The production-perception link in phonologically-conditioned pre-velar /æ/-raising

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1 Introduction

In order to successfully perceive speech, listeners must parse the acoustic signal into individual sounds and map these phonetic sounds onto the phonemes in their phonological inventory. The nature of this mapping, however, is not clear, and different theories to explain it exist (Nguyen, Wauquier, & Tuller, 2009). Prototype theories, such as the featurally underspecified model (Lahiri & Reetz, 2002), are more abstractionist and propose that each phoneme has a single abstract representation, and the incoming sound is mapped to the most similar phoneme. In contrast, exemplar theories propose that each sound a speaker hears is stored as an exemplar of a particular phoneme, along with contextual information such as phonological context and speaker information (Nguyen et al., 2009). Each phoneme is thus represented by a series of exemplars, and contextual information is taken into account when categorizing sounds in incoming speech (Nguyen et al., 2009). Some questions stemming from this include whether or not it is viable to only have one representation of a particular phoneme, and what information contributes to prototype or exemplar formation. More specifically, does an individual's production have a role in their own category formation, and if so, what is that role?

One area in which the answers to these questions might be found is in the perception of phonological processes which vary across speakers, such as pre-velar /æ/-raising in North American English. In this process, some speakers raise /æ/ before /g/, but not /k/ (e.g. in bag, but not back) while others do not raise /æ/ in either context (see, for example, Bauer and Parker (2008); Koffi (2013); Mellesmoen (2018); Rosen and Skriver (2015); Stanley (2018, 2019); Wassink, Squizzero, Scanlon, Schirra, and Conn (2009)). Raising primarily occurs in Canada and in the parts of the United States near the Canadian border. My impressionistic observation, based on discussions with both raisers and non-raisers, suggests that the perception of this pre-velar /æ/-raising also varies amongst speakers:

It is perceptually salient for Americans, but not Canadians. Since there are differences in the perception of pre-velar /æ/ raising, and these differences pattern similarly to the production of /æ/-raising, there may be a link between the perception and production of pre-velar /æ/-raising.

In addition to overall effects of production on perception, there may also be phonological context effects. It is possible that listeners may perceive /æ/ at lower F1s before /g/ than /k/, and that this may be conditioned by their own productions (i.e. raisers may have different boundaries between /æ/ and /ɛ/ before /g/ and /k/, but non-raisers may not). There is some evidence that phonological context effects in perception which display the same patterns as those effects in production. For example, voiced velar stops are both produced (Lisker & Abramson, 1967; Nearey & Rochet, 1994; Volaitis & Miller, 1992) and perceived (Benkí, 2001; Nearey & Rochet, 1994) at longer VOTs than voiced alveolar and labial stops. Furthermore, the vowel coarticulation effects present in the production of /s/ and /ʃ/ are also present in perception (Mann, 1980; Mitterer, 2006; Yu, 2010). However, while these correlations do seem to exist, whether there is actually a link between production and perception is less studied (Yu, 2019). If individuals' phonological context effects in perception are linked to their production, individuals' perception should correlate with their own prooduction. That is, in the case of pre-velar /æ/-raising, raisers and non-raisers should display different phonological context effects in perception.

The purpose of this study is to investigate the possible link between the production and perception of pre-velar /æ/-raising, as well as possible phonological context effects in perception. If a production-perception link exists, one place it may be evident is in the boundary between /æ/ and /ɛ/. If this is the case, non-raisers should have a higher boundary between /æ/ and /ɛ/ than raisers. If there are phonological context effects, the boundary between /æ/ and /ɛ/ should be higher in the raising environment (before /g/) than elsewhere. If phonological context effects on perception occur in conjunction with production effects, this difference may only be present for raisers.

Section 2 discusses the phenomenon of pre-velar /æ/-raising, including previous studies on production and preliminary observations on perception. Section 3 describes previous research on how individual differences are related to speech perception, including the correlation of individuals' production and perception. Section 4 outlines the goals and hypotheses of the current study on the possible link between the production and perception of pre-velar /æ/-raising. Sections 5 and 6 lay out the methodology experiment and analysis of the data, respectively. Section 7 presents the results of both the production and perception study. Section 8 discusses the implications of the results with reference to previous studies and the hypotheses of the current study, as well as possible directions for future research. Section 9 concludes with a summary of the main findings of the study and a brief discussion of its theoretical implications.

2 Pre-velar /æ/-raising

Pre-velar /æ/-raising occurs when /æ/ is raised before the voiced velar stop (/g/). This process is variable in North American English, where some speakers raise and others do not. Stanley (2018, 2019) conducted an online self-report survey and found that /æ/-raising is common in Canada, as well as northern areas of the United States near the Canadian border. /æ/-raising has been documented in British Columbia (Mellesmoen, 2016, 2018), Oregon (Becker, Aden, Best, & Jacobson, 2016), southern Alberta (Rosen & Skriver, 2015), central Minnesota (Koffi, 2013), Seattle (Freeman, 2014; Wassink, 2015), Vancouver (Esling & Warkentyne, 1993) and Wisconson (Bauer & Parker, 2008).

Pre-velar /æ/-raising may vary according to social factors other than region, as well as linguistic factors. In terms of linguistic factors, Stanley (2018) found that raising was more common in high frequency words and in regular past tense forms (word ending in *-ed*). For social factors, Wassink et al. (2009) found that /æ/-raising is more common in casual speech and that men raise more than women.

The perceptual saliency of pre-velar /æ/-raising may be correlated with listeners' own production of the process. For Americans from areas of the states where /æ/-raising is not common (Stanley, 2018, 2019), raised /æ/ may be perceptually very salient, whereas this is not the case for Canadians who participate in /æ/-raising. Several Americans have spontaneously observed to me that when Canadians say *b[æ]g* it sounds like *b*[ɛ]*g* or *b*[e]*g*, suggesting that they hear the raised /æ/ as a mid vowel rather than a low vowel.

Conversely, as a Canadian who participates in /æ/-raising, I was not aware that the /æ/ in *bag* was any different than the one in *back*, prior to having this pointed out to me. Furthermore, conversations I've had with other Canadians suggest that they aren't aware of it, and may not even perceive a difference between the two /æ/s even when they are told about it. This suggests that /æ/-raising may not be perceptually salient for those who participate in raising.

These observations suggest two things. First, that perception of /æ/-raising is variable, and, second, that it may, in some way, be related to listeners' own participation in the process, whereby non-raisers perceive raising and raisers don't. The nature of this link, and whether it exists at all, is not clear. However, there is some evidence to suggest that differences in listener dialect may be correlated with differences in perception (Allbritten, 2011; Clopper, Pierrehumbert, & Tamati, 2010; Dufour, Nguyen, & Frauenfelder, 2007;

Flanigan & Norris, 2000; Jacewicz & Fox, 2012; Schmidt, 2013; Willis, 1972).

Some studies show that listeners classify sounds based on the phonemic system of their own dialect. Jacewicz and Fox (2012) had participants classify vowels from two American English dialects and found that listeners were better at identifying vowels in their native dialect than in a non-native dialect. Clopper et al. (2010) conducted a word recognition task in which listeners heard words spoken by Northern and Midland American English speakers and had to type the word they heard. They found that certain dialect features, such as the *cot-caught* merger, affected perception. For example, speakers from dialects with the *cot-caught* merger were more likely to perceive /ɔ/ and /ɑ/ as the same vowel than those from regions without the merger. Flanigan and Norris (2000) conducted a vowel identification task with a talker from southern Ohio and found that their listeners interpreted the talker with respect to their own vowel systems such that vowels present in their native dialects were identified better by listeners than non-native vowels.

Similar effects have been found in languages other than English as well. In French, Dufour et al. (2007) found that Southern French speakers perceived /ɛ/ and /e/ spoken by a standard French speaker as the same vowel, whereas standard French speakers perceived them as different vowels in a repetition priming task. These differences are consistent with whether or not /ɛ/ and /e/ are contrastive in the listener's dialect. Further, in South American Spanish, Schmidt (2013) found that speakers of dialects where /s/ is weakened were more likely to perceive final /h/ as /s/ than speakers of dialects where /s/ is not weakened.

Other studies (Allbritten, 2011; Clopper et al., 2010) show that certain dialect features are more perceptually salient to non-native listeners than native listeners. Allbritten (2011) had participants rate how southern an American English speaker sounded in a matched guise task and found that non-Southern listeners relied more on drawl and velar fronting in their classifications than Southern listeners. In addition to the effect mentioned above, Clopper et al. (2010) also found that dialect-specific features are most salient to speakers of other dialects, particularly for listeners who had moved across dialect areas as children, and thus had exposure to multiple dialects. My observations about the perceptual saliency of pre-velar /æ/-raising are consistent with these findings, as they suggest that this raising is more salient to listeners who lack this feature in their own dialects.

3 Individual differences in speech perception

Variation in speech perception may be due to factors such as mobility, exposure and geography, as well as both the speaker's and listener's native dialect or language (Allbritten, 2011; Boomershine, 2006; Flanigan & Norris, 2000; Hay & Drager, 2010; Iverson & Evans, 2007; Kraljic, Brennan, & Samuel, 2008). The more a listener has in common with the speaker, the more accurate perception is. Listeners who share a language, dialect, or place of origin with a speaker perceive that speaker more accurately than those that do not (Dufour et al., 2007; Flanigan & Norris, 2000; Jacewicz & Fox, 2012; Liang & van Heuven, 2007; Schmidt, 2013). Furthermore, the degree of similarity between languages, dialects and geographical regions affects speech perception (Allbritten, 2011; Boomershine, 2006; Flanigan & Norris, 2000; Iverson & Evans, 2007).

