3aPP32. Auditory evoked responses to a frequency glide following a static pure tone
Wen-Jie Wang*, Chin-Tuan Tan and Brett A. Martin

*Corresponding author’s address: The City University of New York, New York, NY 10016, wwang2@gc.cuny.edu

In this study, we look at the auditory evoked response to a frequency glide following a static pure tone. A frequency glide is a frequency ramp with specific frequency change range (Δf) and duration (Δt). Frequency change rate (Δf/Δt) and direction (increasing or decreasing frequency) of a glide are important cues for speech perception. P1-N1-P2 acoustic change complex (ACC) responses to increasing or decreasing frequency glides were observed in the recordings of normal hearing subjects. Subjects were also asked to behaviorally discriminate similar stimuli with a fixed Δt at 50 ms or 200 ms and a varying Δt in a separate experiment. Similar findings were obtained with glides at both 500 and 1 kHz base frequency. In these preliminary data, we observed larger N1-P2 responses with the glides of fixed Δt 50 ms at both 500 Hz and 1000 Hz base frequency. However, larger N1-P2 responses for increasing glides than for decreasing glides were only observed with glides at 500 Hz base frequency. Larger N1-P2 response at shorter Δt seems to tally with the smaller behavioral threshold of Δt difference between stimulus with a fixed Δt at 50 ms and stimulus with varying Δt.
INTRODUCTION

A frequency glide is a frequency ramp with specific frequency change range \( \Delta f \) and duration \( \Delta t \). Frequency change rate and direction (increasing or decreasing frequency) of a glide are important cues for speech perception. The investigation of the perceptual ability of the human auditory system to process frequency glides may help us understand the underlying mechanisms for the processing of speech in the human brain.

A specific electrophysiological response, the P1-N1-P2 acoustic change complex (ACC), could be used as a useful index of discrimination capacity for frequency glides. In this paper, the ACC refers to the obligatory P1-N1-P2 complex elicited by an acoustic change during a stimulus (Martin & Boothroyd, 1999), and has been elicited by the onset of a frequency glide following a static pure tone with a sufficient long duration (>300ms) (Arlinger et al., 1976; Clynes, 1969; Ruhm, 1970; Dimitrijevic et al., 2008; Weise et al., 2012).

Previous work has shown that N1-P2 amplitudes increased and N1 latencies decreased with a higher frequency change rate of a glide following a static pure tone (Arlinger et al., 1976; Weise et al., 2012). It is suggested that a large number of sensory level change-detectors were responsible for the elicited evoked potentials (Weise et al., 2012). The amplitude of the evoked potentials elicited depends on the number and synchrony of neurons tuned to the change in frequency.

However, the behavioral correlates of N1-P2 amplitudes elicited by the onset of glide are not clear. When \( \Delta f \) was held constant, the onset of a frequency glide elicited monotonically increasing evoked potential amplitudes with decreasing \( \Delta t \) from 500 ms to 10ms, and the N1 latencies became shorter at the same time (Arlinger et al., 1976). In contrast, there was no correlation between the evoked potential and behavioral results for frequency glide detection. The \( \Delta f \) threshold was constant at 3Hz when the \( \Delta t \) increased from 50 to 200ms (Arlinger et al., 1977).

The present study investigated the relationship between behavioral duration-discrimination thresholds for frequency glides and the auditory evoked ACC responses to the onset of a frequency glide following a static pure tone. Previous studies manipulated \( \Delta f \) rather than \( \Delta t \), to investigate the behavioral (Arlinger et al., 1977) or electrophysiological (Weise et al., 2012) responses to a frequency glide that followed a static pure tone. The hypothesis was that for shorter \( \Delta t \), larger amplitudes and/or shorter latencies would be observed, similar to previous studies. In addition, if duration-discrimination threshold was smaller for glides with shorter \( \Delta t \), it may relate to the larger N1-P2 amplitudes elicited by the glides with shorter \( \Delta t \).

