EFFECT OF AUDITORY FEEDBACK ON HIGH LEXICAL TONES IN DEAF ADULTS WITH COCHLEAR IMPLANTS

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ABSTRACT

The study investigated how auditory feedback can affect fundamental frequencies (F0) of high lexical tones (high-level tone and high-falling tone) produced by deaf speakers of Taiwan Mandarin. Observations made in previous research on non-tonal languages indicated that auditory enhancement in deaf people leads to F0-lowering. Results of the present study showed that high lexical tones in Taiwan Mandarin did not always invite F0-lowering when there is auditory feedback, given that the standard phonetic realization of these tones invites F0-raising.

Keywords: clinical phonetics, cochlear implants, lexical tones, gender, clinical sociolinguistics

1. INTRODUCTION

Speech production relies on both somatosensory and auditory feedback to calibrate it [1]. Auditory feedback can affect both segmental and suprasegmental features. Previous research on deaf speech shows that after cochlear implantation, voice fundamental frequency (F0) drops [2, 3, 4]. It is however noticed that other studies have reported heterogeneous findings: there exists individual variation among deaf users of cochlear implants (CIs) in F0 variation post-implantation [5].

Tonal languages rely on F0 variation to convey semantic meanings. An effect of auditory feedback on F0 may interact with the lexical tone quality and undermine phonemic distinction. Previous research has explored how short-term auditory deprivation may affect F0 in non-tonal languages: a 24-hour deprivation leads to F0 raising, and returning to auditory feedback results in F0 dropping [6]. However, it is not clear how a short-term auditory deprivation would affect lexical tone qualities. Particularly, for lexical tones which occupy higher F0 register to be differentiated from other lexical tones in lower F0 register, the relation between auditory feedback and F0-lowering may be challenged. The present paper works with deaf speakers of Taiwan Mandarin, where four lexical tones exist – Tone 1 (high-level), Tone 2 (low-rising/low-level), Tone 3 (low-falling)[7], and Tone 4 (high-falling). This study investigates how the two high lexical tones – Tone 1 and Tone 4 [8]– are affected by auditory feedback among deaf speakers.

2. RESEARCH DESIGN

Two sentence lists written in traditional Chinese characters were prepared. Participants read aloud the sentence lists before recordings to make sure there was no unfamiliar Chinese character.

Each sentence list had fourteen sentences. The first word in each sentence was bracketed to invite focus. To control for prosody, only the first word in each sentence is examined in the present study.

In the first experiment (On-Off), participants read aloud the first sentence list firstly with the CI and then without the CI. The second reading occurred right after the CI was turned off.

In the second experiment (Off-On), the same participants read aloud the second sentence list without the CI and then with the CI. The second reading occurred right after the CI was turned on.

3. PARTICIPANTS

A total of thirteen deaf participants (six women and seven men) were recruited from Taipei, Taiwan. All spoke Mandarin as the dominant language and received oral education. Five used both single-sided CI and a hearing aid, i.e., bimodal users; eight used only single-sided CI. Participants had profound (sensorineural) deafness. Age and duration of cochlear implant use (in years) are shown in Figure 1.

4. STATISTICS

F0 values are normalized into semitones by the following formula:

$$(1) \quad semitone = \frac{(12ln(F0/Reference))}{ln(2)}$$

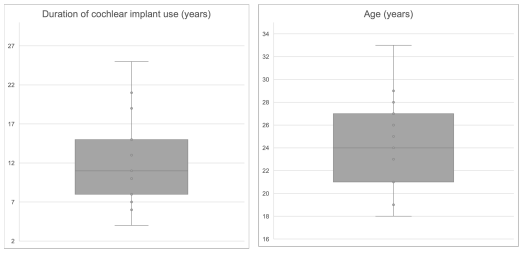

Figure 1: Demographical information

As this study involves inter-speaker comparisons, a speaker-specific reference is adopted [9]. Each speaker's mean Tone 1 is used as the reference value, with auditory feedback in the first On-Off experiment.

