4 onset type x 2 list ANOVAs on accurate responses to identical trials yielded a significant suppression x list interaction ($F1(1,45)=6.41, p<0.02; F2(1,54)=4.18, p<0.05$). However, Tukey HSD tests suggested that the control vs. suppression contrasts were not reliable in either block (all $p>0.79$). In addition, there was no main effect of suppression, nor did suppression interact with any other factors (all $p>0.1$). These findings indicate that suppression did not affect RT to identical trials.

The ANOVA also yielded a significant main effect of onset type ($F1(3,135)=3.63, p<0.02; F2(3,162)=3.67, p<0.02$), and it was not further modulated by prime syllable ($F1(3,135)=1.58, p>0.19; F2(3,162)=2.66, p=0.05$) or any other factors (for all interactions, $p>0.16$). Planned comparisons, however, revealed no reliable contrasts between any of the adjacent onset types.

Nonidentical trials.

The 2 suppression x 2 prime syllable x 4 onset type x 2 list ANOVA produced a significant suppression x list interaction ($F1(1,46)=4.71, p<0.04; F2(1,54)=4.53, p<0.04$). Post-hoc tests (Tukey HSD) showed that the control vs. suppression contrast was marginally significant in the second block (by item, $p<0.02$; albeit not by participant, $p>0.5$)—responses were significantly faster under the control than the suppression condition. The control-suppression contrast was not significant in the first block (both $p>0.99$). In addition, there was no reliable effect of suppression ($F1(1,46)=3.25, p=0.08$).

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5 Block order (i.e., whether the trial appeared in the first or second block of trials) is captured by the list factor (see Table 1 for details).
Unlike the identical trials, however, there was no effect of onset type in responses to the nonidentical trials (both $p>0.2$), nor was there an interaction between onset type and other factors (all $p>0.11$).

2.3.3 Discussion

Findings from Experiments 1 and 2 suggest that people’s sensitivity to the onset hierarchy is irreducible to articulatory factors. However, such sensitivity could also result from auditory failure, rather than phonological restrictions on onset clusters.

To address this possibility, the current experiment used printed materials. Our goal was to determine whether readers were sensitive to the onset hierarchy when the stimuli are devoid of auditory information. Moreover, we were interested in whether this sensitivity reflected articulatory demands. Two opposing hypotheses were proposed. The grammatical account asserts that participants’ sensitivity to the onset hierarchy reflects grammatical well-formedness: the worse-formed an onset, the more likely its misidentification. Accordingly, suppressing articulation should not affect this sensitivity. The motor embodiment account asserts that ill-formed onsets (e.g., $lb$) are dispreferred because these clusters are more difficult to articulate. This account predicts that articulatory suppression should attenuate the sensitivity to the onset hierarchy.

In line with the motor embodiment account, our results revealed that suppression indeed elicited a decrease in readers’ ability to discriminate monosyllables from their disyllabic counterparts. Nonetheless, when considering the better-formed (i.e., obstruent-initial)
syllables, readers were sensitive to the syllable hierarchy regardless of suppression—their sensitivity (d’) declined as the syllables became worse formed (i.e., blif>bnif>bdif). To further evaluate readers’ sensitivity to onset structure, we next tested for the effect of syllable type under the suppression condition, specifically. Planned comparisons showed that blif-type syllables yielded significantly better sensitivity than bnif-type ones ($t_1(138)=3.20, p<0.002; t_2(162)=3.01, p<0.003$). Sensitivity to bnif-type syllables, in turn, was numerically higher than bdif-type onsets (both $p>0.10$, n.s.). This aspect of our findings is inconsistent with the motor embodiment account.

Notably, sensitivity to the worst-formed syllables like lbif was higher than that to the better-formed bdif-type ones (i.e., lbif-bdif; rather than bdif-lbif), irrespective of articulatory suppression. These findings do not lend themselves to the motor embodiment explanation, as people were clearly sensitive to syllable structure. However, the grammatical account can accommodate this reversed effect of onset type by considering the effect or orthographic information.

As discussed earlier, printed materials provide two possible routes for syllable identification—either through phonological decoding or by spelling verification. The phonological decoding process is error-prone, whereas spelling verification is always accurate. If participants are aware of their tendency to misidentify sonorant-initial clusters (e.g., lbif), an encounter with such syllables might prompt them to shift their strategy to a direct orthographic process. And because spelling provides unambiguous cues to the number of syllables, responses to ill-formed syllables are relatively accurate.
In conclusion, our results showed that suppression impaired syllable discrimination. Crucially, the effect of onset type was mostly maintained regardless of suppression; the one exception concerning sonority falls is most likely due to a strategic reliance on spelling verification. The resilience of the syllable hierarchy to suppression challenges the *motor embodiment* account.

