Different responses to altered auditory feedback in younger and older adults reflect differences in lexical bias

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Conflict of Interest: The authors have no conflicts of interest to report.
Funding statement: This work was supported by a Natural Sciences and Engineering Research Council of Canada (NSERC) Discovery Grant to S. Baum and Social Sciences and Humanities Research Council of Canada (SSHRC) grant 435-2016-0747 to M. Clayards.

Abstract

Purpose: Previous work has found that both young and older adults exhibit a lexical bias in categorizing speech stimuli. In young adults this has been argued to be an automatic influence of the lexicon on perceptual category boundaries. Older adults exhibit more top-down biases than younger adults, including an increased lexical bias. We investigated the nature of the increased lexical bias using a sensorimotor adaptation task designed to evaluate whether automatic processes drive this bias in older adults.

Method: A group of older (n=27) and younger adults (n=35) participated in an altered auditory feedback production task. Participants produced target words and non-words under altered feedback that affected the first formant (F1) of the vowel. There were two feedback conditions that affected the lexical status of the target, such that target words were shifted to sound more like non-words (e.g., *less-liss*) and target non-words to sound more like words (e.g. *kess-kiss*).

Results: A mixed-effects linear regression was used to investigate the magnitude of compensation to altered auditory feedback between age groups and lexical conditions. Over the course of the experiment, older adults compensated (by shifting their production of F1) more to altered auditory feedback when producing words that were shifted towards non-words (*less-liss*) than when producing non-words that were shifted towards words (*kess-kiss*). This is in contrast to younger adults who compensated more to non-words that were shifted towards words compared to words that were shifted towards non-words.

Conclusion: We found no evidence that the increased lexical bias previously observed in older adults is driven by a greater sensitivity to top-down lexical influence on perceptual category boundaries. We suggest the increased lexical bias in older adults is driven by post-perceptual processes that arise as a result of age-related cognitive and sensory changes.

Introduction

The already complex task of speech perception becomes more difficult with age, as sensory and cognitive declines cause listening performance to decrease. Older adults are susceptible to a variety of top-down effects, which can both help and hinder the speech recognition process. They have more difficulty recognizing words with dense phonological neighbourhoods (Sommers & Danielson, 1999; Van Engen, 2017) and have more difficulty inhibiting irrelevant responses (Gazzaley, Cooney, Rissman, & D'Esposito, 2005). They also, however, are able to take advantage of contextual and sentential information, allowing them to perform comparably to younger adults in some cases (see Pichora-Fuller, 2008 for review). The question then arises whether the use of such top-down processes in older adults reflects a processing strategy to compensate for sensory declines, or reflects age-related reorganization of perceptual processes (i.e., changes to mechanisms of speech perception that accompany normal aging). We focused on one specific top-down influence, the lexical bias, to investigate whether the increased reliance on top-down information is inherent to older adults' speech processing.

When categorizing stimuli that vary along an acoustic continuum from a word endpoint to a non-word endpoint (e.g. *less-liss*), listeners exhibit a lexical bias, such that they will categorize more of the continuum as a real word (Ganong, 1980). The lexical bias is a way for listeners to compensate for the variability that occurs in speech production, by biasing the perceptual system to perceive speech in real word categories. In younger adults, this lexical bias has been suggested to reflect shifts to the perceptual boundary between phonemes (Bourguignon, Baum, & Shiller, 2014), such that the lexicon exerts an immediate and automatic influence on phonetic processing. In a series of eye-tracking and gating experiments with younger adults, Kingston, Levy, Rysling, and Staub (2016) found that the lexical bias has an immediate effect on speech processing, suggesting that it occurs in the earliest stages of perception. These results suggest that the lexical bias in younger adults is inherent to the perceptual system. Several studies have found that the lexical bias is larger in older adults, suggesting an increased influence of top-down information during older adults' speech perception (Baum, 2003; Mattys & Scharenborg, 2014).

Here, we investigated the nature of the increased lexical bias in older adults. It is possible that older adults share a similar mechanism with younger adults, which drives the baseline lexical bias but increases across the lifespan, possibly due to a stronger influence of the lexicon (Park & Reuter-Lorenz, 2009; Revill & Spieler, 2012). However, the larger lexical bias in older adults could also be the result of age-related changes to cognitive abilities, including working memory and inhibitory deficits (Hasher & Zacks, 1988). There is evidence that older adults take advantage of top-down contextual information when it is available (Pichora-Fuller, 2008) and that verbal and semantic knowledge remain a strength for older adults (Park & Reuter-Lorenz, 2009), thus the increased lexical bias in older adults could be a compensatory mechanism used to offset declines in sensory perception. In other words, age-related changes in cognition may underlie an additional mechanism that drives the larger lexical bias in older adults and differs from that which drives the lexical bias in younger adults.

