

1 **A single exposure to altered auditory feedback causes observable sensorimotor adaptation**
2 **in speech**

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10

11 **Abstract**

12 Sensory errors caused by perturbations to movement-related feedback induce two types
13 of behavioral changes that oppose the perturbation: rapid compensation within a movement, as
14 well as longer-term adaptation of subsequent movements. Although adaptation is hypothesized to
15 occur whenever a sensory error is perceived (including after a single exposure to altered
16 feedback), adaptation of articulatory movements in speech has only been observed after
17 repetitive exposure to auditory perturbations, questioning both current theories of speech
18 sensorimotor adaptation as well as the universality of more general theories of adaptation. Thus,
19 positive evidence for the hypothesized single-exposure or “one-shot” learning would provide
20 critical support for current theories of speech sensorimotor learning and control and align
21 adaptation in speech more closely with other motor domains. We measured one-shot learning in
22 a large dataset in which participants were exposed to intermittent, unpredictable auditory
23 perturbations to their vowel formants (the resonant frequencies of the vocal tract that distinguish
24 between different vowels). On each trial, participants spoke a word out loud while their first
25 formant was shifted up, shifted down, or remained unshifted. We examined whether the
26 perturbation on a given trial affected speech on the subsequent, unperturbed trial. We found that
27 participants adjusted their first formant in the opposite direction of the preceding shift,
28 demonstrating that learning occurs even after a single auditory perturbation as predicted by
29 current theories of sensorimotor adaptation. While adaptation and the preceding compensation
30 responses were correlated, this was largely due to differences across individuals rather than
31 within-participant variation from trial to trial. These findings are more consistent with theories
32 that hypothesize adaptation is driven directly by updates to internal control models than those
33 that suggest adaptation results from incorporation of feedback responses from previous
34 productions.

35

36 Introduction

37 Auditory feedback plays a major role in both the online execution of speech production
38 and the refinement of feedforward speech motor control, as observed when the auditory feedback
39 participants receive about their own speech is perturbed in real time (Houde & Jordan, 1998;
40 Purcell & Munhall, 2006b; Tourville et al., 2008; Villacorta et al., 2007). Two types of behavior
41 have been the primary focus of auditory perturbation studies in speech, which most typically
42 alter a speaker's vowel formants (the resonant frequencies of the vocal tract that distinguish
43 vowels). First, when unpredictable vowel formant perturbations are delivered, speakers produce
44 a *compensation* response—an online, within-trial adjustment to oppose the perturbation (Purcell
45 & Munhall, 2006b; Tourville et al., 2008). Second, consistent perturbations of auditory feedback
46 lead to *sensorimotor adaptation*—a learned change in speech behavior that is observable from
47 the onset of speech and which persists even after the perturbation is removed (Houde & Jordan,
48 1998; Purcell & Munhall, 2006a).

49 These behaviors are widely considered to be driven by sensory prediction errors
50 (differences between expected and perceived sensory feedback), although models differ in the
51 proposed mechanism by which this occurs. In the DIVA (Directions Into Velocities of
52 Articulators) model (Tourville & Guenther, 2011), sensory prediction errors lead to feedback-
53 based corrective motor commands (i.e. the compensation response) which are subsequently
54 incorporated into the feedforward motor program used for future productions of the same
55 syllables, creating the adaptation response (Kawato et al., 1987). An alternative theoretical
56 account of adaptation (Houde & Nagarajan, 2011) suggests sensory prediction errors instead
57 directly lead to updates of internal models in the sensorimotor control system, either to forward
58 models predicting the sensory outcomes of actions (Bastian, 2006; Haith & Krakauer, 2013;
59 Houde & Nagarajan, 2011; Krakauer & Mazzoni, 2011; Shadmehr et al., 2010), to the control
60 policy guiding action (Hadjiosif et al., 2020), or to both (Wolpert et al., 1998; Wolpert &
61 Kawato, 1998).