METHODS

2.1 Subjects

Five subjects with pure-tone air conduction thresholds \( \leq 20 \) dB HL from 250 through 8000 Hz (ANSI s3.6-2004) participated. All subjects had no history of neurological or learning problems.

2.2 Stimuli

The stimulus was made up of a static pure tone at \( f_{\text{initial}} \) and a frequency glide ending at \( f_{\text{final}} \) (Fig.1). The total duration \( t_{\text{total}} \) of the stimulus was fixed in this study, but the duration of the glide \( \Delta t \) was varied. The glide portion of the signal was generated with a quadratic function to ensure a smooth phase transition between the glide and the static pure tone. Also, compared with linear glides used in previous studies, the quadratic change better approximates natural sounds, such as formant transitions in speech or pitch change. The instantaneous frequency of the stimulus is described in the following equation:

\[
f(t) = \begin{cases} 
  f_{\text{initial}} & \text{if } t \leq t_{\text{total}} - \Delta t \\
  f_{\text{initial}} + k \left( t - (t_{\text{total}} - \Delta t) \right)^2 & \text{if } t > t_{\text{total}} - \Delta t 
\end{cases}
\]

in which, \( k = \frac{f_{\text{final}} - f_{\text{initial}}}{(\Delta t)^2} \)

The \( f_{\text{initial}} \) was 500 and 1000 Hz in this study, and the frequency difference \( \Delta f \) between \( f_{\text{initial}} \) and \( f_{\text{final}} \) was fixed at 200 Hz. The \( t_{\text{total}} \) was 500 ms. In ERP recordings, \( \Delta t \) was 50, 100 and 200 ms, i.e. the glides started at 450, 400, and 300 ms after the onset of the stimuli. The detail of \( \Delta t \) in behavioral test was discussed later.

All stimuli had 15ms cosine onset/offset amplitude ramps. Stimuli were generated offline using MATLAB, stored on a PC and presented binaurally at 75 dB SPL using Etymotic ER-3 insert earphones.
FIGURE 1. Schematic representation of 50, 100 and 200 ms glides following a static pure tone. The glides started at 450, 400, and 300 ms after the onset of the stimuli. The dashed lines mark the glides with longer $\Delta t$ than the solid line. There was a fixed frequency ending point for all glides with the same initial frequency. (a) the frequency increasing glides; (b) the frequency decreasing glides.

2.3 Recordings
All testing was performed in a double-walled sound booth. The offset-to-onset stimulus interval was 1.5s, which was sufficient for obtaining clean ERP waveforms without contamination from the evoked potential response to the following trial (Martin et al., 1999). The glide conditions were presented alternately and there were 100 trials for each condition. Subjects were instructed to ignore the stimuli and watch a silent movie.

A 64-channel Neuroscan quick-cap and recording system were used to collect electrophysiological data. Vertical and horizontal eye movements were recorded with electrodes at the outer canthi and at the superior orbital ridge. Electrophysiological signals were digitized continuously (band pass 0.15 - 100 Hz with a roll-off of 6 dB/octave; 1000 Hz sampling rate; 20,000 gain) via Neuroscan Synamps and stored for offline analysis. Electrode impedances were kept below 5kΩ. During recording, all electrodes were referenced to Cz. For data analysis, they were re-referenced to an average reference. The analysis epoch was 900 ms, including 100 ms prior to stimulus onset and 300 ms after the stimulus offset. Single trials were baseline corrected across the entire epoch. Trials contaminated by eye blinks or excessive peak-to-peak deflections ($\pm$ 100 µV for adults) were automatically rejected before averaging.

ACC peak analysis was carried out for the P1-N1-P2 complex response elicited in response to the onset of the frequency ramp. N1 latencies and N1-P2 amplitudes were obtained from each subject at FCz. N1 peaks were defined as the most negative potential in the 100-150 ms after the onset of the frequency glide.