The previous work showing evidence for an increased lexical bias in older adults has relied on categorization behaviour to infer perceptual boundaries. This has shed light on the existence of this lexical bias, but did not provide any insight into the nature of the lexical bias itself, as the results relied on explicit behaviour, which can be influenced by post-perceptual decision biases (e.g., Borsky, Tuller, & Shapiro, 1998). To investigate the nature of older adults' larger lexical bias, we turned to sensorimotor adaptation in speech as a means to avoid any potential post-perceptual compensatory influence. It is well established that speakers will compensate for real-time auditory perturbations during speech production (Purcell & Munhall, 2006b, 2006a). For example, if the first formant (F1) frequency in the vowel /ɛ/ (as in *head*) is shifted down in real-time to sound more like /ɪ/ (as in *hid*), participants will alter their production so that what they hear is closer to what they intended to produce (by producing a higher first formant). This reflects a self-monitoring process during speech production, where perceived errors are corrected through compensatory changes. One can then measure the magnitude of the compensatory response to the auditory perturbation based on the difference from baseline productions recorded before the perturbation. This effect has been shown to be robust, and to persist even when participants are instructed to actively ignore the auditory perturbation (Munhall, MacDonald, Byrne, & Johnsrude, 2009), suggesting that the compensatory changes result from implicit sensorimotor adaptation. Compensation in response to pitch/F0 (e.g., Liu, Chen, Jones, Huang, & Liu, 2011), vowel formant (e.g., Villacorta, Perkell, & Guenther, 2007), and fricative frequency perturbations (e.g., Shiller, Sato, Gracco, & Baum, 2009) have all been extensively investigated.

Previous work investigating speech motor learning has established a link between perceptual boundaries and production targets under conditions of real-time formant manipulation, such that perceptual training to shift a category boundary influenced adaptation to vowel perturbations (Lametti, Krol, Shiller, & Ostry, 2014). Additional work has shown that production targets are also sensitive to lexical effects on perceptual boundaries between words (Bourguignon, Baum, & Shiller 2014). Bourguignon and colleagues found that perturbations that resulted in a change from a non-word to a word (e.g. *kess-kiss*) elicited greater compensation than a change from a word to a non-word (e.g. *chest-chist*). In contrast, there was no difference between the magnitude of compensation to non-words and words when the auditory perturbation did not result in a change of lexical status (e.g. *bet-bit*, *jex-jix*). This parallels the previous study by Lametti et al. (2014) in that compensation was greater when the perturbation crossed a perceptual boundary, which in this case was affected by the lexical bias. Together, these two studies provide evidence that production error monitoring is influenced by perceptual categories. Furthermore, both short-term training and the lexical bias seem to affect these categories in an automatic way that is reflected in the magnitude of sensorimotor adaptation. Thus, these results provide further evidence that the lexical bias in younger adults is the result of automatic shifts in the perceptual system.

Current Study

Using an altered auditory feedback paradigm, we wanted to determine whether the increased lexical bias in older adults is the result of an automatic top-down effect of the lexicon on perceptual category boundaries or reflects some kind of post-perceptual decision bias. Investigating this issue will help disentangle the interaction between linguistic, perceptual, and motor mechanisms for normal aging, by examining how linguistic forces affect sensorimotor adaptation in older adults. There are several possibilities to be considered depending on the direction of the results. Should the older adults show an exaggerated version of the younger adult pattern found by Bourguignon et al. (2014), this would imply that the increased lexical bias observed in older adults in Ganong tasks is the result of greater immediate lexical influence on the perceptual boundary between phonemes. If there is no difference between the older and younger adults, the findings would suggest that there remains the same lexical influence on perceptual categories in younger and older adults, but that there is also an additional mechanism driving the increased lexical effect seen in other studies of older adults’ speech categorization.

Lastly, should the older adults show a different pattern of compensation compared to the younger adults (i.e., if they show more compensation in different conditions of feedback), it could suggest that there is a different mechanism driving the lexical effect in older adults compared to younger adults.

Method

Participants

Groups of native English-speaking younger (n=38, M_{age}=20.8) and older (n=33, M_{age}=70.2) adults were recruited from the Montreal area. Many participants (32 older adults, 18 younger adults) had learned an additional language at school, but none reported higher than an intermediate knowledge of their second language. Four older adult participants were excluded from the analysis due to hearing thresholds above a normal threshold (average of pure tone thresholds at 500, 1000, 2000 Hz > 25 dB HL). Following exclusion criteria outlined in the Data Processing section below, data from 27 older adults (ages 63-86, M_{age}=69.5, 10 males) and 35 younger adults (ages 18-29, M_{age}=20.9, 11 males) were included in our final analysis.

Stimuli

For our target stimuli, we used a subset of the stimuli from Bourguignon et al. (2014) (10 monosyllabic words and 10 monosyllabic non-words, Table 1). The target vowel was always /ɛ/, and our feedback manipulation altered the perception of the vowel in real time to sound more like /ɪ/. Stimuli were chosen such that the lexical status of the target would change when perceived under our feedback manipulation (i.e., words shift towards non-words and vice versa). Note that participants only produced the target stimuli (with /ɛ/) and never the altered stimuli (with /ɪ/).