### 2.4 Experiment 4: Identity discrimination with printed materials and background noise

Results from Experiments 1-3 converge on the same conclusion: people’s preferences of onset clusters are maintained despite articulatory suppression. However, Experiment 3 yielded an advantage of the worst-formed syllables like *lbif*. We suggest that this advantage occurred because the discrimination of these visual stimuli might benefit from the accurate orthographic decoding process (i.e., a visual strategy), and this effect masked readers’ sensitivity to the onset hierarchy.

To test this possibility, in the current experiment, we attempted to discourage the readers from utilizing the orthographic information by obscuring our materials with visual noise. Specifically, we presented the same printed materials (from Experiment 3) against background noise patterns. If the advantage of *lbif*-type syllables reflected a visual strategy, such advantage should be attenuated by visual noise, and these items should now produce lower accuracy relative to better-formed items (as predicted by the *grammatical* account).

To this end, we first examined whether visual noise could decrease or eliminate the advantage in discriminating worst-formed syllables like *lbif*. Inasmuch as the background
interference is effective, our goal is to determine whether readers would remain sensitive
to the onset hierarchy despite articulatory suppression.

2.4.1 Method

Participants. Another 32 Northeastern University undergraduate students took part in this experiment. All of them were native English speakers.

Materials. The materials of this experiment consisted of nonword stimuli presented against black-and-white background visual noise (see Appendix B). The nonword stimuli were those used in Experiment 3, and the discrimination task is otherwise identical to the one used in Experiment 3. The background noise images were a collection of randomly distributed discrete objects that varied in size and contrast. All of these images were generated by a dead leaves model (Lee, Mumford, & Huang, 2001). To better obscure the shape of the letters, two distinct types of patterns were included—either filled with circular- or square-shaped objects (Appendix B1 and B2). As most of the lower- and upper-cased letters of our materials were composed of circular and angular shapes, respectively, the lower-case stimuli (i.e., the primes; e.g., blif) were presented with images filled with round objects, whereas the upper-case stimuli (i.e., the targets; e.g., BELIF) were displayed with patterns of squares. Each circular pattern was randomly paired with one square pattern into a pair. A total of 32 such pairs were included. We randomly assigned 4 pairs to the practice trials and the other 28 to the experimental trials. Each image pair was randomly selected to present with one nonword quartet.

Procedure. The procedure was exactly the same as that of Experiment 3.
2.4.2 Results

*Are readers sensitive to visual noise?*

To determine whether our background noise manipulation was effective, we first examined whether visual noise reduced the anomalous high discrimination accuracy of *lbij*-type syllables. We compared readers’ sensitivity (d’) between Experiments 3 and 4 by adding experiment as a factor (Figure 10). A 2 suppression x 2 prime syllable x 4 onset type x 2 experiment x 2 list ANOVA yielded a significant main effect of experiment \( (F1(1,76)=89.15, p<0.0001; F2(1,108)=405.33, p<0.0001) \), showing that readers’ overall discrimination accuracy was impaired by visual noise. In addition, the experiment factor was marginally modulated by suppression, onset type and experimental list (suppression x onset type x experiment x list interaction, \( F1(3,228)=2.59, p=0.054; F2(3,324)=2.14, p=0.095 \)). The 5-way interaction (suppression x prime syllable x onset type x experiment x list), however, was significant by items (\( F1<1; F2(3,324)=2.58, p=0.05 \)). These findings indicate that suppression altered readers’ performance on various onset types differently between experiments (i.e., with or without visual noise), and this difference further depended on whether suppression was administered in the first or the second block.

Recall that in Experiment 3, the interaction between suppression and onset type was not modulated by experimental list. Accordingly, the high order interaction across experiments (suppression x onset type x experiment x list) specifically comes from Experiment 4, possibly due to the addition of visual noise. To further investigate the effect of visual noise, we examined results from Experiment 4 separately. Of interest is
whether noise eliminated the anomalous advantage of the worst formed syllables (e.g., *lbif*).

*Figure 10.* The effect of articulatory suppression and onset type on sensitivity (*d’*) under the noise-absent and the noise-present conditions (Experiment 3 and 4, respectively). Note: error bars indicate 95% confidence intervals for the difference between the means.