Even when native language or dialect and geographical factors are held constant, differences exist between listeners due to exposure and mobility. Higher degrees of both lead to better perception of non-native dialects (Clopper, 2014; Dahan, Drucker, & Scarborough, 2008; Eisenstein, 1986). For example, L2 speakers perceive dialects they learn and are exposed to better than those they have limited or no exposure to (Eisenstein, 1986).

Despite the ability of such factors to account for some variation in speech perception, individual differences still exist within groups of speakers. This variation has been proposed to be accounted for by individual differences in areas such as cognitive processing (Stewart & Ota, 2008; Sullivan, 2019; Yu, 2010) and production (Fox, 1982; Frieda, Walley, Flege, & Sloane, 2000; Ingram & Park, 1997; Newman, 2003; Perkell et al., 2004). In the realm of cognitive processing, some studies have correlated perception task results with Autism Quotient (AQ) scores (Baron-Cohen, Wheelwright, Skinner, Martin, & Clubley, 2001), finding that high AQ individuals appear to pay more attention to phonetic detail whereas low AQ individuals pay more attention to higher levels of grammar (Stewart & Ota, 2008; Sullivan, 2019; Yu, 2010).

More relevant to the current study, in the realm of production, some studies have found correlations between individuals' production and perception (Fox, 1982; Frieda et al., 2000; Ingram & Park, 1997; Newman, 2003; Perkell et al., 2004). The idea that production and perception are linked is corroborated by an fMRI study which found that production and perception activate the same areas of the brain (Grabski et al., 2013). While the link between production and perception might be explained in part by regional dialect, as suggested by studies which found correlations between perception and dialect (Allbritten, 2011; Clopper et al., 2010; Dufour et al., 2007; Flanigan & Norris, 2000; Jacewicz & Fox, 2012; Schmidt, 2013; Willis, 1972), there is within-group variation in both production and perception (Evans & Iverson, 2007), which suggests that dialect alone is not sufficient to explain this relationship. Several studies (Evans & Iverson, 2007; Fridland & Kendall, 2012; Sumner & Samuel, 2009), suggest that individual variation in production and perception exists within dialects, and that there may be a link between production and perception at the individual level.

Evans and Iverson (2007) tracked the production and perception of vowels in university students who grew up in the same town and were speakers of the same Northern English dialect across their first two years of university, during which time they were exposed to Southern English dialects. In addition to speaking the same dialect, these speakers would all have had similar language exposure growing up, and yet they showed variation in both their production and perception. Speakers who had more Northern accents at the start of the study perceived vowels in a way that mapped more closely to Northern productions than their more Southern-accented counterparts throughout the duration of the study. This suggests that their variation in perception, which cannot be accounted for by exposure or regional dialect, may be the result of a link between production and perception.

Furthermore, Sumner and Samuel (2009) studied the perception of /ɹ/-dropping in three groups of North American English speakers: New York City (NYC) speakers who /ɹ/ dropped, NYC speakers who didn't /ɹ/ drop and non-NYC speakers who didn't /ɹ/-drop. Thus there was dialectal (and exposure) variation between the non-NYC group and the NYC groups, and production variation between the NYC groups. They found that listeners' perception of /ɹ/-dropping varied depending on both these factors. Listeners from New York City who /ɹ/-dropped behaved differently in a long-distance phonological priming task than those who did not /ɹ/-drop; however, both groups also behaved differently compared to listeners from non-/ɹ/-dropping regions on both the long-distance task and on regular lexical and phonological priming tasks. This suggests that individual production may be linked to perception, despite the fact that regional dialect also affects perception.

Finally, Fridland and Kendall (2012) found that both the Euclidian distance between listeners' productions of /e/ and /ɛ/ and their regional dialect had an effect on their classification of vowels in the centre of an /e/ to /ɛ/ continuum, although regional dialect appeared to have a stronger effect. At the individual level, there was considerable variation both within and between dialect regions such that there was overlap between individuals from all three regions, although, on average, the regions showed distinct Euclidian distances. Individual participants' boundary between /e/ and /ɛ/ in perception was correlated with their boundary in production, suggesting that there may be a relationship between the individuals' production and perception.

However, it should be noted that there are also studies that fail to find links between production and perception at the individual level. For example, studies on cue-weighting of laryngeal contrasts in stops which employ a similar production and perception paradigm to that used in this study have failed to find evidence of a correlation between production and perception at the individual level (Idemaru & Holt, 2013; Idemaru, Holt, & Seltman, 2012; Schertz, 2014; Schertz, Cho, Lotto, & Warner, 2015; Shultz, Francis, & Llanos, 2012). This could suggest that there is no, or a minimal, link between production and perception at the individual level; however, given that studies in other areas (Evans & Iverson, 2007; Fridland & Kendall, 2012; Sumner & Samuel, 2009) or using different methodologies (Clayards, 2019) have found individual effects, it is possible that this lack of effect could be due to other factors, such as group differences obscuring individual effects, or because this combination of tasks doesn't capture individual effects. Regardless, it seems like there may be a relationship between perception and production at the individual level, although the best way to capture it is not clear.

4 Linking the production and perception of prevelar /æ/-raising

The goal of the current study is to investigate the relationship between production and perception in phonological-conditioned pre-velar /æ/-raising. More specifically, I am investigating if there is a relationship between listeners' production of /æ/ in the pre-/g/ context and their perceptual boundary between /æ/ and /ɛ/, if this perceptual boundary is phonologically conditioned (i.e. whether it is different before /g/ than before /k/) and whether or not phonological context and production work together to influence the perceptual boundary.

In order to test this, I had native North American English participants complete a word list reading task to gather production data and a forced choice word identification task to gather perception data. My participants were Canadians and Americans who have lived in the greater Toronto area (GTA) for at least one year and would, therefore, have had exposure to raising. If my results are consistent with previous studies (Mellesmoen, 2018; Rosen & Skriver, 2015; Stanley, 2018, 2019), Canadians will raise /æ/ before /g/ in production whereas Americans who are not from a state near the Canadian border will not. In other words, Canadians will be "raisers" and Americans, "non-raisers".

Figure 1 illustrates the possible outcomes of the experiment by showing the predicted perceptual boundaries between /æ/ and /ɛ/ based on raising and context by raisers and non-raisers who are all exposed to both raising and non-raising. This scenario is represented in my experiment with Canadians as raisers and Americans as non-raisers living in the same city where they would have had the opportunity to be exposed to both raisers and non-raisers. Boundary here refers to the point at which listeners perceive /æ/ and /ɛ/ in equal amounts, with each vowel being perceived more frequently on one side of the boundary or the other. The x-axis represents the coda consonant (/g/ or /k/). The y-axis represents the height of the perceived boundary where 0 would be the boundary in an environment where raising never occurs and speakers never hear raising, and 100 represents the boundary in an environment where /æ/ is always raised and non-raised /æ/ is never heard. The red lines represent non-raisers and the blue lines, raisers. The first four panels represent four logical possibilities based on wether raising (both in the environment and by the speaker) and phonological context (coda consonant) affect the perceptual boundary between /æ/ and /ɛ/. The fifth and sixth panels represent additional possibilities in which only the speaker's production of raising, but not the amount of raising in the environment, affects perception (alongside the presence or absence of a phonological context effect).

The first question I seek to answer is: Is there a relationship between listeners' production of /æ/ in the pre-/g/ context and their perceptual boundary between /æ/ and /ɛ/ across the /æ/-/ɛ/ continuum? In other words, do raisers have a higher boundary than non-raisers? If there is a shared representation between production and perception, people who raise in the pre-/g/ context should perceive /æ/ at lower F1s (at higher places of articulation) than those who do not raise, as in the third and fifth panels in Figure 1. If listeners' environment contributes to their perception, a pattern like in panel 3 would be expected, whereas if only their own production has an effect, the pattern in panel 5 would be expected. If there is no shared representation, there should be no distinguishable difference between raisers and non-raisers, as in the first panel in Figure 1.

The second question is: Is the perceptual boundary conditioned by phonological context? In other words, is the boundary different before /g/ (in the raised environment) than before /k/ (the non-raised environment)? If the boundary is phonologically conditioned, listeners should perceive /æ/ at lower F1s (higher places of articulation) before /g/ than before /k/, as in the second panel of Figure 1. If the boundary is not phonologically conditioned, listeners should perceive /æ/ the same way, regardless of the voicing of the following velar, as in the first panel of Figure 1.