Table 1.
Stimuli list by condition.

Word		Nonword	
Target	Change	Target	Change
death	dith	weth	with
depth	dipth	het	hit
nest	nist	fet	fit
less	liss	ket	kit
chest	chist	kess	kiss
test	tist	steff	stiff
chess	chiss	ked	kid
vest	vist	detch	ditch
best	bist	steck	stick
keg	kig	stell	still

Design

Unlike Bourguignon et al. (2014), which used a between-subjects design, all participants completed both speaking conditions of our task: one involving a set of 10 real words and one involving a set of 10 non-words (Table 1). Each condition was comprised of 200 trials (each stimulus produced 20 times in random order). The first 50 trials were carried out under conditions of unaltered feedback to obtain a baseline measure of each participant's vowel production. The feedback manipulation was turned on for the following 100 trials. The procedure for altering speech auditory feedback has been described in detail elsewhere (Bourguignon et al., 2014; Lametti et al., 2014; Mollaei, Shiller, & Gracco, 2013; Shiller & Rochon, 2014). Briefly, as subjects spoke into a head-worn microphone (AKG C520), the speech audio signal was amplified and then split into two identical signals, one of which was altered in near-real-time (15 ms delay) using a digital signal processer that shifted the frequency of formants (VoiceOne, TC Helicon). The vowel manipulation was restricted to the first spectral peak (F1) by mixing the low-frequency component of the processed signal with the high-frequency component of the unprocessed signal. The filter cutoff separating the two signals was set to 1100 Hz for males and to 1350 Hz for females, which corresponds to approximately halfway between the first and second formant values for the production of /ɛ/. The manipulation was then turned off for the last 50 trials to observe any after-effects. The order of conditions (Word/Non-word) was counterbalanced across participants.

Procedure

Participants were seated in a quiet room in front of a computer. They were asked to produce the words that appeared on the screen at a comfortable volume. Participants could see a volume meter on the side of the computer screen, and were asked to maintain a target level for each production. For the Non-word condition, it was explained that the vowel should be pronounced similarly to that of *head*. Subjects heard their amplified and (depending on the phase of the experiment) possibly altered auditory signals through headphones (Beyerdynamic 880 Pro) at approximately 75 dB SPL. Masking noise (approximately 60 dB SPL) was played continuously to reduce the participants' perception of their own air- or bone conducted speech signals. After completing the first speaking condition, participants completed an unrelated speech categorization task before completing the second speaking condition. The entire testing session took approximately one hour.

Data Processing & Analysis

For each trial, a 40 ms segment from the midpoint of the vowel was selected via visual inspection of the waveform and spectrogram. The mean values of the first and second formants (F1 and F2) for each segment were estimated by LPC analysis in MATLAB (MATLAB 2015b, The Mathworks, Inc.). We implemented rather strict trial inclusion criteria because we found the production patterns of our older adult participants to be quite variable and unstable across trials. Spurious formant estimates were eliminated using a two-step procedure involving an absolute trial-to-trial variability criterion (removing > 250 Hz jumps in F1, and > 600 Hz jumps in F2), and a standard-deviation criterion (> 2 SD within a given 50-trial block). Three younger adult and two additional older adult participants were excluded because more than 25% of their trials were removed. We also analyzed each item's average pattern of compensation, and found, unexpectedly, that two items (*keg* in the word condition, and *ked* in the non-word condition) were consistently produced with a significantly lower-than-baseline F1 under altered-feedback conditions (i.e., following the formant perturbation rather than compensating). These two items were excluded from further analysis.

Given that our feedback manipulation was restricted to F1, analyses of subjects' vocal changes focused specifically on this measure. We calculated each participant's baseline F1 production based on their average production of 20 trials preceding the onset of the feedback alteration (Trial 31-50). To check for any baseline differences between groups and conditions, we ran a mixed-factorial ANOVA on baseline F1 production with Age group as the between-subjects variable and Condition (word or non-word) as the within-subjects variable. We then normalized each participant's F1 productions as the proportion change from their baseline F1. Figure 1 shows the average proportion change from baseline in F1 for each Age group and Condition across the entire experiment. In order to examine the effect of trial number, word condition and age group on the degree of speech adapation, we ran a mixed-effects linear regression on proportion change during the shift phase (when the feedback manipulation was on, trials 51-150) with Trial, Condition, and Age Group as predictors (fixed factors). We rescaled Trial to be centered on zero. For Age group and Condition, the older adult age group and the word condition were coded as zero, so as to be the baseline for comparison. In order to account for the repeated-measures nature of the design, Participant was included as a random factor in the model. To account for the possible influence of the different word or non-word items used in the speech task, Item was also included as a random factor. We used the maximal random-effects structure possible for the design (Barr, Levy, Scheepers, & Tily, 2013), with uncorrelated random intercepts and slopes by Condition for each Participant and uncorrelated random intercepts and slopes by Age Group for each Item. All analyses were run in R version 3.4.3 (R Core Team, 2017) and the mixed-effects models were run using the lmerTest package (Kuznetsova, Brockhoff, & Christensen, 2017) which uses the Satterthwaite approximation to estimate p values.