Taking F0 trajectories into consideration, this study does not look at single-point F0 values. Instead, F0 values are automatically extracted at each 10% of the segment interval by a Praat script. To exclude F0 tracking errors, only values from 20% to 80% are included in data analysis. Generalized additive models (GAMs) are fit to the data [10]. Smooth terms are included for scaled time, with speaker and word as random effects.

In each experiment, participants read aloud the same sentence-list twice. Thus, linguistic factors are not included. To control for prosody, vowel duration is included as a factor, and it can reveal how speakers engage with F0 when tokens are longer (more articulatory planning). Previous research shows that bimodal users who use both CI and hearing aid perform lexical tones in a more standard way, compared to unimodal users using single-sided CI [11]. In this study, bimodal users only turned off the CI during auditory deprivation, with the hearing aid on. We predict that bimodal users would be less affected by auditory deprivation. Unimodal/bimodal use is considered as a factor, so is duration of CI use. To test whether there is any sociolinguistic engagement with the experiment [12], gender is considered.

5. FINDINGS

5.1. Auditory deprivation

5.1.1. F0 height of high-level tone

Table 1 shows significant terms that are relevant to the present study. We focus our analysis on the two three-way interaction terms among auditory feedback, vowel duration, and CI use or gender.

The durational effect is significantly larger when there is auditory feedback, in male speakers and bimodal users. This durational effect is significantly reduced in female speakers and single-sided CI users, failing to achieve significance in female speakers (Figure 2 and 3).

	Estimate	Std.Error	*t* value	*p* value
(Intercept)		n.s.		
Gender = woman x **Vowel duration**	1.92	0.58	3.30	<0.001
Auditory feedback = on x **Vowel duration**	6.74	0.47	14.31	<0.001
Device = Single-sided CI x **Auditory feedback** = on x **Vowel duration**	-3.65	0.77	-4.69	<0.001
Gender = woman x **Auditory feedback** = on x **Vowel duration**	-6.08	0.84	-7.19	<0.001

Table 1: Summary of the best-fitting GAM predicting normalized F0 trajectory of Tone 1 in the On-Off experiment

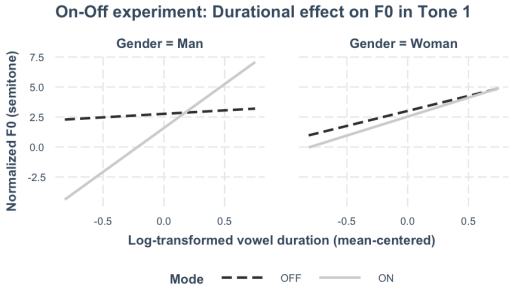

Figure 2: Durational effect by gender and auditory feedback in the On-Off experiment (model prediction)

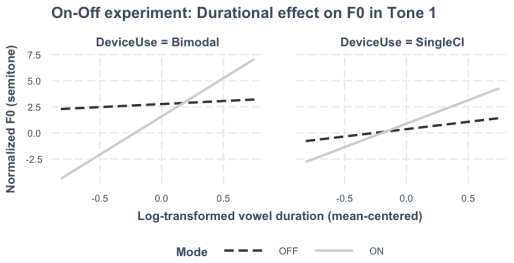

Figure 3: Durational effect by device use and auditory feedback in the On-Off experiment (model prediction)

Longer tokens receive more articulatory planning. When there is auditory feedback, bimodal users and single-sided CI users (to a less extent) treat a higher F0 in tone 1 as a standard speech style; shorter tokens invite less attention from speakers and exhibit the mechanistic effect of auditory feedback on F0.

Men exhibit a vowel durational effect with auditory feedback; no effect of vowel duration is observed among men without auditory feedback. That is, there is a mechanistic effect of auditory feedback on F0 in male speakers. In contrast, regardless of auditory feedback, women realize longer tokens with higher F0 values.