Finally, I would like to know how phonological context and listeners' production of /æ/ interact with each other in the perception of /æ/ and /ɛ/ across the /æ/-/ɛ/ continuum. If the boundary is neither phonologically conditioned, nor conditioned by the listener's production of /æ/, all listeners should have the same boundary, regardless of their own productions, or the following velar consonant, although the boundary might

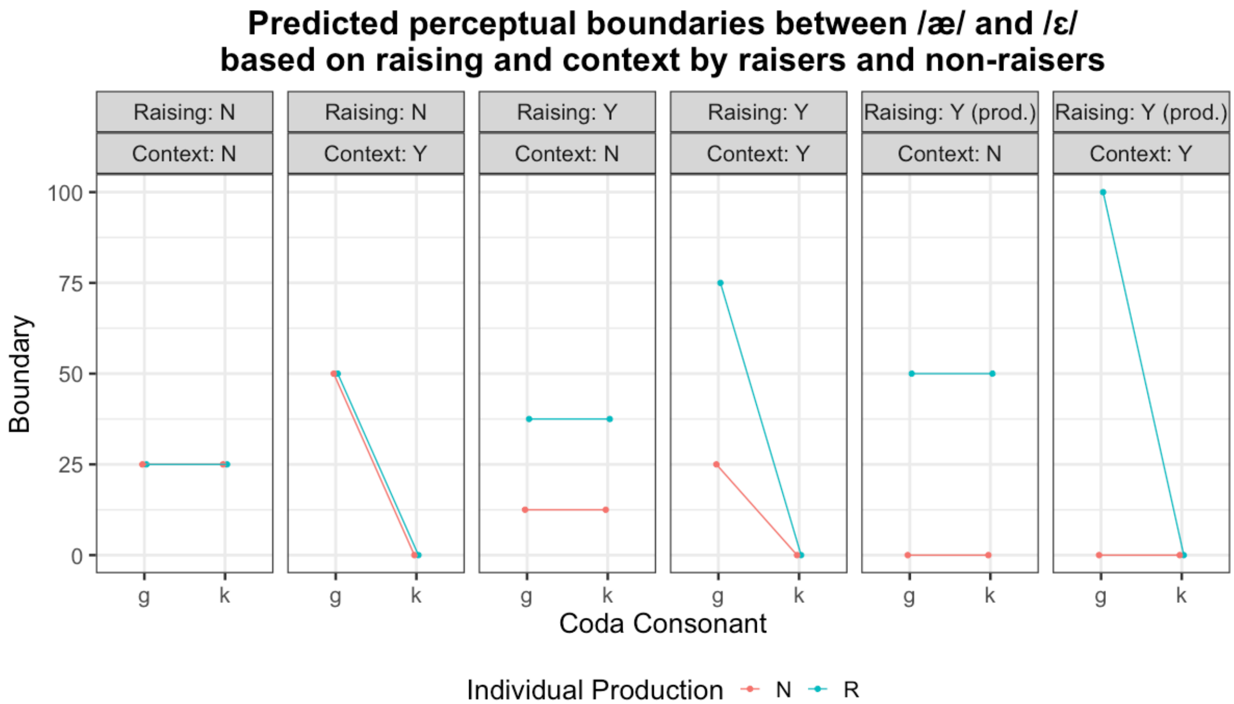

Figure 1: Predicted perceptual boundaries between /æ/ and /ɛ/ based on raising and context by raisers and non-raisers who are all exposed to both raising and non-raising. The x-axis represents the coda consonant (/g/ or /k/). The y-axis represents the height of the perceived boundary where 0 would be the boundary in an environment where raising never occurs and speakers never hear raising, and 100 represents the boundary in an environment where /æ/ is always raised and non-raised /æ/ is never heard. The red lines represent non-raisers and the blue lines, raisers. Each panel represents predictions based on whether or not raising (both in the environment and by the speaker) and context (coda consonant) affect the perceptual boundary between /æ/ and /ɛ/.

reflect the proportion of raising they hear in their community, as shown in the first panel of Figure 1.

If the boundary is phonologically conditioned, but is not conditioned by the listener's production of /æ/, all listeners should still behave the same, but they should have a higher boundary (lower F1) before /g/ than before /k/, as shown in the second panel of Figure 1. The boundary before /g/ might be higher than if phonological context had no effect since speakers are hearing a higher proportion of raised /æ/ before /g/ than they are across both contexts.

If the boundary is not phonologically conditioned, but it is conditioned by listeners' production of /æ/, listeners should perceive /æ/ the same, regardless of the following consonant; however, raisers should perceive /æ/ at lower F1s (higher places of articulation) since their productions contain both raised and unraised /æ/. The boundary between /æ/ and /ɛ/ for raisers should fall somewhere between their raised (before /g/) and unraised (before /k/) productions of /æ/ since all their productions, and not just their raised productions, should help set the boundary, as shown in the third and fifth panel of Figure 1, depending on whether exposure to raising has an effect.

If the boundary is conditioned both by phonological context (voicing of the following velar stop) and listeners' own productions of /æ/, all listeners should perceive /æ/ the same before /k/, since they produce /æ/ similarly in this context and should perceive /æ/ at lower F1s before /g/ than /k/. Raisers should perceive /æ/ at lower F1s (higher places of articulation) than non-raisers, since their own productions also contribute to raising the boundary. If the interaction is additive in nature, raisers' boundary in the /g/ context may be higher than if one of the factors had no effect, as shown in the fourth and sixth panels of Figure 1. As with panels 3 and 5, the difference between panels 4 and 6 has to do with whether exposure has an effect (panel 4) or not (panel 6).

5 Methodology

5.1 Participants

Eighteen native speakers of North American English (9 female, 8 male, 1 other; age range 19-61, mean age 28.44) completed the experiment. All participants had lived in Toronto for at least one year. Seven were American and eleven were Canadian. The American participants were from California (2), Conneticut, New Hampshire, New Mexico, Massachusetts and Virginia. The Canadian participants were from the Greater Toronto Area (5), other regions of Ontario (3), Alberta, Nova Scotia and Manitoba. Participants had normal hearing and normal or corrected vision. Participants received compensation for their time. Three additional participants were excluded from the analysis because they were not native speakers of American English.

5.2 Language background questionnaire

Participants completed a language background questionnaire to ensure that they met the requirements of the study. The questionnaire included questions about the participants' age, residential history, linguistic knowledge and history, and language use. The complete questionnaire can be found in Appendix A.

5.3 Production: Word list reading task

Participants completed a word list reading task, the purpose of which was to obtain measures of their vowel spaces and productions of /æ/, /ɛ/ and /e/ in the /_g/ and /_k/ contexts.

5.3.1 Stimuli

The stimuli consisted of 80 words. Of these words, 58 were target words, consisting of 36 pre-velar words with /æ/, /ɛ/ and /e/ followed by /g/ or /k/ and 20 words containing 10 English monophthongal vowels in both the /b_d/ and /b_t/ contexts. These later 20 words were used to establish participants' vowel spaces. The remaining 24 words were fillers. Of the 36 pre-velar target words, which can be found in Table 1, 3 contained /eg/, 7 contained /ek/, 6 contained /ɛg/, 7 contained /ɛk/, 6 contained /æg/ and 7 contained /æk/. Thirty-four of the words were monosyllabic, and, as much as possible, words in the different contexts contained the same consonant before the vowel. In the 2 bisyllabic words, the target vowel was in the first syllable, and the velar consonant was the coda in that syllable. A complete list of stimuli can be found in Appendix B.

Table 1: Production target words

Initial Consonant	**/eg/(3)**	**/ek/(7)**	**/ɛg/(6)**	**/ɛk/(7)**	**/æg/(6)**	**/æk/(7)**
l	plague	lake	leg	fleck	lag	lack
v/b	vague	bake	beg	beck	bag	back
m		make	meg	mecc	mag	mac
n		snake	neg	neck	nag	knack
p		spake	peg	peck		pack
t		take		tech	tag	tack
s		sake	segment	sector	sag	sack
r	craig					

5.3.2 Procedure

The production study was implemented in PsychoPy (Peirce et al., 2019). The words were presented individually to participants in black sans serif text at the centre of the screen. The entire 80-word list was presented to each participant in three separate blocks, with the words randomized separately in each block for each participant. Participants were instructed to say each word clearly and press the space bar between each word. The production session took place in a sound attenuated booth and was recorded using a Sound Devices 722 digital audio recorder and a DPA 4011 unidirectional cardioid microphone at a sampling rate of 48kHz with 24 bits per sample.

5.4 Perception: Forced choice word identification task

Participants completed a forced choice word identification task to determine their perception of vowels across an /æ/-/ɛ/ continuum before /g/ and /k/.

5.4.1 Stimuli

Stimuli consisted of two 9-step continua from /æ/ to /ɛ/. The first ranged from /bægsən/ to /bɛgsən/, and the second from /bæksən/ to /bɛksən/. Nonce words were chosen for this task to eliminate the possibility of lexical frequency effects (Stanley, 2018, 2019).

To select a speaker for manipulation, 4 native male speakers of North American English, 2 American (one from the Midwest, one for California) and 2 Canadian (one from Ontario, one from Alberta), were recorded saying /bægsən/, /bɛgsən/, /bæksən/ and /bɛksən/ three times each. The stimuli were presented to them orthographically as *bagson*, *begson*, *beckson* and *backson*, respectively. For each speaker, duration measurements for the target vowels (/æ/ and /ɛ/), as well as F1 and F2 measurements at the midpoint of the target vowel, were taken for each token in Praat (Boersma, 2001). The 2 American speakers were selected as possible candidates for manipulation as they had the largest differences in F1 and F2 between /ɛ/ and /æ/.

A perception pre-test was run to select one of the two American speakers for the main perception task and determine the maximum and minimum F1 and F2 for the stimuli. One token each of /bɛgsən/ and /bɛksən/ were selected for each speaker to be manipulated. These tokens were selected such that they were clear and, within each speaker, they were the most similar to each other. Each token was annotated for initial consonant, target vowel (/ɛ/) and the rest of the word in Praat. The vowels were then extracted and manipulated using a Praat script which adjusted the F1, F2 and duration of the vowel to create a 10-step continuum. F1 and F2 were manipulated to be flat across the duration of the vowel. The script then spliced the vowel back into the rest of the word. This manipulation occurred separately for each speaker and token. Each speaker's F1, F2 and duration were manipulated independently, such that their continuum ranged from a vowel with their shortest duration, lowest F1 and highest F2 at one end (most /ɛ/-like) to their highest duration, highest F1 and lowest F2 at the other end (most /æ/-like). All continuum steps were equidistant for all three factors. This manipulation was the same for both tokens. Each token was saved as a wav file and converted to mp3 for the experiment.