An inspection of the *d*-prime means (Figure 11) showed that in the second block of trials, *lbif*-type syllables elicited better discrimination than *bdif*-type ones, similarly to Experiment 3. By contrast, in the first block of trials, this effect was far weaker, and it was absent when suppression was administered. These effects of onset type are tested statistically in the next section.

*Are readers sensitive to onset hierarchy regardless of suppression?*

In this section, we examined the effect of suppression and onset type in Experiment 4. Two sets of analyses were conducted, one on *d*-prime and the other on the RT data.

An inspection of the *d*-prime means (Figure 11) suggested that suppression impaired syllable discrimination, but only in the first block of trials. In addition, readers remained
sensitive to most of the onset hierarchy regardless of suppression. However, the worst formed onsets (e.g., lb) elicited more accurate responses than the plateaus (e.g., bd) in the second block of trials.

Figure 11. The effect of suppression and onset type on sensitivity (d’) in the first and the second block (panel A and B, respectively) of Experiment 4. Note: error bars indicate 95% confidence intervals for the difference between the means.

A 2 suppression x 2 prime syllable x 4 onset type x 2 list ANOVA yielded a significant main effect of suppression ($F1(1,30)=5.53, p<0.03; F2(1,54)=10.59, p<0.002$), suggesting that readers’ performance in syllable discrimination was impaired by the suppression manipulation. In addition, the effect of suppression was modulated by the number of syllables in the prime (for suppression x prime syllable interaction, $F1(1,30)=10.26, p<0.004; F2(1,54)=11.14, p<0.002$) and further by experimental list (Figure 12. suppression x prime syllable x list interaction, $F1(1,30)=5.21, p<0.03$).
The 4-way suppression x prime syllable x onset type x list interaction, however, was not significant ($F1(3,90)=1.42, p=0.24; F2(3,162)=2.31, p=0.079$).

Figure 12. Sensitivity ($d'$) to monosyllabic and disyllabic primes in Experiment 4. Note: error bars indicate 95% confidence intervals for the difference between the means.

Crucially, suppression interacted with onset type and experimental list (suppression x onset type x list interaction, $F1(3,90)=2.70, p=0.05; F2(3,162)=2.13, p=0.1$). Since the list factor captures block order (see Table 1), we next investigated the effect of suppression and onset type in the first and second blocks separately.

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6 To further examine the effect of suppression, we further probed the suppression x prime syllable x list interaction, by analyzing the two experimental blocks separately. An inspection of the means (Figure 12) showed that the effect of suppression was limited to monosyllabic primes in the first block. In the first block of trials, a 2 suppression x 2 prime syllable x 4 onset type ANOVA produced a significant main effect of suppression ($F1(1,30)=8.87, p<0.006; F2(1,54)=21.19, p<0.0001$) and a reliable interaction between suppression and prime syllable ($F1(1,30)=5.65, p<0.03; F2(1,54)=16.08, p<0.0002$). Planned comparisons showed that compared to control condition, suppression significantly decreased discrimination, but only when the prime was monosyllabic ($t1(50)=3.78, p<0.0005; t2(88)=6.01, p<0.0001$). When prime was disyllabic, responses to the control and suppression conditions did not differ significantly (the contrast was only marginally significant by items, $t2(88)=1.9, p<0.07$; by participants, $p=0.21$, n.s.).

In the second block, a 2 suppression x 2 prime syllable x 4 onset type ANOVA showed no effect of suppression. There was no main effect of suppression (both $F<1$), nor was it modulated by prime syllable, or onset type (for interactions, all $p>0.21$).
In the first block of trials (Figure 11A), a 2 suppression x 2 prime syllable x 4 onset type ANOVA yielded a significant main effect of onset type ($F1(3,90)=6.05, p<0.001$; $F2(3,162)=5.19, p<0.002$) that did not interact with other factors (all $p>0.46$). Planned comparisons showed that blif-type syllables elicited significantly better sensitivity than bnif-type ones ($t1(90)=2.55, p<0.02; t2(162)=2.60, p<0.02$) and bdif-type items ($t1(90)=4.14, p<0.0001; t2(162)=3.70, p<0.001$). Other comparisons (e.g., bnif vs. bdif and bdif vs. lbif), however, were not statistically significant (all $p>0.11$). These results demonstrate that in the first block trials, people were sensitive to onset structure.

Furthermore, the anomalous advantage of lbif-type syllables was eliminated.