5.1.2. F0 height of high-falling tone

	Estimate	Std.Error	*t* value	*p* value
(Intercept)		n.s.		
Vowel duration	-2.98	0.59	-5.03	<0.001
Vowel duration x **Gender** = woman	2.45	0.34	7.12	<0.001
Vowel duration x **Duration of CI use**	-0.15	0.02	-6.82	<0.001
Vowel duration x **Device** = Single-sided CI	1.82	0.24	7.40	<0.001
Gender = woman x **Auditory feedback** = on x Vowel duration	1.64	0.43	3.76	0.001

Table 2: Summary of the best-fitting GAM predicting normalized F0 trajectory of Tone 4 in the On-Off experiment

Tone 4 is a high-falling tone. Different from Tone 3, a mid-falling tone, phonemically, Tone 4 occupies a higher F0 register. However, current findings show that longer tokens tend to receive lower F0 in male speakers.

As shown in Table 2, when a person uses CI for more years, their shorter tokens are realized with higher F0. Previous research argues that CI is a source of F0 lowering; yet, the current finding reveals that high F0 in short Tone 4 tokens is not a direct mechanistic product of auditory feedback. Previous research shows that longer duration of CI use contributes to more standard tone production [13]. The current finding may be a case where speakers with longer CI duration have learned a standard speech style of Tone 4 production.

There is no effect of auditory feedback on F0 in Tone 4 in men. Shorter tokens invite higher F0. The effect of vowel duration is significantly reduced among female speakers (Figure 4), but the direction is retained. There does not seem a clear effect of short-term auditory deprivation on F0 in Tone 4 tokens.

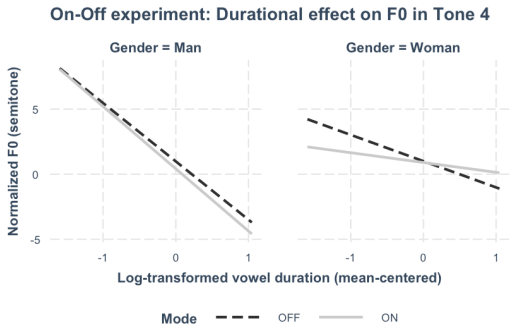

Figure 4: Durational effect on normalized F0 by gender and auditory feedback in the On-Off experiment

5.2. Auditory enhancement

5.2.1. F0 of high-level tone

Without auditory feedback, longer tokens invite lower F0 (Table 3). This durational effect under auditory deprivation is significantly reduced in single-sided CI users, failing to achieve significance. When the speakers return to auditory enhancement, an inverse relation between vowel duration and F0 emerges: longer tokens invite higher F0. Likewise, this interaction is significantly reduced in single-sided CI users.

	Estimate	Std.Error	*t* value	*p* value
(Intercept)		n.s.		
Vowel duration	-3.74	0.24	-15.33	<0.001
Vowel duration x **Auditory feedback** = on	5.71	0.31	18.02	<0.001
Gender = woman x **Vowel duration**	1.48	0.23	6.21	<0.001
Device = Single-sided CI x **Vowel duration**	3.01	0.25	11.75	<0.001
Device = Single-sided CI x **Auditory feedback** = on x Vowel duration	-4.99	0.39	-12.55	<0.001
Gender = woman x **Auditory feedback** = on x Vowel duration	-1.14	0.36	-3.51	0.001

Table 3: Summary of the best-fitting GAM predicting normalized F0 trajectory of Tone 1 in the Off-On experiment

5.2.2. F0 of high-falling tone

The model (Table 4) reveals a significant effect of auditory feedback in general: when speakers return to auditory enhancement, F0 is raised. This effect is significantly larger in longer tokens, and the interaction between vowel duration and auditory

	Estimate	Std.Error	*t* value	*p* value
(Intercept)		n.s.		
Auditory feedback = on	3.21	1.36	2.35	0.01
Vowel duration	-4.52	0.45	-9.98	<0.001
Vowel duration x **Auditory feedback** = on	4.15	0.40	10.32	<0.001
Vowel duration x **Gender** = woman	0.82	0.34	2.39	0.01
Vowel duration x **Device** = Single-sided CI	3.31	0.37	8.72	<0.001
Gender = woman x **Auditory feedback** = on x **Vowel duration**	-1.78	0.47	-3.76	0.001
Device = Single-sided CI x **Auditory feedback** = on x **Vowel duration**	-3.84	0.51	-7.43	0.001

Table 4: Summary of the best-fitting GAM predicting normalized F0 trajectory of Tone 4 in the Off-On experiment

feedback is significantly reduced in female speakers, while remaining in the same direction.