The procedure for this perception pre-test was similar to that of the main perception procedure. Participants heard each token and were asked whether the word they heard was either /bɛgsən/ or /bægsən/, or /bɛksən/ or /bæksən/, which were presented orthographically, as above. Trials were blocked by speaker, and at the end of each block, participants were asked to comment on how natural they thought the speaker was. After completing both speakers, they were asked to rate which speaker they found most natural, and provide any additional comments.

Fourteen participants completed this pre-test. On the forced-choice task, participants responded differently to the two speakers. For the Californian speaker, while the proportion of /æ/ responses increased as the vowel became more /æ/-like, there were no clear floor or ceiling effects. For the speaker from the Midwest, on the other hand, a more clear s-curve with some floor and ceiling effects developed, suggesting that this participant's recordings might be best for manipulation. The feedback portions of the form also support this, as most participants preferred the Midwestern speaker to the Californian speaker. In their comparison of the two speakers, 6 participants found the Midwestern speaker more natural, 3 participants found the Californian speaker more natural, 4 participants found both speakers equally natural and 1 participant did not answer this question. Participants' comments also indicate that they preferred the Midwestern speaker to the Californian speaker. For these reasons, this speaker was selected for the experiment.

A second perception pre-test was run to select a duration for the stimuli and verify that perception of the endpoints of the continuum was categorical. The Midwestern speaker's /bɛgsən/ and /bɛksən/ tokens selected above were manipulated using the same procedure as above, this time with a 9-step F1 and F2 continuum and a 5-step duration continuum. F1 and F2 were manipulated to range from the speaker's minimum F1 (631Hz) and maximum F2 (2096Hz) to his maximum F1 (883Hz) and minimum F2 (1544Hz) in 9 equidistant steps. Each step on this F1-F2 continuum was then manipulated such that a separate token was created for each duration on the 5-step duration continuum. These steps were equidistant and ranged from the speaker's minimum vowel duration (69ms) to his maximum vowel duration (234ms) from the analysis above. Each token was saved as a wav file and converted to mp3 for the experiment.

The duration pre-test included the same forced-choice task as the first pre-test. The stimuli were blocked by continuum (/b_ksən/ or /b_gsən/), and participants heard 2 blocks for each continuum. Blocks alternated between the two continua. Each block contained one repetition of each stimulus item. Eight participants completed the duration pre-test. For all durations, participants responded near-categorically towards the endpoints of the continuum. Participants had near-categorical responses at more points approaching the endpoints of the continuum at the duration of 193ms, so this was selected as the duration for the stimuli.

The stimuli used in the main experiment were the tokens from the 9-step continuum at 193ms used in the duration pre-test. These tokens ranged in F1 and F2 from the speaker's minimum F1 (631Hz) and maximum F2 (2096Hz) (most /ɛ/-like) to his maximum F1 (883Hz) and minimum F2 (1544Hz) (most /æ/-like) in 9 equidistant steps and all had a duration of 193ms. Their intensity was normalized to 70dB. Each token was saved as a wav file and converted to mp3 for the experiment.

5.4.2 Procedure

The perception experiment was implemented using jsPsych (de Leeuw, 2015) using scripts modified from those developed by Hyoung Seok Kwon and Na-Young Ryu. Participants heard each token individually and were presented with words representing the endpoints from the continuum the word came from (e.g. *begson* /bɛgsən/ or *bagson* /bægsən/). They then clicked on whichever of those two words they thought they heard. Trials were blocked by continuum. Each participant heard two blocks of each continuum containing 5 repetitions each, for a total of 4 blocks and 180 trials (10 repetitions of each continuum). Blocks alternated by continuum, beginning with the /b_ksən/ continuum. Each of the first two blocks contained 4 practice trials (2 repetitions of each of the endpoints of the continuum) to familiarize the participant with the task and the trial. Stimuli were randomized within each block and for each participant.

5.5 Order of Tasks

Participants began by signing the informed consent form (Appendix C). They always completed the production task before the perception task and had a break between the two tasks while the perception task was being set up. This was done to avoid biasing their production as the perception task was quite transparent. It is possible that hearing their production could have biased participants' performance in the production task; however, the results suggest that there was no effect. The language background questionnaire was either completed before the production task, or between the production and perception tasks. Following the study, participants were debriefed, given their compensation and thanked for their time.

6 Analysis

6.1 Production

For the production task, the first vowel in each word was annotated from the onset of the vowel to the beginning of the closure of the following stop in Praat (Boersma, 2001). F1 and F2 measurements were taken at the 1/3 point of each target vowel using a Praat script. The 1/3 point of the vowel was chosen to minimize possible effects of any diphthongization (Fox & Jacewicz, 2009).

To look for possible errors, the mean and standard deviations of F1 and F2 for each word were calculated by participant. Any token that was more than two standard deviations away from the mean was excluded. No tokens met this criteria, so none were excluded. Additionally, each participant's vowel space tokens were visually examined for possible errors. Any tokens that patterned with a vowel other than the one they were supposed to have were excluded as possible errors. (This does not include tokens for vowels which were overlapping.) Based on this, the 6 tokens listed in Table 2 were excluded. Note that as only one token of each word per participant was excluded, each exclusion left two tokens of the target word for that participant for analysis.

Table 2: Excluded vowel space tokens

Participant	**Token**	**Patterns with**
4	/bɔd/	o
5	/bɑt/	u
5	/bɑd/	u
16	/bot/	ʌ
19	/bod/	ɔ, ɑ
20	/bɔd/	o

After exclusions, F1 and F2 for the vowels were Lobanov normalized by participant using the normVowels() function from the phonR package (McCloy, 2016) in R (R Core Team, 2018). All the vowels were entered into the function together. While data for /e/ before /g/ and /k/ was collected, this was excluded from the following analyses as it patterned independently from /æ/ for F1 and F2 whereas there was sometimes overlap between /æ/ and /ɛ/ for these two variables.

Full interaction mixed effects linear regression models were constructed to assess the effect of velar voicing on the realization of /æ/ using the lmer() function from the lme4 package (Bates, Mächler, Bolker, & Walker, 2015) in R (R Core Team, 2018). The F1 or F2 values for all the /æ/ and /ɛ/ tokens were the response variables. The predictor variables were vowel (/æ/ or /ɛ/), coda consonant (/t/, /d/, /k/ or /g/) and the speaker's country of origin (Canada or the United States), as well as all interactions between these variables. Vowel (/æ/ = - 0.5; /ɛ/ = 0.5) and country (Canada = -0.5, United States = 0.5) were sum coded. Coda consonant was Helmert-coded such that /g/ was compared to the other three consonants, /d/ was compared to the voiceless consonants and /t/ and /k/ were compared to each other. This variable was coded this way as the expected effect was that /æ/ would be raised before /g/ relative to the other consonants. /d/ was compared to the voiceless consonants to look for a possible effect of voicing. The random effects were random intercepts for participant and item and a random slope for vowel by participant. Other possible random slopes were the slopes for vowel and the interaction between vowel and consonant by participant and the slope for country by item. However, the model failed to converge when these slopes were added, so they were excluded.

To examine the nature of the difference of the three-way interaction between country, vowel and coda consonant in the F1 model, a post-hoc regression analsis was done by running separate regression models for each group (country), which were identical to the above models except that country and all interactions involving country were removed as predictor variables. This enabled me to look at whether participants in each country were raising /æ/ before /g/ to see if the difference between the two countries was one of raising vs. not raising, or one of degree of raising.

Each participant's mean normalized F1 of /æ/ in the /g/ context was subtracted from their mean normalized F1 of /æ/ in the /d/ context to get a measure of their individual degree of raising. This measure was chosen because difference in F1 was the primary measure of interest, and incorporating both F1 and F2 using Euclidean distance would have required incorporating a more complex measure for the direction of the difference between /æd/ and /æg/. The primary purpose of this measure was to serve as a measure of individual production for the perception analysis; however, a linear regression model was also constructed with the lm() function in R (Bates et al., 2015) to assess the effect of speaker country of origin on this measurement with the difference in F1 as the response variable and country as the predictor variable. Country was sum coded as above.

6.2 Perception

Perception data was coded as 0 if the participant selected the /ɛ/ variant, or 1 if they selected the /æ/ variant. Two full interaction mixed effects logistic regression models were constructed using the glmer() function from the lme4 package (Bates et al., 2015) and the lmerTest package (Kuznetsova, Brockhoff, & Christensen, 2017) to obtain significance values in R (R Core Team, 2018) to assess the effect of coda consonant, country of origin and individual production (using the measure introduced in the last paragraph of section 6.1 - the difference between mean F1 for /æ/ before /g/ and /d/) on perception. The response variable for both models was the perception task results (/æ/ (1) or /ɛ/(0)). The predictor variables were coda consonant (/k/ or /g/), continuum step and either participant country of origin (Canada or the United States) or individual production. Two separate models were used as country of origin and individual production were highly correlated.