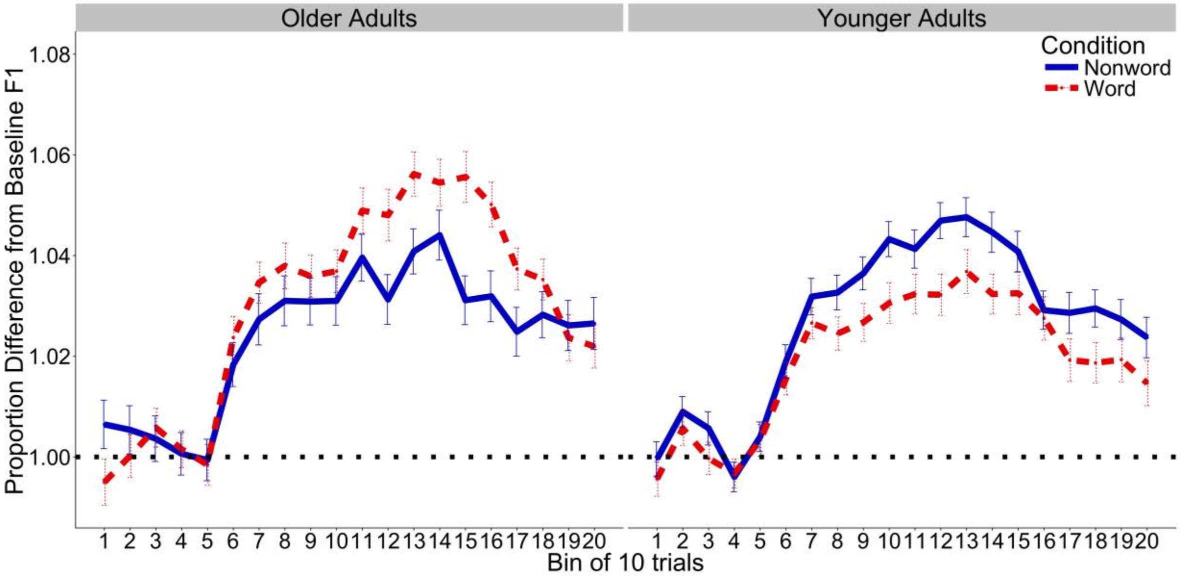

Figure 1. Proportion difference from baseline F1 for the older and younger adults in the two experimental conditions. Bins are averages of 10 trials. The dotted horizontal line represents the baseline. Error bars represent standard error of the mean.

Results

We first present the results of the ANOVA that compared the baseline measurements between age groups and conditions. We found that our older adults had a lower baseline production of F1 (M_{Word}=681.2 Hz, $M_{Nonword}$=674.8 Hz) compared to the group of younger adults (M_{Word}=754.5 Hz, $M_{Nonword}$=734.6 Hz, F(1, 58)=7.26, p=0.009). Participants produced real words with a higher F1 (M_{Word}=720.1 Hz) compared to non-words ($M_{Nonword}$=708.6 Hz, F(1, 58)=8.62, p=0.004), but there was no significant interaction between age group and lexical condition (F(1, 58)=2.2, p>0.05). As mentioned in the previous section, we normalized each participant's production to reflect proportion change in F1 relative to their baseline for a given condition, so any further differences reflect changes in the magnitude of compensation to altered feedback and not the baseline differences.

The results of the mixed-effects linear regression described above are summarized in Table 2. We found significant two-way interactions between Trial and Condition, and between Trial and Age group. These interactions suggest that as the shift phase progressed, both groups compensated less in the Non-word condition than the older adults in the Word condition (Trial x Condition: β=-0.009, t=-2.58, p=0.009) and that the younger adult group compensated less across conditions than the older adults in the Word condition (Trial x Age group: β=-0.01, t=-3.13, p=0.002). This is all qualified by the remaining significant three-way interaction, which suggests that unlike the older adults, the younger adults compensated more in the Non-word condition compared to the Word condition as the experiment progressed (β=0.01, t=3.07, p=0.002).

Table 2.
Fixed effects estimates from a linear mixed-effects regression investigating the three-way interaction of Trial, Age Group, and Condition on Proportion change in F1.