62 Both the compensation-based and internal-model hypotheses of sensorimotor adaptation
63 predict that learning in speech occurs continuously, such that changes in speech production
64 should be evident even after a single trial with altered auditory feedback. Such *one-shot*
65 *adaptation* has been observed in limb control, where a visuomotor perturbation on an isolated
66 trial affects reach direction on the following trial (Diedrichsen et al., 2005; Joiner et al., 2017;
67 Ruttle et al., 2021). However, the occurrence of such one-shot adaptation has not been
68 definitively established in speech. Although Cai and colleagues (Cai et al., 2012) observed that
69 first formant (F1) production in the first 50 ms of perturbed trials which closely followed another
70 perturbed trial tended to oppose the preceding perturbation's direction, more recent work
71 explicitly testing for such single trial effects did not find evidence of a measurable change (Daliri
72 et al., 2020). This failure to find one-shot adaptation in speech questions both current theories of
73 speech sensorimotor adaptation as well as the universality of domain-general theories (e.g.,
74 Houde & Nagarajan, 2011; Kawato et al., 1987; Hadjiosif et al., 2020).

75 Here, we aim to further investigate the mechanisms underlying sensorimotor adaptation
76 by measuring one-shot adaptation in speech. To detect this potentially small effect, data from six
77 prior studies (Niziolek et al., 2014; Niziolek & Guenther, 2013; Niziolek & Parrell, 2021; Parrell
78 et al., 2017, 2021) were compiled for this analysis (131 total participants, 18-40 participants per
79 study). In all studies, participants read aloud monosyllabic words while receiving real-time
80 auditory playback of their speech. On a given trial, this feedback was either veridical
81 (*unperturbed trials*) or unpredictably perturbed via an upward or downward shift in F1

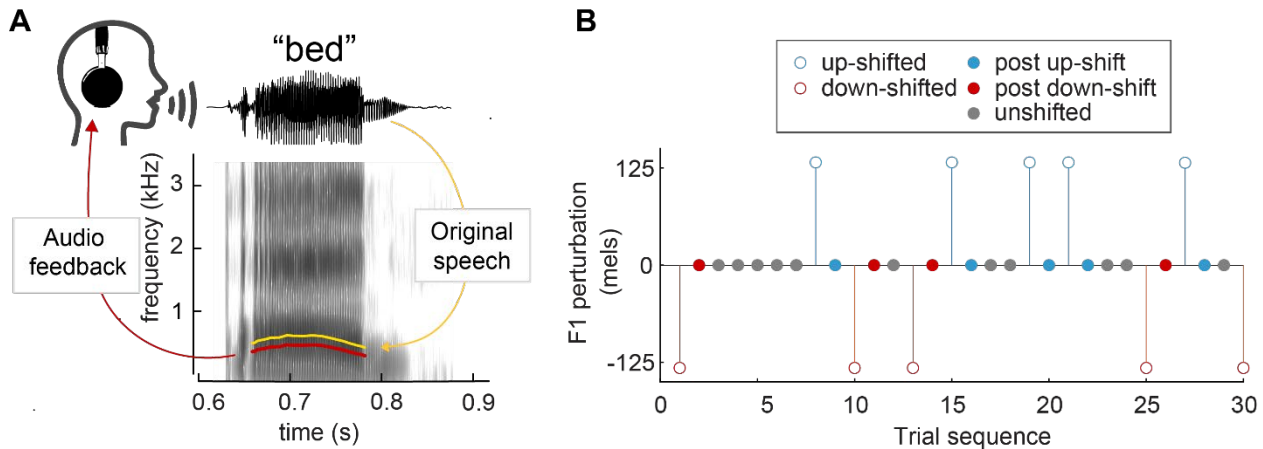


Figure 1: F1 perturbation methodology. *A:* A spectrogram of the word ‘bed’, demonstrating an applied downward F1 perturbation. The F1 frequency of the audio feedback (red) is lowered from the original utterance (yellow). *B:* Sample trial sequence from Study 4. Open circles indicate trials in which an F1 perturbation was applied, and closed circles indicate trials in which no perturbation occurred. “Up-shift” and “down-shift” trials were used to calculate the compensation response. “Post up-shift” and “post down-shift” trials were used to calculate the one-shot adaptation response. For analysis, all shift magnitude values were converted to mels.