In the second block of trials (Figure 11B), a 2 suppression x 2 prime syllable x 4 onset type ANOVA also yielded a marginally significant main effect of onset type ($F1(3,90)=3.60, p<0.02; F2(3,162)=2.14, p=0.097$), which was not modulated by any other factors (for all interactions, $p>0.28$). Planned comparisons revealed that the discrimination of blif-type onsets did not differ from bnif-type items ($p>0.8$), which, in turn, elicited significantly better sensitivity than bdif-type ones ($t1(90)=2.47, p<0.016; t2(162)=1.76, p=0.08$). Unlike the first block of trials however, in the second block, the worst-formed lbif-type syllables produced significantly better discrimination accuracy relative to bdif-type ones ($t1(90)=2.97, p<0.004; t2(162)=2.31, p<0.03$)—a result that mirrors the findings from Experiment 3.
Additional analyses on RT\textsuperscript{7} (Figure 13) did not exhibit any effect of suppression or onset type.

\textit{Figure 13. The effect of suppression and onset type on correct response time (RT) to identical (panel A and B) and nonidentical trials (panel C and D) in Experiment 4. Note: error bars indicate 95\% confidence intervals for the difference between the means.}

\textsuperscript{7}The effect of suppression and onset type was examined for identical and nonidentical trials separately. For identical trials, a 2 suppression x 2 prime syllable x 4 onset type x 2 list ANOVA yielded a significant suppression x list interaction (F1(1,30)=7.06, p<0.013; F2(1,54)=10.90, p<0.002). However, post-hoc comparisons found no significant effect of suppression in either block (all p>0.35). Likewise, none of the effects (main effect or interactions) involving the onset type factor were significant (all p>0.07).

In the nonidentical trials, a 2 suppression x 2 prime syllable x 4 onset type x 2 list ANOVA also exhibited a significant suppression x list interaction (F1(1,30)=10.42, p<0.004; F2(1,54)=7.86, p<0.008), and it was further modulated by prime syllable (suppression x prime syllable x list interaction, F1(1,30)=5.86, p<0.03; F2(1,54)=4.33, p<0.05). We probed the 3-way interaction by investigating each block separately. The effect of suppression was not significant in either block (all p>0.16), and it was not reliably modulated by other factors (all p>0.22). Furthermore, the main effect of onset type was not significant in either block (all p>0.12), nor did it interact with any other factors (all p>0.21).
To sum up, our results suggest two conclusions. First, the visual noise manipulation effectively decreased readers’ discrimination accuracy, and with it, the anomalous lbif-advantage was completely eliminated in the first block of trials.

Regardless of suppression, however, readers were sensitive to most of the onset hierarchy. Specifically, as the syllables became better formed, discrimination of obstruent-initial clusters (e.g., bl, bn, bd) improved.

2.4.3 Discussion

Findings from Experiment 3 indicate that lbif-type syllables elicited unexpectedly better discrimination relative to bdif-type ones. We suggest this benefit is due to a visual verification strategy that masked their grammatical ill-formedness.

To test this explanation, the current experiment attempted to discourage the use of a visual strategy by obscuring the printed items with noisy background patterns. The visual strategy explanation predicts that the high discrimination of lbif-type syllables should be attenuated by visual noise, and their expected grammatical dispreference relative to better-formed syllables should now emerge.

Comparing Experiments 3 and 4, visual noise decreased reader’s overall discrimination accuracy. Critically, consistent with the visual strategy explanation, this manipulation reduced the advantage of lbif-type syllables in discrimination—this advantage was completely eliminated in the first block of trials and it only emerged in the second block. Such late emergence might occur because visual verification is a controlled (i.e., attention demanding) strategy that develops over time. Crucially, in the absence of learning (i.e., in the first block), and under the suppression load, the lbif advantage disappeared.
We should note, however, that the *grammatical* account predicts that *lbif*-type items should result in the lowest discrimination accuracy. The results of Experiment 4 did not support this prediction. The explanation for this finding is unclear. It is possible that, despite visual noise and attention, participants in Experiment 4 nonetheless relied on the visual verification strategy. The resulting advantage of *lbif* (on graphemic grounds) could have cancelled out its grammatical disadvantage. Further research is still needed to test this possibility. What is clear from these results, however, is that readers can remain sensitive to onset type despite articulatory suppression. This aspect of our findings is evidently inexplicable by the *motor embodiment* account.