2.4. Psychoacoustic measures
Behavioral thresholds for glide duration discrimination were measured for frequency glides whose $\Delta t$ was fixed at 50 or 200 ms, respectively. The direction of the glides was either increasing or decreasing, but kept same within a run. Thresholds were determined with a three-interval forced choice procedure with a two-down one-up rule, which adaptively tracks the point on the psychometric function corresponding to 70.7% correct (Levitt, 1971). Each interval contained one frequency glide following a static pure tone, and the listener’s task was to detect the interval in which the stimulus was perceived different from the other two. The inter-interval time was set at 500ms, and the inter-trial interval was 1.5 second after a response was given. Feedback was provided after each trial.

The difference of duration between the testing glide and the standard glide was set at 250ms initially. Then the difference was decreased after two correct responses, and increased following each incorrect response. The transition from increasing to decreasing value, or vice versa, defined a reversal. Up to the 4th reversal, the duration difference was changed by a step size at 50 ms. This step size was then decreased to 20ms until the 8th reversal, and became 5ms thereafter. A block ended when the 14th reversal was reached. The threshold measured in a block of trials was defined as the mean of the $\Delta t$ at last seven reversals.

RESULTS

The group-mean waveforms obtained for each glide condition at FCz (the electrode site giving the largest amplitude) are displayed in Fig 2 & 3 for glides that followed a 500 and 1000 Hz static pure tone, respectively. All stimuli produced a clear P1-N1-P2 complex at onset. The onset N1 responses were very similar across conditions, peaking at about 105 ms (Table 1 & 2). The onset N1-P2 amplitudes were slightly larger in response to the 500 Hz tone compared with the 1 kHz tone (the group-mean N1-P2 peak amplitudes at FCz: 4.8 and 4.2 µV for the 500 and
1000 Hz tone). There is a second P1-N1-P2 complex occurring after the onset of the glide. This is the acoustic change complex (ACC). The N1-P2 amplitudes of the ACC were generally smaller (the group mean peak amplitudes at FCz: 3.3 and 2.5 μV for the 500 and 1000 Hz tone, respectively) than those obtained in response to the onset of the stimuli. The latencies of N1 were longer (the group mean peaking at 124 and 214 ms across conditions) than the latencies of the onset responses.

The N1 responses of the ACC showed evidence of duration-specific changes of the glides. The N1-P2 amplitudes of the ACC were larger in response to the 50 ms glide compared with both the 100 ms and 200 ms glides (Table 1). The group mean N1-P2 peak amplitudes at FCz for 500Hz glides across direction conditions were 3.86, 3.25, 2.70 μV for the 50, 100 and 200 ms glides, respectively. The group mean N1-P2 amplitudes at FCz for 1000 Hz glides across direction conditions were 2.63, 2.39, 2.44 μV for the 50, 100 and 200 ms glides, respectively. In addition, N1 latencies of the ACC increased with longer duration of the glides (Table 1). The group mean N1 latencies increased from 112, 123 to 126 ms with the increase of the glide duration from 50, 100 to 200ms at 500 Hz across direction conditions. At 1 kHz, the N1 latencies increased from 110, 128 to 137 ms with the increase of the glide duration from 50, 100 to 200ms at 500 Hz across direction conditions.

The effect of frequency direction of the glide was more evident at 500 Hz. The larger N1-P2 responses for increasing glides than for decreasing glides were only observed across conditions of the glide duration at 500 Hz. The group-mean N1-P2 peak amplitudes at FCz were 3.53 and 3.0 μV for the increasing and decreasing glides, respectively. At 1 kHz, the group-mean N1-P2 peak amplitudes at FCz were 2.56 and 2.49 μV for the increasing and decreasing glides, respectively.
There may be some interaction between the effect of the duration of glides and the frequency direction. At both 500 and 1000 Hz, the largest difference between N1-P2 peak amplitudes was observed at 50 ms glide duration. The differences in the group mean N1-P2 amplitude at FCz were 1.29 and 0.67 \( \mu \text{V} \) for the 500 and 1000 Hz, respectively.