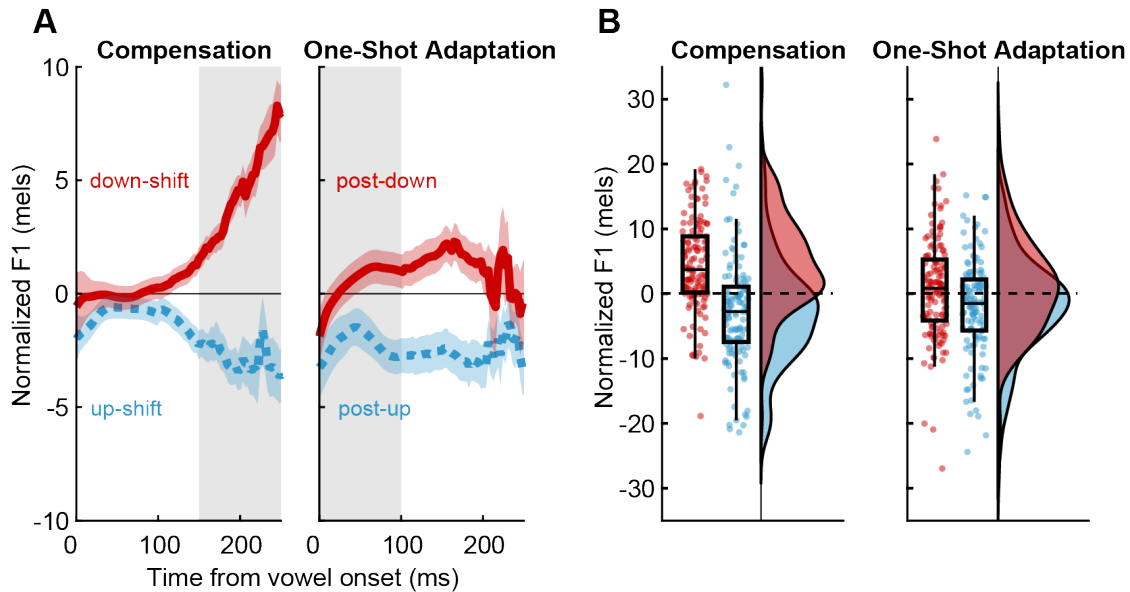
82 (perturbed trials) (Figure 1A). Perturbed trials were used to calculate compensation responses,
83 and unperturbed trials which occurred directly after a perturbed trial (*post-perturbation trials*)
84 were used to calculate one-shot adaptation responses (see Figure 1B). We hypothesized that F1
85 frequency values would be higher for trials that occurred directly after a downward perturbation
86 and lower in trials that occurred directly after an upward perturbation, such that they echo the
87 preceding compensation responses’ F1 values.

88 This approach also allows us to test the feedback-command-based hypothesis of
89 adaptation in speech, which suggests that there should be a correlation between the magnitude of
90 compensation and subsequent one-shot adaptation at the trial level. While this correlation has
91 been observed in reaching (Albert & Shadmehr, 2016), most studies have failed to identify such
92 a clear relationship in speech (Daliri, 2021; Franken et al., 2019; Lester-Smith et al., 2020;
93 Parrell et al., 2017; Raharjo et al., 2021), possibly because they did not use such a direct trial-to-
94 trial measurement method. The presence of such a relationship at the trial level would be
95 compatible with both the feedback-command-based and internal-model hypothesis of adaptation;
96 alternatively, the absence of such a relationship would only support the internal-model
97 hypothesis.