**Chapter 3. General Discussion and Conclusion**

Across languages, certain onset clusters are systematically preferred to others (e.g., \(bl > bn > bd > lb\); English: Berent et al., 2007; Spanish: Berent et al., 2012b; French: Maïonchi-Pino et al., 2012; Hebrew: Berent, Vaknin-Nusbaum, Balaban, & Galaburda, 2013). Similar preferences have also been observed in the behavior of individual speakers—as the onset becomes worse formed (i.e., dispreferred), misidentification rate increases. These preferences are inexplicable by participants’ linguistic experience, as they emerge even in languages that lack onset clusters altogether (Korean: Berent et al., 2008; Mandarin: Zhao & Berent, 2015). It is also unlikely that these preferences are due to auditory/phonetic reasons, since similar findings were obtained with printed materials (Berent, 2008; Berent & Lennertz, 2010; Tamási & Berent, 2014). However, it is still unclear whether this systematic preference reflects universal grammatical restrictions on language structure or motor demands imposed by articulatory simulation (i.e., *motor*
embodiment). To adjudicate between these possibilities, the present research investigated whether people remain sensitive to onset structure despite articulatory suppression.

If the onset hierarchy results from grammatical constraints, as predicted by the grammatical account, then our participants should respect this hierarchy even when articulatory activity is suppressed. By contrast, if the onset hierarchy arises from motor demands, as asserted by the motor embodiment account, then participants’ sensitivity to this hierarchy should be attenuated under articulatory suppression.

To test these predictions, the current study utilized a mechanical method to suppress participants’ articulatory simulations. During task performance, participants were instructed to accommodate two tongue depressors in their mouth—one above and one below their tongue. Of interest is whether suppression attenuated, or even eliminated participants’ grammatical preferences concerning syllable structure.

In line with the motor embodiment hypothesis, results from all four experiments showed that articulatory suppression indeed impaired participants’ overall performance. Contrary to this hypothesis, however, participants remained highly sensitive to the syllable structure of auditory stimuli (Experiments 1 and 2) irrespective of suppression. Moreover, the effect of suppression with auditory stimuli emerged only in the second block of trials. These findings suggest that during syllable identification/discrimination, listeners do not engage in articulatory simulation automatically; rather, simulation is a controlled process that develops throughout the experimental session. Motor simulation, therefore, is unlikely the sole source of onset hierarchy.
It is still possible, however, that these results with auditory materials arise from difficulties to extract auditory/phonetic cues. To address this possibility, we extended our investigation to printed words. When presented visually (Experiments 3 and 4), our stimuli elicited more complex results. In line with the grammatical account, in each experiment, readers respected part of the onset hierarchy (i.e., bl>bn>bd), and this effect was found regardless of suppression. This aspect of the findings is clearly inconsistent with either the auditory/phonetic or the motor embodiment explanations. Surprisingly, the worst formed syllables (e.g., lbif) produced the most accurate discrimination. We suggest that this unexpected advantage is due to a visual strategy of spelling verification. Because spelling offers reliable cues for discriminating monosyllables (e.g., lbif) from their disyllabic counterparts (e.g., lebif), this strategy should yield relatively accurate responses. Worst-formed syllables (e.g., lbif) are most likely to invoke this strategy since their phonological decoding is error-prone, on the one hand, and since their unique graphemic/phonological structure (i.e., sonorant-initial clusters) distinguishes them from all other monosyllables, on the other. The selective spelling verification should thus confer an advantage to lbif-type syllables, and this effect could have masked their grammatical ill-formedness. In line with this explanation, we found that the anomalous advantage of lbif-type stimuli was eliminated in the presence of visual noise (in the first block of Experiment 4). Together, these results suggest that the onset hierarchy reflects neither articulatory demands nor auditory/phonetic difficulties in processing auditory materials.

To further test the auditory/phonetic explanation, we submitted our findings from the auditory materials (Experiments 1 and 2) to a series of step-wise regression analyses.
These analyses gauge the effect of the duration and intensity of the burst release associated with stop consonants (e.g., \(b\) in \(blif\)). Past research (Kang, 2003; Wilson & Davidson, 2013; Wilson, Davidson, & Martin, 2014) has shown that participants sometimes misinterpret the burst as evidence for an intermediate schwa, and consequently, they misidentify the monosyllabic input as disyllabic (e.g., as \(belif\)). Our analysis contrasted this phonetic explanation by comparing the unique phonetic effect of the burst (its intensity and duration) with the effect of onset type in turn. The definition and measures of burst were obtained from Berent et al. (2008), and the summary statistics of these measures are provided in Table 4.