Coda consonant (/g/ = -0.5, /k/ = 0.5) and country (Canada = -0.5, United States = 0.5) were sum coded. Individual production values were centred around the mean. The F1 of each continuum step was used as a proxy measure for each step. This measure was normalized by taking the z-score of each continuum step so the numbers were comparable to the other predictor variables. The random effects were a random intercept for participant and random slopes for continuum step, coda consonant and the interaction between continuum step and coda consonant.

7 Results

7.1 Production

Figure 2 shows the production of /æ/ and /ɛ/ before /g/, /k/, /d/ and /t/ for Canadian and American speakers. The large text represents the mean F1 and F2, the smaller text represents individual tokens. The ellipses represent 1 standard deviation of the normal density contour. /æ/ is lower and further back than /ɛ/ for both groups of speakers, although this difference is larger for Canadian speakers. Both vowels are higher before voiced consonants than voiceless consonants in both places of articulation (which is consistent with some previous work, see, for example Hillenbrand, Clark, and Nearey (2001)); however, voiced velars are higher than voiced alveolars whereas voiceless velars are lower than voiceless alveolars (although these differences are quite small). Most interestingly, whereas /æg/ patterns with the other /æ/s in terms of backness and height for Americans, it is more front and raised than the other /æ/s for Canadians, patterning more closely with /ɛk/ and /ɛt/.

The linear regression model for F1 (Table 3) shows significant effects for the difference between the production of vowels before /g/ compared to the other vowels, as well as /d/ compared to the voiceless vowels. In both cases, F1 is lower (i.e. the vowel is

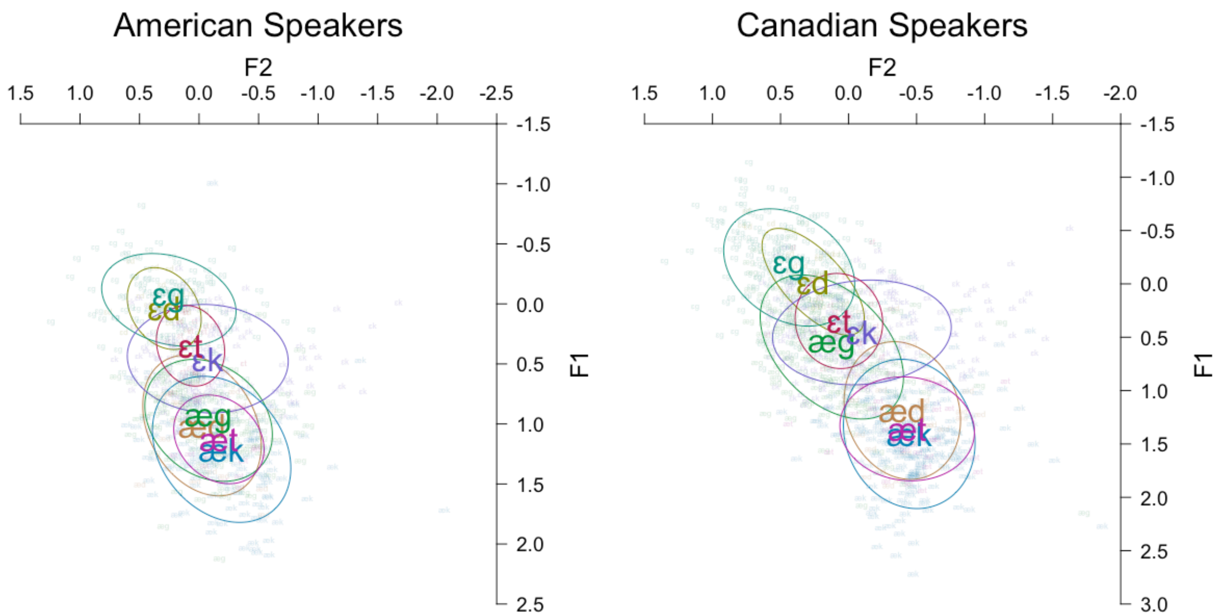

Figure 2: Vowel space charts for /æ/ and /ε/ before /g/, /k/, /d/ and /t/ for Canadian and American Speakers. F1 and F2 values are Lobanov normalized

higher). There is also a significant effect for vowel quality, whereby F1 is lower for /ε/ than /æ/. There is no overall effect of country, nor is there a significant interaction between vowel quality and any of the coda consonant comparisons. There is, however, an interaction between the comparison between coda /g/ and country whereby the difference in F1 between /ε/ and /æ/ is greater for Canadians than Americans. There is also a three way interaction between the comparison between coda /g/ and the other consonants, vowel and country whereby Canadians have a greater difference in F1 between /æg/ and /æ/ before the other consonants, than Americans. Post-hoc analyses of this three-way interaction show a significant interaction between vowel and the difference between /g/ and the following consonant for Canadians (Estimate = 0.31106, *SE* = 0.13531, df = 21.98010, t = 2.299, p = 0.0314), but not Americans (Estimate = -0.16754, *SE* = 0.14468, df = 22.00000, t = -1.158, p = 0.25926), suggesting that Canadians raise /æ/ before /g/, but Americans do not.

The linear regression model for F2 (Table 4) shows a significant effect for the difference between the production of vowels before /g/ compared to the other vowels, but not for the differences between any other vowels. Vowels have higher F2s (i.e. they are more front) when followed by /g/ than by other vowels. There is also a significant effect of vowel whereby /ε/ has higher F2s than /æ/. There is a significant two-way interaction between country and the comparison between /g/ and the other consonants. The difference in F2 between /ε/ and /æ/ is greater for Canadians than Americans. There is also a significant

Table 3: Mixed effects linear regression model with F1 as the response variable, vowel (V: /æ/ or /ɛ/), coda consonant (codaC: /t/, /d/, /k/ or /g/) and the speaker's country of origin (country: Canada or the United States), random intercepts for participant and item and a random slope for vowel by participant

	Estimate	***SE***	**df**	**t-value**	**p**	
(Intercept)	6.442e-01	4.028e-02	2.309e+01	15.994	<0.001	***
codaCg_others	-4.007e-01	6.669e-02	2.221e+01	-6.009	<0.001	***
codaCd_[-voi]	-2.844e-01	1.189e-01	2.221e+01	-2.393	0.0256	*
codaCk_t	-8.679e-02	1.121e-01	2.221e+01	-0.774	0.4468	
Vɛ	-9.283e-01	9.125e-02	3.249e+01	-10.173	<0.001	***
countryUS	-4.859e-03	2.770e-02	5.008e+01	-0.175	0.8614	
codaCg_others:Vɛ	7.175e-02	1.334e-01	2.221e+01	0.538	0.5960	
codaCd_[-voi]:Vɛ	-2.160e-01	2.377e-01	2.221e+01	-0.909	0.3732	
codaCk_t:Vɛ	-4.181e-02	2.241e-01	2.221e+01	-0.187	0.8537	
codaCg_others:countryUS	3.392e-01	4.178e-02	1.549e+03	8.119	<0.001	***
codaCd_[-voi]:countryUS	4.839e-02	7.447e-02	1.549e+03	0.650	0.5159	
codaCk_t:countryUS	-1.749e-02	7.021e-02	1.549e+03	-0.249	0.8033	
Vɛ:countryUS	1.004e-01	1.021e-01	2.107e+01	0.983	0.3367	
codaCg_others:Vɛ:countryUS	-4.786e-01	8.357e-02	1.549e+03	-5.727	<0.001	***
codaCd_[-voi]:Vɛ:countryUS	1.828e-02	1.489e-01	1.549e+03	0.123	0.9023	
codaCk_t:Vɛ:countryUS	3.410e-02	1.404e-01	1.549e+03	0.243	0.8082	

three-way interaction between country, vowel and the comparison between /g/ and the other consonants. Canadians have a greater difference in F2 between /æg/ and /æ/ before the other consonants than Americans.

Figure 3 shows the difference between participants' mean F1 for /æg/ and mean F1 for /æd/ arranged from the largest difference to the smallest difference. Most of the participants with larger differences are Canadian, while most of the participants with smaller differences are American. A linear regression model (Table 5) shows that this effect is significant.

7.2 Perception

The proportion of /æ/ responses in the perception task by continuum point and coda consonant are shown in Figure 4. As F1 gets higher (the vowel becomes more /æ/-like), the proportion of /æ/ responses increases. The proportion of /æ/ responses is higher when the coda consonant is /g/ than /k/ across the continuum, particularly in the middle of the continuum, and at higher values of F1. The mixed effects logistic regression models

Table 4: Mixed effects linear regression model with F2 as the response variable, vowel (V: /æ/ or /ɛ/), coda consonant (codaC: /t/, /d/, /k/ or /g/) and the speaker's country of origin (country: Canada or the United States), random intercepts for participant and item and a random slope for vowel by participant

	Estimate	***SE***	**df**	**t-value**	**p**	
(Intercept)	-0.02468	0.08013	26.83754	-0.308	0.7604	
codaCg_others	0.27716	0.12708	22.02714	2.181	0.0401	*
codaCd_[-voi]	0.19091	0.22649	22.02714	0.843	0.4083	
codaCk_t	0.08774	0.21354	22.02718	0.411	0.6851	
Vɛ	0.35303	0.15841	25.81606	2.229	0.0348	*
countryUS	0.07027	0.05415	17.82846	1.298	0.2109	
codaCg_others:Vɛ	-0.03906	0.25416	22.02714	-0.154	0.8793	
codaCd_[-voi]:Vɛ	0.18555	0.45299	22.02714	0.410	0.6860	
codaCk_t:Vɛ	0.13826	0.42708	22.02718	0.324	0.7492	
codaCg_others:countryUS	-0.35077	0.02838	1549.00123	-12.359	<0.001	***
codaCd_[-voi]:countryUS	0.06488	0.05058	1549.00120	1.283	0.1998	
codaCk_t:countryUS	-0.00793	0.04769	1549.00148	-0.166	0.8680	
Vɛ:countryUS	-0.20287	0.09684	18.33756	-2.095	0.0503	.
codaCg_others:Vɛ:countryUS	0.29783	0.05676	1549.00124	5.247	<0.001	***
codaCd_[-voi]:Vɛ:countryUS	-0.09076	0.10117	1549.00120	-0.897	0.3698	
codaCk_t:Vɛ:countryUS	-0.03293	0.09538	1549.00148	-0.345	0.7300	