Fixed effect	Estimate	Std. Error	t statistic	p value	
Intercept	1.044	0.008	131.83	<0.001	***
Trial	0.019	0.002	7.91	<0.001	***
Condition (Nonword)	-0.012	0.011	-1.1	0.28	
Age Group (YA)	-0.015	0.009	-1.60	0.11	
Trial x Condition (Nonword)	-0.009	0.004	-2.58	0.009	**
Trial x Age Group (YA)	-0.010	0.003	-3.13	0.002	**
Condition (Nonword) x Age Group (YA)	0.021	0.012	1.73	0.08	
Trial x Condition (Nonword) x Age Group (YA)	0.014	0.005	3.07	0.002	**

In an effort to unpack the significant two- and three-way interactions in this model, we ran additional models that split the data by age group and by condition, allowing us to focus on the differences in compensation between the lexical conditions within each age group. When the data was split by Age group, there was a significant interaction between Trial and Condition for the older adults ($\beta=0.009$, $t=2.44$, $p=0.01$), supporting that older adults compensate more in the Word condition than in the Non-word. The same interaction is only marginal for the younger adult data ($\beta=-0.005$, $t=-1.79$, $p=0.07$), but the direction of the interaction supports that younger adults compensate more in the Nonword condition than in the Word condition. When the data was split by Condition, there was a significant interaction between Trial and Age group for the Word condition ($\beta=-0.01$, $t=-3.11$, $p=0.002$), suggesting that younger adults compensate less in the Word condition compared to older adults. The same interaction was not significant when looking at the Non-word condition data (Trial x Age Group: $\beta=0.004$, $t=1.22$, $p>0.05$). Figure 2 compares the proportion change in F1 between the two age groups for each condition, focusing on only the trials where the feedback manipulation was on (trials 51-150). These additional analyses highlight the variability in the data and unfortunately do not allow for conclusive results within the age groups, although they do support the notion that older and younger adults are behaving differently under the two different types of lexical change.

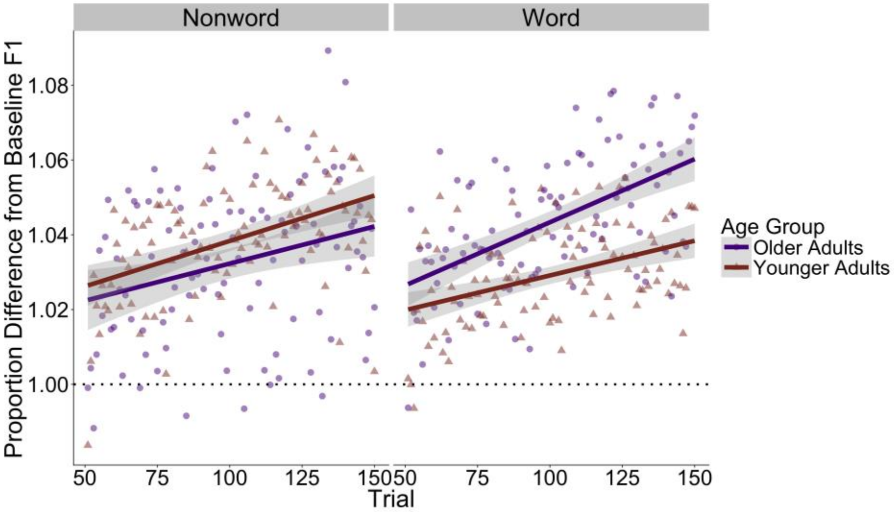

Figure 2. Average proportion difference from baseline F1 for the older and younger adult groups in the Word and Nonword conditions for the shift phase of the experiment (Trial 51-150). Fitted solid line approximates the line of best fit. Dotted horizontal line represents the baseline.

Discussion

We set out to test whether the increased lexical bias found in older adults' speech perception was inherent to the perceptual system. The pattern for the younger adults found here and by Bourguignon et al. (2014), where participants compensated more to non-words than to words, points towards an immediate effect of top-down lexical status on the perceptual category boundary. We expected to see an amplification of this pattern in older adults if the same mechanism were at work. The older adults, however, compensated similarly to the two conditions initially, and gradually compensated more to words than to non-words (see Figure 1). At the very least, this confirms that older adults still rely on auditory feedback to monitor their speech output and are able to adapt accordingly (despite, in some cases, poorer perceptual input due to poorer hearing). We did not find the same relative relationship between conditions (i.e., more compensation in the Non-word condition than in the Word condition) in the older adults as in the younger adults, suggesting that there are additional mechanisms at play when older adults compensate for perceptual feedback. This raises some interesting possibilities for the older adults, which we examine below.

Using a task that is driven by implicit error-monitoring, we did not replicate the behavioural pattern found by categorization tasks (i.e. larger changes in category boundary due to lexical bias in older adults). The contrast between our results and the previous work investigating the lexical bias in older adults provides evidence that the increased lexical bias in older adults is driven by a post-perceptual process. This is also supported by recent findings that the lexical influence on perceptual learning was not larger in older adults than in younger (Colby, Clayards, & Baum, 2018; Scharenborg & Janse, 2013). Taken together with the current results, this is evidence that the lexical bias in older adults is not always larger than in younger adults, especially with tasks that require adaptation. This suggests that the difference in the magnitude of the bias found in older adults may result from how lexical influence is measured, which in turn reflects whether the bias is inherent to the perceptual system or a more controlled post-perceptual bias.