**Table 4. Duration (ms) and intensity (dB) of burst release in Experiments 1-2.**

| Experiment | Onset Type | Burst Duration (ms) | | Burst Intensity (dB) | |
|------------|------------|---------------------| | Mean | SD | Mean | SD |
| 1          | blif       | 10.11 3.14          | | 60.5 5.42 |
|            | bnif       | 9.58 3.29           | | 59.07 6.29 |
|            | bdif       | 10.28 4.67          | | 62.04 5.03 |
| 2          | blif       | 9.92 3.15           | | 60.4 5.42 |
|            | bnif       | 9.53 3.39           | | 59.09 6.4  |
|            | bdif       | 9.61 3.43           | | 61.65 4.97 |

Our analyses examined the effect of the phonetic properties of the burst on participants’ sensitivity (\(d'\)), and they were conducted separately for the suppression and control conditions. To test participants’ sensitivity to phonetic cues, we first entered onset type in the first step, and then forced burst duration and intensity (together) as the last predictor. Results (Table 5) showed that, in the control condition of both experiments, phonetic cues uniquely captured less than 8% of the variance (Experiment 1: \(\Delta R^2=0.032\); Experiment 2: \(\Delta R^2=0.079\)), and this effect was either significant (in Experiment 2) or marginally significant (in Experiment 1). Interestingly, once suppression was
administered, the unique effect of phonetic cues was no longer reliable in either of the experiments. Thus, participants in our experiments were sensitive to phonetic cues, but this effect was eliminated (rather than increased) by articulatory suppression.

A second set of analyses next investigated whether participants were also sensitive to the phonological structure of the syllable. To assess the unique phonological effect of onset type, we reversed the order of predictors. In these models, the phonetic properties of the burst were entered first, whereas onset type was entered last. We found that participants were highly sensitive to onset type even after controlling for phonetic factors, and this effect obtained in both experiments irrespective of suppression. Not only did the unique effect of onset type survive suppression, but its size (all $\Delta R^2>0.46$) was far larger than that of that of the burst (all $\Delta R^2<0.08$). We conclude that the phonological effect of onset type is not subsumed by the phonetic properties of the burst, and it obtains irrespective of articulatory suppression. These findings challenge both the role of auditory/phonetic factors and the *motor embodiment* account.

Additional challenges to the auditory/phonetic account are presented by the documentation of the onset hierarchy among dyslexic participants—individuals whose auditory/phonetic systems are demonstrably impaired (Berent et al., 2013). Other evidence against the auditory/phonetic explanation is presented by the past results with printed materials, mentioned earlier (e.g., Tamási & Berent, 2014, Experiment 3; Lennertz, 2010, Experiment 4). These results showed that people respect the full onset hierarchy even in the absence of auditory input. Furthermore, regression analyses suggested that the sensitivity to syllable structure is inexplicable by the orthographic similarity of the stimuli to the English lexicon. These findings indicate that onset
hierarchy is possibly shaped by abstract linguistic restrictions, rather than statistical orthographic knowledge alone.

Table 5. The unique effect of (A) phonetic cues (burst intensity and duration); and (B) onset type in step-wise regression analyses of sensitivity (d’ ) in Experiments 1-2. In each experiment, the analysis is conducted separately for the suppression and control conditions.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Condition</th>
<th>Step</th>
<th>Predictor</th>
<th>Δ $R^2$</th>
<th>$\Delta F$</th>
<th>df</th>
<th>$P$ value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Control</td>
<td>1</td>
<td>onset type</td>
<td>0.517</td>
<td>94.078</td>
<td>1, 88</td>
<td>0***</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>burst intensity and duration</td>
<td>0.032</td>
<td>3.076</td>
<td>2, 86</td>
<td>0.051†</td>
</tr>
<tr>
<td></td>
<td>Suppression</td>
<td>1</td>
<td>burst intensity and duration</td>
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<td>2.726</td>
<td>2, 87</td>
<td>0.071†</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>onset type</td>
<td>0.49</td>
<td>93.425</td>
<td>1, 86</td>
<td>0***</td>
</tr>
<tr>
<td>2</td>
<td>Control</td>
<td>1</td>
<td>onset type</td>
<td>0.592</td>
<td>127.75</td>
<td>1, 88</td>
<td>0***</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
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<td>2.539</td>
<td>2, 86</td>
<td>0.085†</td>
</tr>
<tr>
<td></td>
<td>Suppression</td>
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<td>burst intensity and duration</td>
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<td>2.469</td>
<td>2, 87</td>
<td>0.091†</td>
</tr>
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<td></td>
<td></td>
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<td>onset type</td>
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<td>125.306</td>
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<tr>
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<td>Control</td>
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<td>onset type</td>
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<td>1, 82</td>
<td>0***</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
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<td>7.311</td>
<td>2, 80</td>
<td>0.001**</td>
</tr>
<tr>
<td></td>
<td>Suppression</td>
<td>1</td>
<td>burst intensity and duration</td>
<td>0.103</td>
<td>4.661</td>
<td>2, 81</td>
<td>0.012†</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>onset type</td>
<td>0.464</td>
<td>85.804</td>
<td>1, 80</td>
<td>0***</td>
</tr>
<tr>
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<td></td>
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<tr>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