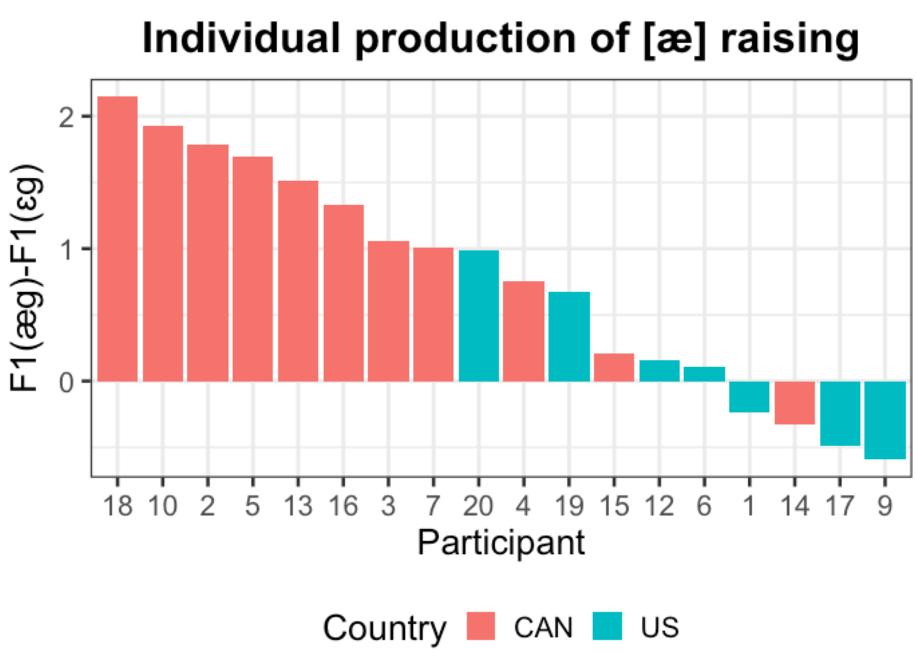

Figure 3: Difference between mean F1 of /æ/ before /g/ and /d/ by participant

Table 5: Linear regression model with difference in F1 (between /æg/ and /æd/) as the response variable and the speaker's country of origin (Canada or the United States) as the predictor variable

	Estimate	*SE*	t-value	p	
(Intercept)	0.5952	0.1047	5.685	<0.001	***
countryUS	-0.5524	0.1679	-3.290	0.00461	**

(Tables 6 and 7) show main effects of continuum step (F1) and coda consonant consistent with these observations. There are no interactions between continuum step and coda consonant in either model.

Perception does not appear to vary by the speaker's country of origin. As shown in Figure 5, both Americans and Canadians display the same pattern. This is reflected in the regression model (Table 6) as there is no main effect of country, and no two-way interactions between country and either continuum step or coda consonant. Crucially, there is also no three-way interaction between country, coda consonant and continuum step, which suggests there are no differences between the two groups.

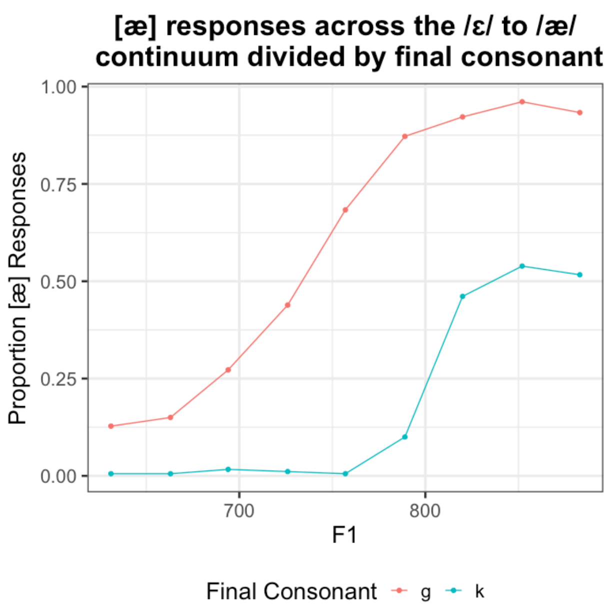

Figure 4: Difference between mean F1 of /æ/ before /g/ and /k/ by participant

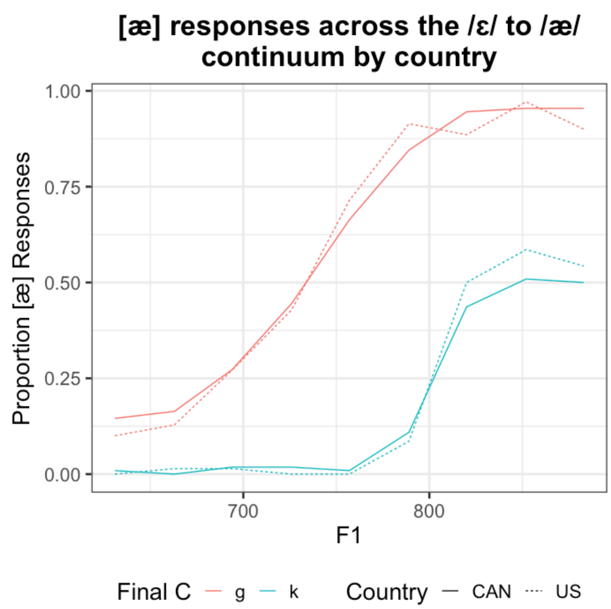

Figure 5: Difference between mean F1 of /æ/ before /g/ and /k/ by participant

Figure 6 compares participants' production to their overall perception. Proportion of /æ/ responses does not seem to vary as degree of /æ/-raising increases, suggesting that there is no effect of production on overall perception. Figure 7 compares participants' production to their perception in the two different contexts, as measured by their pro-

Table 6: Full interaction mixed effects logistic regression model with perception response (/æ/ or /ɛ/) as the response variable, coda consonant (codaC: /k/ or /g/), participant country of origin (country: Canada or the United States) and continuum step (F1step) as predictor variables, a random intercept for participant and random slopes for continuum step, coda consonant and the interaction between continuum step and coda consonant

	Estimate	***SE***	**z-value**	**p**	
(Intercept)	-1.15486	0.15967	-7.233	< 0.001	***
F1step	2.68583	0.35789	7.505	< 0.001	***
codaCk	-4.25070	0.54845	-7.750	< 0.001	***
countryUS	0.08175	0.29183	0.280	0.779	
F1step:codaCk	-0.23356	0.45062	-0.518	0.604	
F1step:countryUS	-0.03136	0.70302	-0.045	0.964	
codaCk:countryUS	0.32039	1.06666	0.300	0.764	
F1step:codaCk:countryUS	0.54815	0.85813	0.639	0.523	

portion of /æ/ responses in the pre-/k/ context subtracted from their proportion of /æ/ responses in the pre-/g/ context. This figure shows more variation than in the overall response rate (Figure 6); however there is no clear pattern. Difference in proportion of /æ/ responses does not appear to increase as degree of raising in production increases, suggesting that there is no effect of production on contextual response rate. These observations are born out in the regression model (Table 7) which shows no significant effects for the individual production measure, or the interactions between the production measure and coda consonant, the production measure and continuum step or the production measure, coda consonant and continuum step, on the perception of /æ/.

In summary, the results of the study show differences in production across groups and in perception across coda consonant context, but no correlation between production and perception. In production, Canadians raise /æ/ before /g/, but Americans do not. In perception, /æ/ is perceived more often before /g/ than /k/, but this does not vary by country or individual production.