Older adults, compared to younger adults, have been shown to have more difficulty inhibiting top-down information once it has been activated. Declines in attentional control have been proposed as the mechanism behind this difficulty in older adults (Inhibitory Deficit Hypothesis; Hasher & Zacks, 1988). Gazzaley et al. (2005) found that older adults have difficulty ignoring task-irrelevant information, and that this difficulty can impair their working memory performance. There is a growing body of literature to suggest that such deficits also influence successful speech processing in older adults. For instance, both word frequency and neighbourhood density have been found to impact word recognition in older adults, with high frequency words and high density neighbourhoods being harder to ignore for older adults (Revill & Spieler, 2012; Sommers & Danielson, 1999). As pertains to the present study, this reduced inhibition suggests that once the lexical items in the Word condition have been identified as targets, older adults may overcompensate as the shift phase progresses due to increased post-perceptual influence of the activated lexical targets on production. This bolsters their compensation response to real words being shifted towards non-words, which results in the larger magnitude of compensation seen in the Word condition compared to the Non-word condition. Whether the pattern of results we found with older adults is the result of age-related inhibitory decline or the modulation of top-down resources to compensate for sensory declines are not mutually exclusive and not separable with the present data.

Increased cognitive load in younger adults has been found to increase lexical effects in speech perception tasks (Mattys, Barden, & Samuel, 2014; Mattys & Wiget, 2011). Mitterer and Mattys (Mitterer & Mattys, 2017) propose that decreased working memory capacity under conditions of increased cognitive load (i.e., dual-tasks) interferes with speech encoding. To compensate for poorer encoding, top-down effects, like the lexical effect, may thus be relied upon under such conditions. As previously established, older adults show declines in working memory compared to younger adults (for a review of age-related cognitive changes affecting speech, see Johns, Myers, & Skoe, 2018), which may therefore interfere with their ability to encode speech and subsequently increase lexical bias. It is worth noting that Mattys and Scharenborg (2014) investigated the effect of cognitive load on the lexical bias in older adults, and found that the increase in reliance on top-down information under divided attention remained similar between older and younger adults. Mattys and Scharenborg (2014) also did not find a relationship between discrimination abilities and the lexical bias in either younger and older adults. Revill & Spieler (2012) also found that noisier speech input did not make younger adults behave like older adults in an eye-tracking task. Thus, while poorer encoding might explain aspects of the increased top-down influence in older adults, these previous results suggest that encoding difficulties are not the full story behind older adults' increased lexical bias. Future work should directly compare the lexical bias under conditions with low and high cognitive load using a task that does not require explicit decision-making to tease apart this effect in older adults.

Given that the older adult productions seem more variable than those of the younger adults, it is possible that less-defined production targets have the effect of blurring the influence of the lexicon. Because we are using a production measure to examine a perception bias, it is possible that age-related changes in speech motor control have obscured our results. Due to age-related changes to the vocal tract, older adults produce overall lower F1 frequencies than younger adults (Torre III & Barlow, 2009; Xue & Hao, 2003), which we also found in our baseline comparison. Non-speech oral motor control has been found to change with age (Ballard, Robin, Woodworth, & Zimba, 2001) and there is evidence to suggest the connection between lexical and phonological representations weakens with age (Mortensen, Meyer, & Humphreys, 2006), both of which could contribute to overall variability in older adults' speech production. Previous work with younger adults has provided evidence that speakers with precise production targets are also better at discriminating phonetic contrasts (Perkell, Guenther, et al., 2004; Perkell, Matthies, et al., 2004), further linking speech perception and production targets. Because older adults showed a different pattern of compensation to the lexical conditions compared to younger adults, it is possible that weaker, more diffuse production targets in older adults nullified the immediate influence of the lexicon on phonetic boundaries that might have been measured through sensorimotor adaptation.

One way to potentially disentangle our current results, where several age-related factors including cognitive and perceptual changes, might be interacting to influence sensorimotor adaptation, would be to investigate these effects in young hearing-impaired individuals, who may increasingly rely on top-down information to compensate for sensory declines (depending on the severity of the hearing loss). In this case, one might expect less reliance on auditory feedback in general which might appear as weaker sensorimotor adaptation and yet increased reliance on top-down information that would be reflected in other speech perception tasks.

The effect of age on speech perception and production is complex, and here we attempted to investigate the interaction between motor, perceptual, and linguistic factors. Our results suggest that the relationship between the lexicon and the perceptual-motor system is different in younger and older adults. Further investigation is necessary to narrow down the explanation and examine the processes driving the differences in lexical bias across the lifespan. However, it seems clear from our findings that the larger lexical bias in older adults is not simply the result of a larger automatic perceptual shift to the phonetic category boundary.