($\dagger$-p<0.1; *-p<0.05; **-p<0.01; ***-p<0.001)
We next asked whether the effect of onset structure in our experiments with printed materials (Experiments 3-4) likewise reflects such abstract knowledge. To address this question, we assessed several statistical properties of the printed materials, including the number of orthographic neighbors (i.e., the number of words obtained by substituting a single letter), the neighbors’ summed frequency, the word’s bigram count (i.e., number of words sharing two adjacent letters in the whole word) and its bigram frequency. The summary statistics of these properties are provided in Table 6.

Table 6. The statistical properties of the materials used in Experiments 3-4.

<table>
<thead>
<tr>
<th>Onset Type</th>
<th>Number of Neighbors</th>
<th>Neighbors’ Frequency</th>
<th>Bigram Count</th>
<th>Bigram Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>blif</td>
<td>3</td>
<td>3.04</td>
<td>93.93</td>
<td>29.69</td>
</tr>
<tr>
<td>bnif</td>
<td>0</td>
<td>1.04</td>
<td>80.77</td>
<td>12.99</td>
</tr>
<tr>
<td>bdif</td>
<td>1</td>
<td>1.73</td>
<td>107.62</td>
<td>10.59</td>
</tr>
</tbody>
</table>

We contrasted the effect of these statistical measures and onset structure in a series of step-wise regression analyses. Given that the superior discrimination of sonority falls (e.g., *ibif*) clearly violates the *grammatical* account (most likely, due to a visual verification strategy discussed earlier), we limited the analyses to obstruent-initial syllables (e.g., *blif, bnif, bdif*). To measure the unique effect of statistical properties, we first forced onset type into the model and then entered the statistical properties (number of neighbors, neighbors’ frequency, bigram count, and bigram frequency) together as the last predictor. We next gauged the unique effect of onset type by reversing the order of predictors, with onset type entered in the last step. Because the effect of onset type

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8The neighborhood measures were obtained from the Speech and Hearing Lab Neighborhood Database (Nusbaum, Pisoni, & Davis, 1984), and the bigram measures were based on Kučera and Francis (1967) database, excluding words that contain apostrophes, hyphens or spaces.
obtained irrespective of suppression\textsuperscript{9}, these regression analyses were conducted across suppression conditions in both experiments. To further ensure that suppression did not affect the unique effect of onset type, we then repeated these analyses under the suppression condition only. All analyses used sensitivity (d’) as the dependent measure. Results from both experiments (Table 7) showed that statistical properties did not uniquely capture participants’ behavior. By contrast, the unique effect of onset type was significant even after controlling for the contribution of statistical properties. Critically, the unique effect of onset type was significant in both experiments even under the suppression condition. These results converge with previous findings, suggesting that the onset hierarchy cannot be explained only by statistical similarity of the stimuli. The fact that these conclusions obtain with printed materials, and even under suppression, further challenges both the auditory/phonetic and the motor embodiment accounts. Together, these findings suggest that the restriction on onset structure might emanate from an abstract grammatical source.

Summarizing, then, this dissertation examined whether the restrictions on syllable structure reflect abstract linguistic knowledge, or whether they are embodied in sensory and motor constraints. Contrary to the sensory embodiment account, we found that the effect of syllable structure obtains irrespective of stimulus modality (auditory or printed materials), and it is inexplicable by either phonetic cues or the orthographic similarity of the materials to English words.

\textsuperscript{9} In Experiment 3, onset type did not interact with other experimental factors. In Experiment 4, although there was a 3-way (suppression x onset type x list) interaction, the effect of onset type among the obstruent onsets was virtually identical in either suppression conditions. This higher order interaction in Experiment 4, then, was mostly likely due to the \textit{lbif}-type syllables that were not presented in the regression analyses. Therefore, we conducted the regression analyses across suppression conditions in both experiments.
Table 7. The unique effect of (A) statistical properties (number of orthographic neighbors, neighbors’ frequency, bigram count and frequency of the whole word); and (B) onset type in step-wise regression analyses in Experiments 3-4. Data is comprised of d’ responses to the obstruent-initial syllables (e.g., blif, bnif, bdif).