98 99 Results

100 Compensation

101 In the 150-250 ms time window after vowel onset, perturbed trials in which an upward F1
102 shift occurred (*up-shifted trials*) had reliably lower F1 values (-3.99 ± 34.13 mels) than trials in
103 which a downward F1 shift occurred (2.69 ± 33.5 mels) (*down-shifted trials*) ($\beta = -6.93$, S.E. =
104 0.66 , $p < 0.001$, $d = 0.21$). This was also reflected at the individual level; participants’ average
105 F1 in the 150-250 ms time window was substantially lower across up-shifted trials (-2.75 ± 8.68



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Figure 2: Behavioral responses to auditory perturbations. **A:** The average F1 trajectory for trials that were measured in relation to either upward (blue) or downward (red) perturbations, compiled across participants. Time window of interest is highlighted, illustrating the time period of interest for compensation (left) and one-shot adaptation (right). **B:** The probability distribution and boxplot of participants' average compensation (left) and one-shot adaptation (right) from trials occurring during or directly after (respectively) up-shifted trials (blue) and down-shifted trials (red).

107 mels) compared to their average F1 in the same time window across down-shifted trials ($4.40 \pm$
 108 6.96 mels) (paired t-test, $t(130) = -7.00$, $p < 0.001$, $d = 0.91$, Fig 2B, left panel).

109 *One-shot adaptation*

110 Participants produced one-shot adaptation responses which paralleled the directional
 111 pattern seen in the compensation response, though at a lower magnitude. In the 0-100 ms time
 112 window after vowel onset, F1 values on trials that occurred immediately after an upward F1 shift
 113 (-1.55 ± 26.98 mels) were reliably lower than on trials that occurred immediately after a
 114 downward F1 shift (0.59 ± 27.8 mels) ($\beta = -2.14$, S.E. = 0.53 , $p < 0.001$, $d = 0.079$). Likewise,
 115 participants' average F1 were lower across trials that occurred directly after an up-shifted trial ($-$
 116 2.08 ± 7.4 mels) than across trials that occurred after a down-shifted trial (0.82 ± 7.73 mels)
 117 (paired t-test, $t(130) = -2.98$, $p = 0.0034$, $d = 0.38$, Fig 2B, right panel).

118 *Relationship between behavioral responses*

119 At the participant level, there was a significant positive relationship
 120 between compensation and one-shot adaptation ($\beta = 0.14$, S.E. = 0.058 , $p = 0.015$, $\eta^2 = 0.02$),
 121 such that participants who produced larger compensation responses tended to adapt more (Fig.
 122 3A). Conversely, the trial-level model revealed no main effect of compensation response ($\beta = -$
 123 0.033 , S.E. = -0.053 , $p = 0.53$) (Fig. 3B). However, we did observe a small but significant
 124 interaction between shift magnitude and compensation response ($\beta = 0.16$, S.E. = 0.052 , $p =$