Acknowledgements

The authors would like to thank Esther Janse for her comments on a previous version of this manuscript and Victoria Poulton for her help collecting data.

References

Ballard, K. J., Robin, D. A., Woodworth, G., & Zimba, L. D. (2001). Age-Related Changes in Motor Control During Articulator Visuomotor Tracking. *Journal of Speech Language and Hearing Research*, *44*(4), 763. https://doi.org/10.1044/1092-4388(2001/060)

Barr, D. J., Levy, R., Scheepers, C., & Tily, H. J. (2013). Random effects structure for confirmatory hypothesis testing: Keep it maximal. *Journal of Memory and Language*, *68*(3), 255–278. https://doi.org/10.1016/j.jml.2012.11.001

Baum, S. R. (2003). Age differences in the influence of metrical structure on phonetic identification. *Speech Communication*, *39*(3–4), 231–242. https://doi.org/10.1016/S0167-6393(02)00028-6

Borsky, S., Tuller, B., & Shapiro, L. P. (1998). “How to milk a coat:” The effects of semantic and acoustic information on phoneme categorization. *The Journal of the Acoustical Society of America*, *103*(5), 2670–2676. https://doi.org/10.1121/1.422787

Bourguignon, N. J., Baum, S. R., & Shiller, D. M. (2014). Lexical-perceptual integration influences sensorimotor adaptation in speech. *Frontiers in Human Neuroscience*, *8*(April), 1–9. https://doi.org/10.3389/fnhum.2014.00208

Colby, S. E., Clayards, M., & Baum, S. R. (2018). The role of lexical status and individual differences for perceptual learning in younger and older adults. *Journal of Speech Language and Hearing Research*, *61*, 1855–1874.

Ganong, W. F. (1980). Phonetic categorization in auditory word perception. *Journal of Experimental Psychology: Human Perception and Performance*, *6*(1), 110–125.

Gazzaley, A., Cooney, J. W., Rissman, J., & D’Esposito, M. (2005). Top-down suppression deficit underlies working memory impairment in normal aging. *Nature Neuroscience*, *8*(10), 1298–1300. https://doi.org/10.1038/nn1543

Hasher, L., & Zacks, R. T. (1988). Working Memory, Comprehension, and Aging: A review and a new view. *Psychology of Learning and Motivation*, *22*, 193–225.

Johns, A. R., Myers, E. B., & Skoe, E. (2018). Sensory and cognitive contributions to age-related changes in spoken word recognition. *Language and Linguistics Compass*, *12*(2), e12272. https://doi.org/10.1111/lnc3.12272

Kingston, J., Levy, J., Rysling, A., & Staub, A. (2016). Eye Movement Evidence for an Immediate Ganong Effect. *Journal of Experimental Psychology: Human Perception and Performance*, *42*(12), 1969–1988. https://doi.org/10.1037/xhp0000269

Kuznetsova, A., Brockhoff, P. B., & Christensen, R. H. B. (2017). lmerTest Package: Tests in Linear Mixed Effects Models. *Journal of Statistical Software*, *82*(13), 1–26. https://doi.org/10.18637/jss.v082.i13

Lametti, D. R., Krol, S. A., Shiller, D. M., & Ostry, D. J. (2014). Brief Periods of Auditory Perceptual Training Can Determine the Sensory Targets of Speech Motor Learning. *Psychological Science*, *25*(7), 1325–1336. https://doi.org/10.1177/0956797614529978

Liu, P., Chen, Z., Jones, J. A., Huang, D., & Liu, H. (2011). Auditory feedback control of vocal pitch during sustained vocalization: A Cross-Sectional study of adult aging. *PLoS ONE*, *6*(7), 1–8. https://doi.org/10.1371/journal.pone.0022791

Mattys, S. L., Barden, K., & Samuel, A. G. (2014). Extrinsic cognitive load impairs low-level speech perception. *Psychonomic Bulletin and Review*, *21*(3), 748–754. https://doi.org/10.3758/s13423-013-0544-7

Mattys, S. L., & Scharenborg, O. (2014). Phoneme categorization and discrimination in younger and older adults: A comparative analysis of perceptual, lexical, and attentional factors.