The interaction between vowel duration and auditory feedback is significantly reduced in single-sided CI users – no clear trend of vowel durational effect during auditory deprivation (Figure 5).

The F0-raising during auditory enhancement is inconsistent with the prediction that CI leads to F0-lowering. A Tone 4 token with high F0 is aligned with standard Mandarin speech, showing that the effect of auditory feedback does not universally lead to a lower F0; instead, it is constrained by Mandarin phonology.

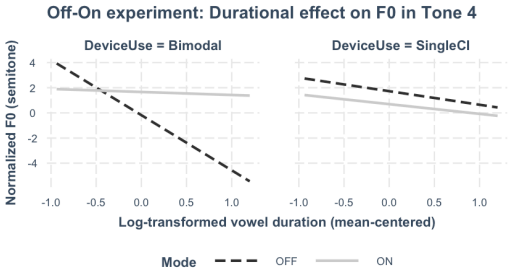

Figure 5: Durational effect by CI use and auditory feedback in the Off-On experiment

6. DISCUSSION

In the On-Off experiment, F0 in Tone 1 is less affected by auditory feedback in single-sided CI users; in the Off-On experiment, F0 in both tones is less affected by auditory feedback in single-sided CI users. It is inconsistent with the prediction that bimodal users, with the hearing aid on during auditory deprivation, would be less affected by auditory deprivation. Future research is needed to investigate why bimodal users, compared to unimodal users, are more affected by the removal of auditory feedback generated by CI alone.

Gender plays an important role in the present study. Tone 1 in women is nearly unaffected by auditory deprivation in the On-Off experiment, but Tone 1 in men shifts toward higher F0 in short tokens, as predicted by the theory that CI results in F0-lowering. In the Off-On experiment, both women and men shift to higher F0 in long Tone 1 tokens and lower F0 in short Tone 1 tokens. Short Tone 1 tokens in men follow the mechanism that auditory feedback drives F0 lowering and auditory deprivation drives F0 raising. The F0-raising in longer tokens of Tone 1, instead, may be driven by attention paid to speech made possible by auditory feedback. While auditory feedback leads to F0-raising in longer Tone 1 tokens, the effect is modulated by attention paid to speech, driving a style-shift to standard speech [14]: high-level tone goes higher in F0.

Auditory feedback does not seem to have much effect on F0 in Tone 4 in the On-Off experiment. In the Off-On experiment, however, longer Tone 4 tokens invite higher F0 when the auditory feedback is recovered. That is, F0-raising is modulated by attention paid to speech during auditory enhancement. The lack of shift in F0 of Tone 4 in the On-Off experiment indicates that Tone 4 may be a linguistic variable whose phonetic realization invites more awareness from speakers; in contrast, Tone 1 is directly affected by auditory deprivation among men but less so among women, meaning that women in general seem to be more sensitive to shift in F0 and apply more effort to maintain F0 when the auditory feedback is just off.

The present research shows that the effect of auditory feedback on F0 is largely conditioned by the phonology of lexical tones in a tonal language like Mandarin. In standard realization of high tones, including high-level and high-falling tone, F0 should move upwards rather than downwards; this directly challenges the mechanistic effect of auditory enhancement, which is supposed to lower F0. The interaction between vowel duration and auditory feedback reveals different effects of auditory feedback on short tokens and long tokens: the former usually follows the relation between F0-raising/lowering and auditory deprivation/enhancement, and the latter instead is under more speaker control and therefore invites F0 movements that are associated with standard speech.

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