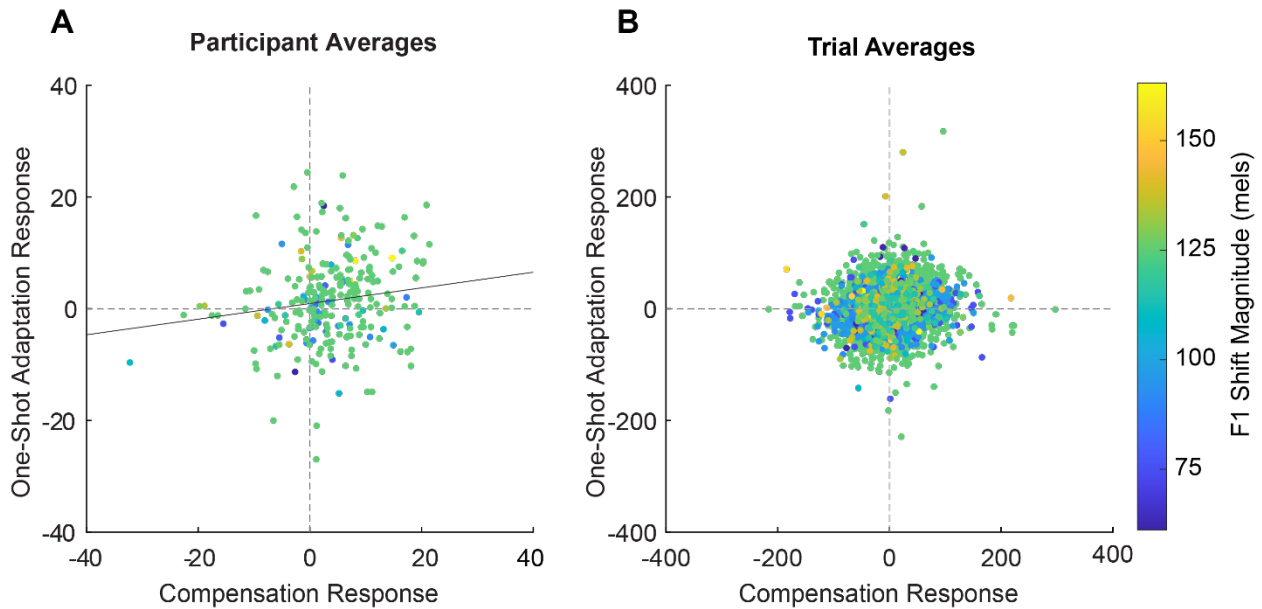


Figure 3: Correlation between compensation and one-shot adaptation. **A:** The correlation between participant average compensation and one-shot adaptation responses. Each participant contributed two data points: their average response to up-shifted and their average response to down-shifted trials. The average applied F1 shift magnitude is displayed via the color gradient (blue = low shift magnitude, yellow = higher shift magnitude). The trend line ($y = 0.14x + 0.93$) represents the main effect of compensation on one-shot adaptation obtained from the linear mixed model used to analyze this relationship. **B:** The relationship between the trial-level compensation and subsequent one-shot adaptation response. Likewise, the average applied F1 shift magnitude is displayed via the color gradient.

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127 0.0023, $\eta^2 = 0.0009$). Along with the finding that larger shift magnitudes led to larger one-shot
128 adaptation responses ($\beta = 7.46$, S.E. = 3.34, $p = 0.03$, $\eta^2 = 0.04$), this suggests that compensation
129 is predictive of adaptation only at larger shift magnitudes. A post-hoc Monte Carlo simulation
130 confirmed that this effect is unlikely to be caused solely by variation in response magnitude
131 across participants ($p < 0.05$).

132 Discussion

133 At both the trial and participant level, one-shot adaptation was detected in post-
134 perturbation trials, where F1 values in the first 100 ms of unshifted trials reliably opposed the
135 perturbation in the previous trial. This shows that learning occurs continuously when the
136 sensorimotor system detects a discrepancy between expected and perceived auditory feedback, as
137 predicted by current models of sensorimotor adaptation in speech. While the magnitude of this
138 one-shot adaptation may be small (1-2 mels), it is relatively substantial when accounting for the
139 fact that a typical perturbation of ~ 100 -150 mels causes a change in F1 an average of only 40-50
140 mels over the course of 100 or more trials (Katseff et al., 2012; MacDonald et al., 2010; Munhall
141 et al., 2009; Purcell & Munhall, 2006a). Moreover, our estimate of one-shot adaptation is likely
142 conservative. First, most of the studies involved multiple stimulus words in pseudorandom order;
143 in $\sim 53\%$ of the trial pairs, participants pronounced different words on the perturbed and
144 subsequent unperturbed trial. Although sensorimotor learning can generalize across words with

145 the same vowel (Rochet-Capellan et al., 2012), such generalization is only partial, and a larger
146 adaptation effect likely would have emerged with uniform word pairs. Second, in our planned
147 analysis of one-shot adaptation responses, we measured F1 frequency during the first 100 ms of
148 each vowel in relevant utterances. However, using the 50-150 ms window would have avoided
149 the inclusion of the consonant transition in our measurement. In these data, this would have
150 yielded an average adaptation effect of 2.21 ± 7.81 mels, somewhat larger than that of the values
151 obtained by averaging across the first 100 ms (1.45 ± 7.57 mels).