8 Discussion

The results of the production study indicate that Canadians and Americans behave differently in terms of pre-velar /æ/-raising. Canadians raise /æ/ before /g/, but Americans do not. This is consistent with the findings of Stanley (2018;2019), as none of the Americans came from states near the American border where /æ/-raising is common in his study. With regards to the other studies, none of the participants came from areas that had been

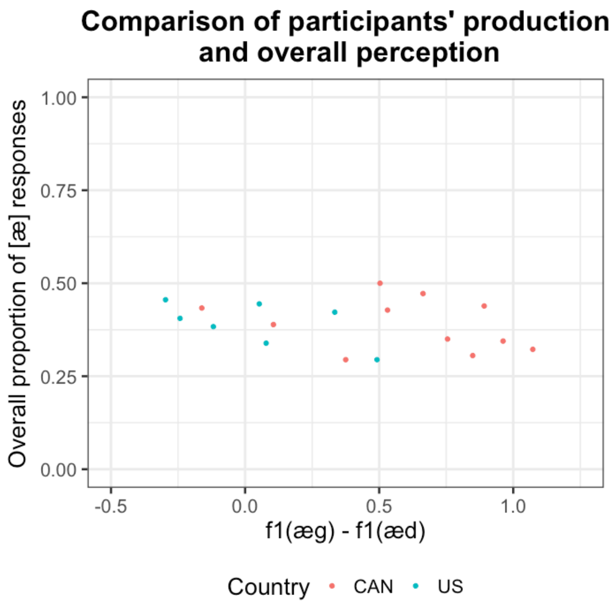

Figure 6: Scatterplot of participants' overall proportion of [æ] responses in the perception task (y-axis) and their difference in F1 between /æg/ and /æd/ in production (x-axis)

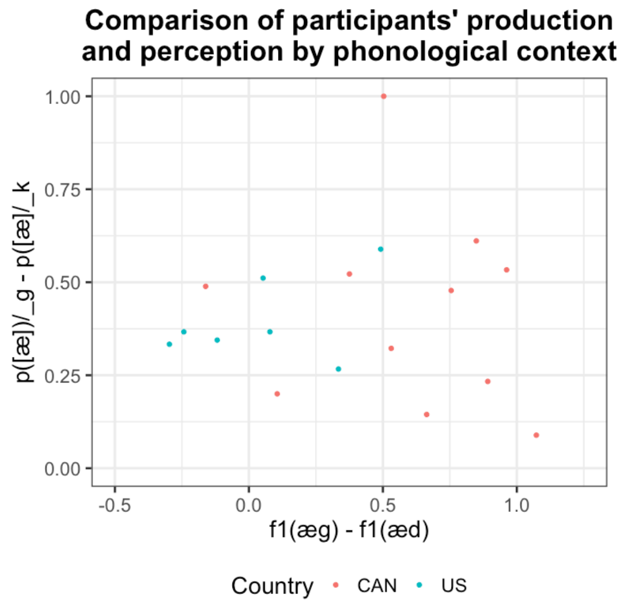

Figure 7: Scatterplot of participants difference proportion of [æ] responses in the /g/ and /k/ contexts in the perception task (y-axis) and their difference in F1 between /æg/ and /æd/ in production

Table 7: Mixed effects logistic regression model with perception response (/æ/ or /ɛ/) as the response variable, coda consonant (codaC: /k/ or /g/), individual production (deltaF1) and continuum step (F1step) as predictor variables, a random intercept for participant and random slopes for continuum step, coda consonant and the interaction between continuum step and coda consonant

	Estimate	***SE***	**z-value**	**p**	
(Intercept)	-1.17908	0.15729	-7.496	6.57e-14	***
F1step	2.67879	0.35525	7.541	4.68e-14	***
codaCk	-4.30762	0.55871	-7.710	1.26e-14	***
deltaF1	-0.37092	0.31649	-1.172	0.241	
F1step:codaCk	-0.33548	0.43477	-0.772	0.440	
F1step:deltaF1	-0.09993	0.81312	-0.123	0.902	
codaCk:deltaF1	0.03156	1.25524	0.025	0.980	
F1step:codaCk:deltaF1	-1.07184	0.94876	-1.130	0.259	

previously studied, except Alberta (Rosen & Skriver, 2015), so, while the results don't contradict those findings, they can't confirm them either. However, while these group differences appear to be present, I don't have enough participants in each group, particularly the American group, to make robust generalizations from. Therefore, any results relating to group differences ought to be considered tentative.

In the case of Alberta, the results seem to be contradictory to the previous findings, as the participant from Alberta did not appear to participate in /æ/-raising in this study, unlike in Rosen and Skriver (2015) where participants were found to raise /æ/ before /g/. In fact, the two Canadian participants who do not appear to participate in /æ/-raising in this study are both from the Canadian prairies. It is possible that this is because these participants do not raise, but it could also be because they raise /æ/ before both /d/ and /g/, so the measure of raising in Figure 3 is not a good measure of their raising. However, two participants is not enough to generalize from, so more participants from this region would be needed to make a more conclusive statement.

Amongst the American participants, there were two participants who appear to participate in /æ/-raising. As with the Canadian non-raisers, this can't really be generalized from without more data, but it is worth noting that, whereas other participants spent the majority of their childhood and youth (up to age 18) in one place, with any change in location occurring before age 6, these participants moved several times in their youth. They also both had a Canadian parent, although this was also true of some of the other participants. While one or both of these things may be related to their /æ/-raising, data from more American /æ/-raisers would be necessary to determine if there are any effects.

The main research questions in this study focus on the perception of /æ/ in the prevelar context and whether it is correlated with phonological context or the participant's own production of /æ/ in these contexts. The results of the perception study indicate that /æ/ is perceived more often before /g/ than /k/ across a continuum ranging from /æ/ to /ɛ/ suggesting an effect of phonological context, but that this doesn't vary by the participant's country of origin, or their own production. This is most similar to the predictions in panel 2 of Figure 1, in which only phonological context, and not the listeners' production or raising, conditions the boundary between /æ/ and /ɛ/. This can be seen in Figure 5, in which both raisers (Canadians) and non-raisers (Americans) switch from perceiving /æ/ to /ɛ/ between an F1 of 700 and 750Hz before /g/ and between 800 and 850Hz before /k/. The patterns for both groups are similar, with a higher boundary (lower F1) before /g/ than /k/.

In terms of phonological context, the results of the perception study indicate that participants perceive /æ/ more often across the /æ/-/ɛ/ continuum in the pre-/g/ context than the pre-/k/ context. There is evidence that the perceptual boundary between /æ/ and /ɛ/ shifts depending on this context. Figure 4 shows that /ɛ/ is perceived near-categorically at the first five steps of the continuum (lower F1 values), whereas /g/ is never perceived categorically as /ɛ/, despite the fact that the continuum was created from an /ɛ/ token. Furthermore, the proportion of /æ/ responses begins to rise before

/g/ almost right away, between the second and third steps, whereas, the perception of /æ/ doesn't increase before /k/ until after the fifth step, suggesting /ɛ/ is perceived at higher F1s before /k/ than /g/, and thus the boundary between /æ/ and /ɛ/ is lower before /k/ than before /g/.

Perception of /æ/ before /k/ levels out at about 0.500 in the last three steps of the continuum, whereas perception of /æ/ before /g/ begins to level out at a near categorical level at the fourth last step of the continuum. The fact that the pre-/g/ continuum levels out before the pre-/k/ continuum suggests that /æ/ is perceived at lower F1s before /g/ than /k/ and that the boundary between /æ/ and /ɛ/ is higher before /g/ than /k/.

One surprising finding was that perception of /æ/ before /k/ levels out around the 0.500 mark. There are a few possible reasons for this. On one hand, it is possible that the continuum needed to be expanded to include higher and lower F1s to allow more listeners to hit the floor and ceiling. This might also explain why perception of /æ/ before /g/ never hits the floor. However, it should be noted that floor and ceiling effects were observed in both pre-tests, and that the speaker with the larger F1 and F2 range sounded less natural to listeners, so this could also have created unnatural sounding tokens. On the other hand, this could be due to the fact that the tokens were manipulated from a natural /ɛ/ token, rather than a natural /æ/ token, since /æ/ is longer and has different diphthongization than /ɛ/ (Crystal & House, 1988; Fox & Jacewicz, 2009). There is some evidence for this, as several speakers heard /ɛ/ categorically before /k/. The fact that the curve does level out, despite being at 0.500, also supports this idea. Having tokens manipulated from both /æ/ and /ɛ/ could reveal whether or not this is indeed the case. However, in spite of this, there are still differences in perception of /æ/ before /g/ and /k/, which suggests that the perceptual boundary of the vowel shifts depending on the voicing of the velar consonant.

It is also possible that differences in higher formants (F3 and above) could account for the differences in perception across the two continua. Since the vowel for each continuum came from different tokens, and only F1 and F2 were manipulated, there are still differences in the vowels between the two continua. In order to know if this had an effect, it would be necessary to use only one vowel token and embed it in both contexts. For example, taking the /bɛksən/ vowel, creating the continuum and embedding the resulting vowels in both the /b_gsən/ and /b_ksən/ contexts.

In terms of the listener's own production, there does not seem to be a correlation between individual production and perception. If this were the case, participants' proportion of /æ/ responses in the perception experiment would be expected to increase as their degree of raising increases. However, as shown in Figure 6, participants' overall perception of /æ/ does not vary with their production of /æ/-raising, suggesting that there is no correlation between individual production and overall perception.

There is also no interaction between production and phonological context. Figure 7 shows participants' mean proportion of /æ/ responses in the production task relative to the difference in perception of /æ/ in the /g/ and /k/ contexts. If there was a relationship between these two we would expect to see a discernible pattern whereby the difference in perception between the /k/ and /g/ continua increased as degree of raising increased, however this is not the case, suggesting that any link between production and perception may not be dependent on individuals' production.

In addition to there being no correlation between individual production and perception, or interaction between production and phonological context, there is also no effect of country of origin on perception, or interaction between country and phonological context. This is unexpected given that some previous studies (Evans & Iverson, 2007; Fridland & Kendall, 2012; Sumner & Samuel, 2009) have found such effects, although it is possible that there is no effect, given that there are also other studies that have not found a link between production and perception at the individual level (Idemaru & Holt, 2013; Idemaru et al., 2012; Schertz, 2014; Schertz et al., 2015; Shultz et al., 2012). However, the fact that, when I was debriefing my participants, all the American participants were aware that Canadians raise /æ/ before /g/, whereas the Canadian participants were not, seems to suggest that, at some level, perception is correlated, if not with individual production, at least with the linguistic environment an individual was raised in.