Psychology and Aging, *29*(1), 150–162. https://doi.org/10.1037/a0035387

Mattys, S. L., & Wiget, L. (2011). Effects of cognitive load on speech recognition. *Journal of Memory and Language*, *65*(2), 145–160. https://doi.org/10.1016/j.jml.2011.04.004

Mitterer, H., & Mattys, S. L. (2017). How does cognitive load influence speech perception? An encoding hypothesis. *Attention, Perception, & Psychophysics*, *79*(1), 344–351. https://doi.org/10.3758/s13414-016-1195-3

Mollaei, F., Shiller, D. M., & Gracco, V. L. (2013). Sensorimotor adaptation of speech in Parkinson's disease. *Movement Disorders*, *28*(12), 1668–1674. https://doi.org/10.1002/mds.25588

Mortensen, L., Meyer, A. S., & Humphreys, G. W. (2006). Age-related effects on speech production: A review. *Language and Cognitive Processes*, *21*(1–3), 238–290. https://doi.org/10.1080/01690960444000278

Munhall, K. G., MacDonald, E. N., Byrne, S. K., & Johnsrude, I. (2009). Talkers alter vowel production in response to real-time formant perturbation even when instructed not to compensate. *The Journal of the Acoustical Society of America*, *125*(1), 384–390. https://doi.org/10.1121/1.3035829

Park, D. C., & Reuter-Lorenz, P. (2009). The adaptive brain: aging and neurocognitive scaffolding. *Annual Review of Psychology*, *60*(1), 173–196. https://doi.org/10.1146/annurev.psych.59.103006.093656

Perkell, J. S., Guenther, F. H., Lane, H., Matthies, M. L., Stockmann, E., Tiede, M., & Zandipour, M. (2004). The distinctness of speakers' productions of vowel contrasts is related to their discrimination of the contrasts. *The Journal of the Acoustical Society of America*, *116*(4), 2338–2344. https://doi.org/10.1121/1.1787524

Perkell, J. S., Matthies, M. L., Tiede, M., Lane, H., Zandipour, M., Marrone, N., … Guenther, F. H. (2004). Distinctness of speakers' /s/ - /ʃ/ contrast is related to their auditory discrimination and use of an articulatory saturation effect. *Journal of Speech, Language, and Hearing Research*, *47*(6), 1259–1269.

Pichora-Fuller, M. K. (2008). Use of supportive context by younger and older adult listeners: balancing bottom-up and top-down information processing. *International Journal of Audiology*, *47 Suppl 2*, S72-82. https://doi.org/10.1080/14992020802307404

Purcell, D. W., & Munhall, K. G. (2006a). Adaptive control of vowel formant frequency: Evidence from real-time formant manipulation. *The Journal of the Acoustical Society of America*, *120*(2), 966–977. https://doi.org/10.1121/1.2217714

Purcell, D. W., & Munhall, K. G. (2006b). Compensation following real-time manipulation of formants in isolated vowels. *The Journal of the Acoustical Society of America*, *119*(4), 2288–2297. https://doi.org/10.1121/1.2173514

R Core Team. (2017). R: A language environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing.

Revill, K., & Spieler, D. (2012). The effect of lexical frequency on spoken word recognition in young and older listeners. *Psychology and Aging*, *27*(1), 80–87. https://doi.org/10.1037/a0024113.The

Scharenborg, O., & Janse, E. (2013). Comparing lexically guided perceptual learning in younger and older listeners. *Attention, Perception & Psychophysics*, *75*(3), 525–36. https://doi.org/10.3758/s13414-013-0422-4

Shiller, D. M., & Rochon, M. L. (2014). Auditory-perceptual learning improves speech motor adaptation in children. *Journal of Experimental Psychology: Human Perception and*

Performance, *40*(4), 1308–1315. https://doi.org/10.1037/a0036660

Shiller, D. M., Sato, M., Gracco, V. L., & Baum, S. R. (2009). Perceptual recalibration of speech sounds following speech motor learning. *The Journal of the Acoustical Society of America*, *125*(2), 1103–1113. https://doi.org/10.1121/1.3058638

Sommers, M. S., & Danielson, S. M. (1999). Inhibitory processes and spoken word recognition in young and older adults: The interaction of lexical competition and semantic context. *Psychology and Aging*, *14*(3), 458–472. Retrieved from http://psycnet.apa.orgjournals/pag/14/3/458

Torre III, P., & Barlow, J. A. (2009). Age-related changes in acoustic characteristics of adult speech. *Journal of Communication Disorders*, *42*(5), 324–333. https://doi.org/10.1016/j.jcomdis.2009.03.001

Van Engen, K. J. (2017). Clear speech and lexical competition in younger and older adult listeners. *The Journal of the Acoustical Society of America*, *142*(2), 1067–1077. https://doi.org/10.1121/1.4998708

Villacorta, V. M., Perkell, J. S., & Guenther, F. H. (2007). Sensorimotor adaptation to feedback perturbations of vowel acoustics and its relation to perception. *The Journal of the Acoustical Society of America*, *122*(4), 2306–2319. https://doi.org/10.1121/1.2773966

Xue, S. A., & Hao, G. J. (2003). Changes in the human vocal tract due to aging and the acoustic correlates of speech production: a pilot study. *Journal of Speech, Language, and Hearing Research*, *46*(3), 689–701. https://doi.org/10.1044/1092-4388(2003/054)