152 Though the magnitude of an individual's average compensation response was predictive
153 of their average one-shot adaptation response, such a general relationship was not reliable at the
154 trial level, where compensation only displayed predictive power at higher shift magnitudes.
155 While theories of adaptation based on changes to internal models would not require the presence
156 of this trial-level relationship, the compensation-based adaptation framework of the DIVA model
157 would predict a larger and more consistent effect. In sum, our results question whether these two
158 behavioral responses have such a direct feedforward relationship, or if this relatively weak
159 correlation could best be explained by compensation and one-shot adaptation responses
160 occurring via separate mechanisms driven by the same sensory error (as may be predicted by
161 internal-model hypotheses).

162 Overall, these results provide evidence that a single exposure to altered auditory feedback
163 induces "one-shot" adaptation in the speech sensorimotor system. This is consistent with current
164 models of adaptation in speech specifically and in human movement more broadly; within these
165 frameworks, one-shot adaptation is an effect that may continually build upon itself to create
166 more enduring adaptation responses. The expected relationship between compensation and
167 adaptation was observed mainly at the participant, rather than trial, level. While not conclusive,
168 these results are more consistent with models of adaptation that rely on updates to internal
169 models compared to models that use feedback corrections to update future feedforward
170 commands. Our results provide evidence that adaptation in speech may operate in a similar
171 manner as in other motor domains. As a well-learned natural behavior that relies primarily on
172 implicit learning, speech offers a unique, ecologically valid paradigm to further our
173 understanding of the underlying mechanisms driving sensorimotor adaptation.

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177 **Methods**

178 *Participants*

179 We reanalyzed data from six previous studies examining online compensation responses to
180 formant frequency alterations with similar speech stimuli and perturbation schedules. Data were
181 included if participants met inclusion criteria for their respective studies and if the formant shifts
182 they received were opposite or near-opposite each other (separated by an angle of $180 \pm 20^\circ$
183 when plotted together in F1/F2 space). Data from 91 participants met these criteria; 40 of these
184 participants contributed to two of the included studies. All participants were native speakers of
185 American English and reported no history of speech, hearing, or neurological disorders.

186 *Auditory perturbation*

187 Details of the six studies are provided in Table 1. In all studies, participants spoke aloud
 188 monosyllabic English words containing the vowel /ɛ/ (as in *head*), which were presented as text
 189 on a screen. Simultaneously, participants heard real-time auditory feedback of their speech
 190 through headphones. On a pseudorandom subset of trials (25-50%), auditory feedback was
 191 altered with one of two real-time feedback perturbation systems, Audapter (Cai et al., 2008;
 192 Tourville et al., 2013) or Feedback Utility for Speech Production (FUSP) (Katseff et al., 2012;
 193 Parrell et al., 2017) (Fig. 1). Briefly, linear predictive coding (LPC) was used to model the vowel
 194 portion of the signal and apply a formant shift in real time during speech. Unaltered trials (50-
 195 75% of trials) underwent the same processing pipeline but with no alteration to the formants,
 196 such that auditory feedback in all trials had the same (minimal) delay. The magnitude and
 197 direction of the applied formant shift varied slightly across studies. Studies 1, 2, 3, and 4 shifted
 198 F1 upward and downwards at a consistent magnitude (in mels or Hz) that was applied to all
 199 participants. Studies 5 and 6 each calculated participant-specific shift magnitudes for both F1 and
 200 F2 (in mels or Hz) along a vector pointing from the target vowel /ɛ/ to adjacent vowels /ɪ/ (as in
 201 *hid*) and /æ/ (as in *had*). For these studies, only the F1 portion of the vector was considered in
 202 the analysis; perturbations that increased F1 (/ɛ/ to /æ/) were considered “up” shifts and
 203 perturbations that decreased F1 (/ɛ/ to /ɪ/) were considered “down” shifts. All formant values
 204 were converted into mels for purposes of this analysis.