There are a few possible explanations for why there was no group or individual effect of production on perception in this study. One is that there may be an effect of exposure. In this case, the fact that all participants had lived in Toronto for at least a year and been exposed to raising (as evidenced by Americans' awareness of Canadian pre-velar /æ/-raising), may have altered the way the participants completed the task. It is also possible that, as the experiment took place in Toronto and was administered by a Canadian, they assumed the speaker in the task was Canadian, and so made their judgements accordingly. Some studies (Hay & Drager, 2010; Niedzielski, 1999) suggest that listeners alter their perception based on factors such as the perceived dialect of the speaker.

Some other studies, such as that of Sumner and Samuel (2009), suggest that exposure may have an effect on perception, however, the effects of this particular study seem to be based on long term exposure. In contrast, Evans and Iverson (2007), found that perception didn't change with exposure across a shorter timespan, more similar to the exposure phase of participants in this study. Of the American participants, most came to Toronto for school, and none had been in Toronto for more than four years. However, as the tasks used in these studies and my own study are all very different, it is not clear whether exposure would have had an effect on my study, or whether or not these two studies are tapping into different aspects of perception.

In order to assess whether or not exposure has an effect on perception in my study, it would be useful to run the study with participants from more homogenous populations which have limited exposure to raising or non-raising. For example, running the study with participants from rural villages in Canada and the United States.

Another possibility is that the task used in the perception study doesn't tap into the aspect of perception that allows Americans, but not Canadians, to be aware of /æ/-raising. It is possible that a different type of perception task would be better at capturing this. Possibilities include a similar kind of task, but with a rating scale rather than a forced choice task, a priming task as was done by Sumner and Samuel (2009), or something like Evans and Iverson (2007)'s goodness optimization procedure in which they had participants judge the goodness of vowel tokens to obtain a best exemplar of a particular vowel. Regardless, more participants are needed to determine if this lack of group effect is robust or not.

A final possibility is that participants treat nonce words differently than real words. Nonce words were used to control for possible lexical frequency effects as there are very few minimal real word CVC quadruplets with /ɛ/ and /æ/ as vowels and /k/ and /g/ as final consonants and, of those quadruplets, none had only high frequency words (e.g. *bag*, *beg* and *back* are all more frequent than *beck*). However, it might be interesting to look at how the results might differ if real words were used rather than nonce words.

9 Conclusion

This study did not find a correlation between production and perception in terms of the height of the perceptual boundary between /ɛ/ and /æ/. Despite this, it has provided some insight into the perception and production of pre-velar /æ/-raising. In the realm of production, the findings of Stanley (2018, 2019) appear to be confirmed. Canadians appear to raise whereas Americans do not; however more participants are needed to confirm this effect. On the other hand, there was no effect of individual or group differences on perception. However, there appears to be a clear effect of phonological context on the perception of /æ/ before velars. It is perceived more often before /g/ than before /k/ across the continuum, suggesting that vowel perception is related in some way to production. As this effect doesn't seem to be correlated to listeners' own productions or their country of origin, this link may have more to do with exposure than individual production.

The fact that the voicing of the following velar consonant has an effect on listeners' perception of /æ/ and /ɛ/ across the continuum, and not just at the ambiguous points in the middle, suggests either that a person can have multiple phonetic representations of the same vowel depending on phonological context, or that there is one representation, but that it can somehow be adjusted based on the following context. It is not, however, clear which of these two possibilities is the case, nor is it clear how they could be differentiated. If it is the later case, one might expect that gradient effects of VOT manipulation in the following consonant would result in changes in vowel percpetion, but that assumes that it is phonetic, rather than phonological, context that the vowel is adjusted for. Regardless, the results do suggest that each vowel cannot be represented by one static, context-independent representation.

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Appendix A: Language Background Questionnaire

Language Background Questionnaire
Participant ID:

The purpose of this questionnaire is to learn something about your language history: what languages you know and what languages you hear on a regular basis.

1. Year of Birth, Age

2. Sex (Circle one): Male , Female, Other, Prefer not to answer

3. As far as you know, is your hearing normal? Yes, No
   If no, please explain:

4. Have you ever been diagnosed with a speech, language or reading problem? Yes, No
   If yes, please explain:

5. Where were you born?

City:
State/Province:
Country:

6. Please list all the places you have lived (you can exclude places you lived for less than 3 months), and what ages you lived there

Location (City, State/Province, Country), Age
e.g. Ottawa, Ontario, Canada, 4-6 years

7. Please answer the following questions about backgrounds of your parents (and other adults who lived in your house while you were growing up).

Birthplace (City, Province/State, Country)
First language(s)

Language(s) they speak to you (give percentages)

8. For each of the following situations, please write the language(s) you prefer to speak

Talking to family:
Talking to friends:
Talking to others:

9. Please answer the following questions about any languages you speak

At what age were you first exposed to this language? (Leave blank for your first language)

Do you feel comfortable speaking this language?
Was/is this language regularly spoken in your home growing up?
Did you regularly speak this language in your home growing up?
In school, was this a language of instruction?
Have you ever taken supplementary classes in this language?

10. What percentage of the time do you currently use each language you speak in the following situations? The percentages in each row should add up to 100%

At home (with family) – speaking
At home (with family) – listening
At school (with friends, classmates, professors) – speaking
At school (with friends, classmates, professors) – listening
At work (with colleagues) – speaking
At work (with colleagues) – listening
In moments of leisure (with friends, in places of leisure/extra-curricular activities) – speaking
In moments of leisure (with friends, in places of leisure/extra-curricular activities) – listening

11. For the following questions, provide a rating on a scale from 1 (beginning learner) to 10 (completely native)

For each language you speak:

How would you rate your ability to speak this language?
How would you rate your ability to understand this language?

Appendix B: Production Stimuli

Target pre-velar stimuli

Initial Consonant	/eg/(3)	/ek/(7)	/ɛg/(6)	/ɛk/(7)	/æg/(6)	/æk/(7)
l	plague	lake	leg	fleck	lag	lack
v	vague	bake	beg	beck	bag	back
m		make	meg	mecc	mag	mac
n		snake	neg	neck	nag	knack
p		spake	peg	peck		pack
t		take		tech	tag	tack
s		sake	segment	sector	sag	sack
r	craig					

Target vowel space stimuli

Vowel	/b_d/	/b_t/
/i/	bead	beat
/ɪ/	bid	bit
/e/	bade	bait
/ɛ/	bed	bet
/æ/	bad	bat
/u/	booed	boot
/o/	bode	boat
/ʌ/	bud	but
/ɔ/	bawd	bought
/ɑ/	bod	bot

Filler stimuli

Hudson

hut

bite

bide

tight

tide

the house
the houses
He houses people
louse
lousy
clout
cloud
loud
lout
light
lied
dragon
wagon
laptop
pencil
goat
cellphone
toon

Appendix C: Consent Form

Informed Consent for "The Production-Perception Link"
Contact researcher: Lisa Sullivan, lisa.sullivan@mail.utoronto.ca
Department of Linguistics, University of Toronto

What is the purpose of this study?
We are interested in learning more about how people produce and understand speech.

Why am I being invited to participate? What will I be asked to do if I decide to participate?
You are being asked to participate in this study because you are a native speaker of North American English. You will be asked to sit in a quiet room and complete the tasks below:

Listen to words, and/or sentences and press buttons to indicate what you heard
Read words and/or sentences (audio recording will be taken)
Complete a language background and demographic questionnaire
Complete a survey about how you pronounce certain words

How long will the task take? Will I be compensated for my participation?
The task will take approximately 30 minutes to complete. You will receive $5 for your participation.

Are there any risks? Are there any costs or benefits to me?
There are no foreseeable risks beyond what would be encountered in everyday life, or costs other than your time. There are no direct benefits to you, but you will be helping to contribute to a better understanding of how humans produce and understand speech.

Can I stop at any time?
You can decide to stop at any time with no negative consequences. You can also tell us after the experiment that you do not want your data to be used, in which case your data will be deleted. We remove identifying information after you leave the session, so we won't be able to delete your data after this point.

What will happen to the data? Will my information be confidential?
We will analyze the responses of all participants. The principal investigator and supervisor will have access to the data. Prior to analysis, any personal information will be removed from the data.

Will the data be used for anything else?
Our findings will be shared with the academic community and possibly the general public, and the recordings may be used in future studies about speech perception. Any personally identifying information will be removed.

How can I find out about the results of this study? Where can I get more information?
If you would like to be informed about the results of this study, or if you have further questions, please contact the researcher, Lisa Sullivan (lisa.sullivan@mail.utoronto.ca) or research supervisor, Jessamyn Schertz (jessamyn.schertz@utoronto.ca). To get more information about your rights as a research participant, please contact the Office of Research Ethics, 416-946-3273, or ethics.review@utoronto.ca.

The research study you are participating in may be reviewed for quality assurance to make sure that all laws and guidelines are followed. If chosen, (a) representative(s) of the Human Research Ethics Program (HREP) may access study-related data and/or consent materials as part of the review. Information accessed by the HREP will be upheld to the same level of confidentiality that has been stated by the research team.

I have read the description above and understand that my participation in this study is voluntary, and that I can stop at any time or ask that my data be discarded. If I have any further questions about the study, I can contact the researcher at the email address above.

______________________	______________________	______________
Name (printed)	Signature	Date
______________________	______________________	______________
Person obtaining consent (printed)	Signature	Date