**TABLE 1.** Average ± standard deviation of mean N1 latency and N1-P2 amplitudes of stimulus onset and ACC responses as a function of \( \Delta t \) of the glides following a 500 Hz static pure tone. Five subjects were included.

<table>
<thead>
<tr>
<th>Stimuli</th>
<th>Glide duration (ms)</th>
<th>Onset N1 latency (ms)</th>
<th>Onset N1-P2 amplitude (( \mu \text{V} ))</th>
<th>ACC N1 location (ms)</th>
<th>ACC N1 latency (ms)</th>
<th>ACC N1-P2 amplitude (( \mu \text{V} ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>500Hz</td>
<td>50ms</td>
<td>105.4 ±6.73</td>
<td>4.76 ±3.25</td>
<td>568.8 ±4.09</td>
<td>118.8 ±4.09</td>
<td>4.5 (±2.07)</td>
</tr>
<tr>
<td></td>
<td>increasing 100ms</td>
<td>107.2 ±5.54</td>
<td>4.73 ±2.27</td>
<td>524.6 ±3.91</td>
<td>124.6 ±3.91</td>
<td>3.38 (±1.41)</td>
</tr>
<tr>
<td></td>
<td>200ms</td>
<td>104 ±5.43</td>
<td>4.98 ±2.52</td>
<td>428 ±1.41</td>
<td>128 ±1.41</td>
<td>2.72 (±1.62)</td>
</tr>
<tr>
<td>500Hz</td>
<td>50ms</td>
<td>104.8 ±8.5</td>
<td>5.1 ±1.8</td>
<td>571 ±27.21</td>
<td>121 ±27.21</td>
<td>3.21 (±1.45)</td>
</tr>
<tr>
<td></td>
<td>decreasing 100ms</td>
<td>106.4 ±6.43</td>
<td>4.81 ±2.46</td>
<td>522 ±8.72</td>
<td>121.4 ±11.15</td>
<td>3.11 (±0.99)</td>
</tr>
<tr>
<td></td>
<td>200ms</td>
<td>103.8 ±9.28</td>
<td>4.67 ±2.15</td>
<td>424 ±8.72</td>
<td>124 ±8.72</td>
<td>2.69 (±1.03)</td>
</tr>
</tbody>
</table>

* N1 latencies of ACC = ACC N1 location – (500ms – glide duration).

Behaviorally, the duration threshold was smaller for the 50 ms standard glides than for the 200ms (Table 3). Four subjects’ data were included here. The rest one had difficulty with the behavioral task and the data was eliminated from the analysis here. According to these preliminary results, the differences between \( \Delta t \) threshold and the standard glides, across direction conditions, were 50.8 to 118.7 ms in average for 50 and 200 ms glides. At 1 kHz, this difference increased from 65.5 to 160.5 ms in average across direction conditions.

In addition, the frequency direction may also have a stronger effect at 500 Hz as shown in AEP responses. The threshold of \( \Delta t \) was shorter for the frequency increasing than the decreasing glide with both 50 and 200 ms standard glides. This \( \Delta t \) threshold differences between increasing and decreasing glides were about 9.5 and 11 ms for 50 and 200 ms standard glides, respectively.

**TABLE 2.** Average ± standard deviation of mean N1 latency and N1-P2 amplitudes of stimulus onset and ACC responses as a function of \( \Delta t \) of the glides following a 1000 Hz static pure tone. Five subjects were included.