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207 **Table 1. Summary of the included studies**

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	Study 1 (Parrell et al., 2017)	Study 2 (Parrell et al., 2021)	Study 3 (Niziolek & Parrell, 2021)	Study 4 (Niziolek & Parrell, 2021)	Study 5 (Niziolek & Guenther, 2013)	Study 6 (Niziolek et al., 2014)
# of participants included in analysis	14/14	13/15	40/40*	40/40*	11/18	15/17
# of outliers	1	1	0	0	0	0
Words	beck, bet, deck, debt, pet, tech	dead, fed, said, shed	bed, dead, head	bed, dead, head	bed, bet, dead, deb, debt, ped, tech, ted	head
# of trials	160	120	240	240	400	800
# of perturbed trials	80 (50%)	60 (50%)	80 (33.33%)	80 (33.33%)	100 (25%)	400 (50%)
F1 shift magnitude (mels)	123.6 ± 10	125	125	125	107.9 ± 29.9	94.3 ± 6.8
Perturbation method	FUSP	Audapter	Audapter	Audapter	Audapter	FUSP

209 * the same group of participants contributed to both studies 3 & 4

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213 *Behavioral measures and statistical analysis*

214 Our primary measure of interest was one-shot adaptation, an adaptive response that
215 persists in the trial following an isolated perturbation. In order to examine whether one-shot
216 adaptation is related to feedback-based corrections on the previous trial, we additionally
217 measured the online compensation response. These behavioral responses were examined at both
218 the trial level and the participant level.

219 Trials with a length of less than 100 ms were excluded from analysis (<1%). Two
220 participants were excluded from the analysis as outliers (average compensation or one-shot
221 response > 4 S.D. from mean).

222 *Compensation*

223 At the *trial level*, compensation response was operationalized as the mean normalized F1
224 produced during the 150-250 ms time window of trials in which a perturbation occurred
225 (*perturbation trials*). More specifically, participant- and word-specific baseline F1 trajectories
226 were first calculated from the F1 trajectories of unperturbed trials (*baseline trials*). The F1
227 trajectory of each perturbation trial was then normalized by subtracting the word-specific
228 baseline mean F1 trajectory from it. The compensation response for each perturbation trial was
229 then defined as the mean F1 value within 150-250 ms after vowel onset, after the typical onset
230 latency of compensation. A 200-300 ms time window was originally planned for this analysis;
231 however, only 46% of produced vowels had a duration of at least 300 ms, whereas 80% of
232 vowels lasted until the end of the 150-250 ms time window.

233 Average compensation response was also calculated at the *participant level*,
234 operationalized as a participant's mean normalized F1 across the 150-250 ms window of their
235 perturbation trials. Again, the F1 trajectory of each perturbation trial was normalized via a
236 participant- and word-specific baseline. Then for each participant, two average F1 trajectories
237 were calculated: one trajectory that averaged the normalized trajectories across all trials
238 containing an upward perturbation and one trajectory that averaged across all trials containing a
239 downward perturbation. The participant's average compensation response for each perturbation
240 direction (up and down) was calculated as the mean F1 value in the 150-250 ms time window
241 after vowel onset of these averaged perturbation trajectories.

242 In the *trial level* analysis, a linear mixed model was employed to investigate the effect of
243 perturbation direction on compensation response: *Compensation response* ~ *perturbation*
244 *direction* + (1 | *participant*) + (1 | *study*). Effect size was calculated by dividing β by the residual
245 standard deviation. At the *participant level*, a paired t-test was used to evaluate the distribution
246 of participants' mean compensation response to upward perturbations vs. downward
247 perturbations. Cohen's D was calculated to determine effect size.

248 *One-shot adaptation*

249 At the *trial level*, one-shot adaptation response was calculated as the mean normalized F1
250 produced in the first 100 ms of unperturbed trials that occurred directly after a perturbed trial
251 (*post-perturbation trials*). Again, participant- and word-specific baseline trajectories were
252 calculated, though using F1 trajectories from unperturbed trials that directly followed another
253 unperturbed trial (*baseline trials*). The F1 trajectories of each post-perturbation trial were then
254 normalized by subtracting the word-specific baseline mean F1 trajectory. The one-shot
255 adaptation response for each post-perturbation trial was calculated as the mean F1 value in the
256 first 100 ms of the normalized trajectory. Only F1 values from the initial 100 ms of the vowel

257 were included, limiting the influence of auditory-based feedback control mechanisms, which
258 have a latency of 100-150 ms in speech (Cai et al., 2012; Parrell et al., 2017; Tourville et al.,
259 2008).