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Condition</th>
<th>Step</th>
<th>Predictor</th>
<th>$\Delta R^2$</th>
<th>$\Delta F$</th>
<th>df</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>onset type</td>
<td>0.123</td>
<td>11.464</td>
<td>1, 82</td>
<td>0.001**</td>
</tr>
<tr>
<td>3</td>
<td>Across Suppression</td>
<td>2</td>
<td>statistical properties</td>
<td>0.077</td>
<td>1.88</td>
<td>4, 78</td>
<td>0.122</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>statistical properties</td>
<td>0.158</td>
<td>3.715</td>
<td>4, 79</td>
<td>0.008**</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>onset type</td>
<td>0.041</td>
<td>4.044</td>
<td>1, 78</td>
<td>0.048*</td>
</tr>
<tr>
<td></td>
<td>Suppression</td>
<td>1</td>
<td>onset type</td>
<td>0.17</td>
<td>16.811</td>
<td>1, 82</td>
<td>0***</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>statistical properties</td>
<td>0.082</td>
<td>2.125</td>
<td>4, 78</td>
<td>0.086*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>statistical properties</td>
<td>0.199</td>
<td>4.916</td>
<td>4, 79</td>
<td>0.001**</td>
</tr>
<tr>
<td></td>
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<td>2</td>
<td>onset type</td>
<td>0.052</td>
<td>5.46</td>
<td>1, 78</td>
<td>0.022*</td>
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<td>4</td>
<td>Across Suppression</td>
<td>1</td>
<td>onset type</td>
<td>0.165</td>
<td>16.169</td>
<td>1, 82</td>
<td>0***</td>
</tr>
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<td></td>
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<td>2</td>
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<td>4, 78</td>
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<td>2.896</td>
<td>4, 79</td>
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<td>Suppression</td>
<td>2</td>
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<td>7.204</td>
<td>1, 78</td>
<td>0.009**</td>
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<td></td>
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<td>onset type</td>
<td>0.074</td>
<td>6.588</td>
<td>1, 82</td>
<td>0.012*</td>
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<td>4, 78</td>
<td>0.379</td>
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<td>statistical properties</td>
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<td>5.33</td>
<td>1, 78</td>
<td>0.024*</td>
</tr>
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</table>

(†-p<0.1; *-p<0.05; **-p<0.01; ***-p<0.001)

Our results do not support the articulatory embodiment account either. We found that articulatory suppression clearly impaired participants’ overall performance, a finding that could reflect the contribution of articulatory simulation to perception. Critically,
suppression spared the effect of onset type. These results are consistent with the previous TMS findings of Berent and colleagues (Berent et al., 2015). As in our present study, the disruption to the articulatory motor system by TMS did impair overall sensitivity \( (d') \) in the syllable count task, but participants’ sensitivity to the onset hierarchy remained intact even under TMS.

The convergence between our behavioral experiments and the TMS research is of great importance because methodologically, they complement each other. Indeed, each method of suppression exhibits both advantages and disadvantages. TMS has the advantage of targeting specific motor sites without imposing additional attentional demands that are likely associated with mechanical suppression. However, mechanical suppression can address several potential limitations of the previous findings from TMS (Berent et al., 2015). First, TMS disruption might not suppress the articulator of interest fully, and it typically targets only a single articulator at a time (e.g., either tongue or lip but not both). Moreover, TMS effects may not be selective, as the electromagnetic pulses could also disrupt adjacent cortical regions that are irrelevant to articulatory motor control. Finally, TMS might impair other language-relevant functions, rather than motor activities alone. Therefore, in the evaluation of the motor embodiment account, one needs to consider both behavioral and TMS findings. The convergence between our present results and the previous TMS findings is thus significant. The results from both studies indicate that English speakers might possess broad grammatical preferences that are irreducible to articulatory simulation, statistical properties or auditory cues. Articulatory simulation might well contribute to speech perception, but it does not subsume the grammatical effect of syllable structure.
References


### Appendices

Appendix A. Monosyllabic nonwords used in Experiments 1-4.

<table>
<thead>
<tr>
<th>Large sonority rise</th>
<th>Small sonority rise</th>
<th>Sonority plateau</th>
<th>Sonority fall</th>
</tr>
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<tbody>
<tr>
<td>blif</td>
<td>bwif</td>
<td>bdif</td>
<td>lbif</td>
</tr>
<tr>
<td>brap</td>
<td>bnaph</td>
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<td>tpak</td>
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</table>
Appendix B. Example stimuli presentation of Experiment 4.

B1. Prime “blif”.
B2. Target “BLIF”.