<table>
<thead>
<tr>
<th>Stimuli</th>
<th>Glide duration (ms)</th>
<th>Onset N1 latency (ms)</th>
<th>Onset N1-P2 amplitude (( \mu \text{V} ))</th>
<th>ACC N1 location (ms)</th>
<th>ACC N1 latency (ms)</th>
<th>ACC N1-P2 amplitude (( \mu \text{V} ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000Hz</td>
<td>50ms</td>
<td>103.6 ±4.39</td>
<td>4.48 ±1.81</td>
<td>560.4 ±10.5</td>
<td>110.4 ±10.5</td>
<td>2.97 (±1.62)</td>
</tr>
<tr>
<td></td>
<td>increasing 100ms</td>
<td>105.4 ±5.81</td>
<td>4.13 ±1.83</td>
<td>526.6 ±6.91</td>
<td>126.6 ±6.91</td>
<td>2.4 (±0.55)</td>
</tr>
<tr>
<td></td>
<td>200ms</td>
<td>105 ±3.54</td>
<td>4.04 ±1.88</td>
<td>436.8 ±12.56</td>
<td>136.8 ±12.56</td>
<td>1.87 (±0.86)</td>
</tr>
<tr>
<td>1000Hz</td>
<td>50ms</td>
<td>104.2 ±4.34</td>
<td>4.34 ±1.88</td>
<td>558.6 ±108.6</td>
<td>2.29 (±0.86)</td>
<td></td>
</tr>
</tbody>
</table>
### **TABLE 3.** Average ± standard deviation of mean N1 latency and N1-P2 amplitudes of the ACC responses, and behavioral thresholds of $\Delta t$. Four subjects were included.

<table>
<thead>
<tr>
<th>Stimuli</th>
<th>Glide duration (ms)</th>
<th>ACC N1 latency (ms)</th>
<th>ACC N1-P2 amplitude (μV)</th>
<th>$\Delta t$ threshold (ms)</th>
<th>$\Delta t$ threshold - standard glide (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>500Hz</td>
<td>50ms</td>
<td>118.8±4.09</td>
<td>4.5±2.07</td>
<td>96.08±32.21</td>
<td>46.08±32.21</td>
</tr>
<tr>
<td>Increasing</td>
<td>200ms</td>
<td>128±1.41</td>
<td>2.72±1.62</td>
<td>313.2±29.88</td>
<td>113.2±29.88</td>
</tr>
<tr>
<td>500Hz</td>
<td>50ms</td>
<td>121±27.21</td>
<td>3.21±1.45</td>
<td>105.55±17.74</td>
<td>55.55±17.74</td>
</tr>
<tr>
<td>decreasing</td>
<td>200ms</td>
<td>124±8.72</td>
<td>2.69±1.03</td>
<td>324.2±32.48</td>
<td>124.2±32.48</td>
</tr>
<tr>
<td>1000Hz</td>
<td>50ms</td>
<td>110.4±10.5</td>
<td>2.97±1.62</td>
<td>132.78±74.78</td>
<td>82.78±74.78</td>
</tr>
<tr>
<td>increasing</td>
<td>200ms</td>
<td>136.8±12.56</td>
<td>1.87±0.86</td>
<td>342.23±58.48</td>
<td>142.23±58.48</td>
</tr>
<tr>
<td>1000Hz</td>
<td>50ms</td>
<td>108.6±8.79</td>
<td>2.29±1.54</td>
<td>98.23±23.75</td>
<td>48.23±23.75</td>
</tr>
<tr>
<td>decreasing</td>
<td>200ms</td>
<td>137.6±13.99</td>
<td>3±0.8</td>
<td>378.83±52.96</td>
<td>178.83±52.96</td>
</tr>
</tbody>
</table>

* N1 latencies of ACC = ACC N1 location – (500ms – glide duration).

**DISCUSSION**

Frequency glides following a static pure tone evoked ACC responses. In these preliminary data, ACC responses showed evidence of duration-specific changes. Such that N1-P2 amplitudes were was larger for short glides compared to longer glides. N1 latencies of the ACC increased with longer duration of the glides. The effect of frequency direction of the glide was more evident at 500 Hz, with larger N1-P2 amplitudes for increasing glides than for decreasing glides. This observation was present across the three glide duration conditions. Behaviorally, the duration discrimination threshold was smaller for the 50 ms glides than for the 200 ms glides. Smaller behavioral $\Delta t$ thresholds in response to 50 ms glides seems to tally with the larger N1-P2 response for the 50 ms $\Delta t$ conditions.

**REFERENCES**