260 At the *participant level*, the one-shot adaptation response was calculated as a
261 participant's mean normalized F1 in the first 100 ms of their average post-perturbation trial F1
262 trajectory. Again, the F1 trajectory of each post-perturbation trial was normalized via a
263 participant- and word-specific baseline. Then for each participant, two average F1 trajectories
264 were calculated: one trajectory that averaged the normalized trajectories across all trials that
265 occurred after an upward perturbation and one trajectory that averaged across all trials that
266 occurred after a downward perturbation. The participant's average one-shot adaptation response
267 for each perturbation direction (up and down) was calculated as the mean F1 value in the first
268 100 ms of these averaged post-perturbation trajectories.

269 At the *trial level*, a linear mixed model was employed to investigate the effect of
270 perturbation direction on one-shot adaptation: *One-shot adaptation response* ~ *perturbation*
271 *direction* + (*I* | *participant*) + (*I* | *study*). Effect size was calculated by dividing β by the residual
272 standard deviation. At the *participant level*, a paired t-test was implemented to assess the
273 distribution of participants' mean one-shot adaptation response to upward perturbations vs.
274 downward perturbations. Cohen's D was calculated to determine effect size and conduct a power
275 estimation.

276 *Relationship between behavioral responses*

277 In order to assess the relationship between compensation and the one-shot adaptation that
278 followed it, we fitted a linear mixed-effects model to one-shot adaptation with compensation,
279 perturbation magnitude, and perturbation condition as fixed factors and with participant as a
280 random intercept. Separate analyses were conducted at the participant level (averaging across all
281 trials) and at the individual trial level. To avoid problems in the linear models caused by
282 predictors of very different scales, each perturbation magnitude was normalized by dividing by
283 the mean of all perturbation magnitudes across participants. Study was not included as a separate
284 random intercept in the model as it introduced singularity to the model due to its collinearity with
285 participant and shift magnitude. In order to remove the directional difference between up and
286 down perturbation conditions and maintain standardized magnitude measure between the two
287 perturbation directions, compensation and one-shot adaptation responses from upward-shifted
288 trials were multiplied by -1.

289 At the trial level, compensation response was intended to be included as a random slope
290 by participant, however was removed because the model failed to converge. In order to
291 determine whether this trial level relationship was just a reflection of the participant level
292 distribution and not specific to the trial-to-trial relationships, a Monte Carlo simulation was run
293 on the trial level model. For each participant, a random sample of one-shot adaptation and
294 compensation responses was taken from a set of normal distributions. These distributions were
295 calculated based on that participant's mean and standard deviation of responses separately in the
296 respective up and down shifted conditions. The extracted random samples were then run through
297 the same statistical tests as the original trial level dataset. This simulation was run 1000 times.
298 The resulting distribution of η^2 values revealed that an effect size of the magnitude observed in
299 the original dataset ($\eta^2 = 0.0009$) occurred in <1% of the random samples (95% = 0.000427).

300 All statistical analysis was conducted in R (R Core Team, 2020). Linear mixed effects
301 models and their simplest explanatory models (calculated via stepwise regression) were

302 generated using the *lme4* package (Bates et al., 2015). Statistical significance of the final model
303 was assessed with the *lmerTest* package, which uses the Satterthwaite method to estimate
304 degrees of freedom (Kuznetsova et al., 2017). Power analyses for t-tests were conducted with the
305 *pwr* package (Champely, 2020). Correlation between compensation and one-shot adaptation was
306 then assessed with a Pearson R correlation coefficient using the *MuMIn* package (Barton, 2020).
307 Effect sizes were calculated using the *effectsize* package (Ben-Shachar et al., 2020). Data and
308 analysis code is available at <https://github.com/blab-lab/postMan>. Some of the functions rely on
309 additional code available at <https://github.com/carrien/free-speech>.

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