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# Build-up effect of auditory stream segregation using amplitude-modulated narrowband noise

Harley J. Wheeler  
*James Madison University*

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# Build-up Effect of Auditory Stream Segregation Using Amplitude-Modulated Narrowband Noise

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An Honors Program Project Presented to  
the Faculty of the Undergraduate  
College of Health and Behavioral Studies  
James Madison University

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by Harley James Wheeler

May 2016

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Accepted by the faculty of the Department of Communication Sciences and Disorders, James Madison University, in partial fulfillment of the requirements for the Honors Program.

FACULTY COMMITTEE:

HONORS PROGRAM APPROVAL:

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Project Advisor: Yingjiu Nie, Ph.D.  
Assistant Professor, Communication Sciences and Disorders

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Bradley R. Newcomer, Ph.D.,  
Director, Honors Program

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Reader: Lincoln Gray, Ph. D.  
Professor, Communication Sciences and Disorders

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Reader: Christopher Clinard, Ph. D.  
Assistant Professor, Communication Sciences and Disorders

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## PUBLIC PRESENTATION

This work was accepted for presentation, in full, at the American Auditory Society's Annual Scientific and Technology Conference on March the 4<sup>th</sup>, 2016.

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## Abstract

Recent psychoacoustic experiments (Böckmann-Barthel et al., 2014; Deike et al., 2012) have re-examined research regarding stream segregation and the build-up effect. Stream segregation is the ability to discern auditory objects within a stream of information, such as distinguishing one voice amongst background noise or an instrument within an orchestra. Initial works examining this topic proposed that auditory information is not immediately distinguished as various streams, but rather that differences accumulate over time, allowing listeners to segregate information following a period of build-up (i.e., the build-up effect); whereas more current findings indicate a build-up period is unnecessary for segregation. This experiment's methods were based on those of older studies of stream segregation and the build-up effect, but aimed to gather first perceptual responses to stimuli within a window of time more realistic than prior studies, in which subjects seemed to hesitate before giving their first responses of their stream perception. The main differences explored were prompting and training of subjects, allowing subjects to become familiar with stimuli prior to data gathering, and re-instructing subjects if their response times seemed to indicate they still did not understand the task. Another goal of this experiment was to gather data to further assess current beliefs of an inability of cochlear implant-wearing (CI) listeners to harness auditory cues in streaming of information, due to degraded information relative to that of normal-hearing (NH) listeners (Cooper & Roberts, 2009).

Normal-hearing and cochlear implant listeners in this experiment indicated whether they experienced one or two auditory streams during a 24.7 second window of stimuli presentation consisting of alternating A and B noise bursts. This experiment examined correlations between spectral difference, amplitude-modulation rate, and initial response of stream number perception.

Results from this experiment indicated that spectral cues are often salient enough to result in high probabilities of a segregated or integrated perception in NH listeners, though not in CI listeners. These findings are congruent with prior research. Findings also indicate that in conditions without spectral separation, AM-rate differences greater than two-octaves generate a build-up of segregated perception in NH listeners. Overall, while observations of CI listeners thus far suggest possible build-up segregation elicited by robust spectral cues, no data indicate that AM-rate cues are being harnessed to aid in streaming.

## Introduction

Grouping of auditory components from a common source is one of the essential functions of the auditory system, and the degree to which listeners can perform this task greatly influences their ability to identify auditory objects in varied listening environments. A listener's capability to perform this function allows tasks such as listening to one speaker amongst noise or a single instrument within an orchestra to be accomplished. All listeners, with normal hearing (NH) and with auditory sensory aids such as cochlear implants (CI) alike, must combat the issue of recognizing auditory objects in complex environments. This operation is thought to be based on various processes, one of which is auditory stream segregation. In respect with the time course of stream segregation, a traditional notion is that all incoming auditory information is initially integrated (combined into one stream of sound), until auditory cues are sufficiently accumulated and segregation into multiple streams may occur, showing a build-up effect (Bregman, 1990).

Acoustic characteristics examined thus far in relation to auditory stream segregation are spectral difference (Böckmann-Barthel et al., 2014; Cooper & Roberts, 2009; Deike et al., 2012), temporal envelope (Singh & Bregman, 1997; Vliegen et al., 1999; Vliegen & Oxenham, 1999; Grimault et al. 2000, 2001; Roberts et al., 2002), and amplitude-modulation rate (Grimault et al., 2001; Hong & Turner, 2006, 2009; Nie & Nelson, 2015). Studies in stream segregation thus far have utilized pure tones (Bregman & Campbell, 1971; Warren & Obusek, 1972; van Noorden, 1975; Dannenbring & Bregman, 1976a), harmonic tone complexes (Deike et al., 2012; Böckmann-Barthel et al., 2014), and bandpass noises (Dannenbring & Bregman, 1976b; Bregman et al., 1999; Nie et al., 2014).

Contradictory findings on whether CI users have been able to segregate auditory streams with degraded spectral contrast but well-preserved temporal information have been

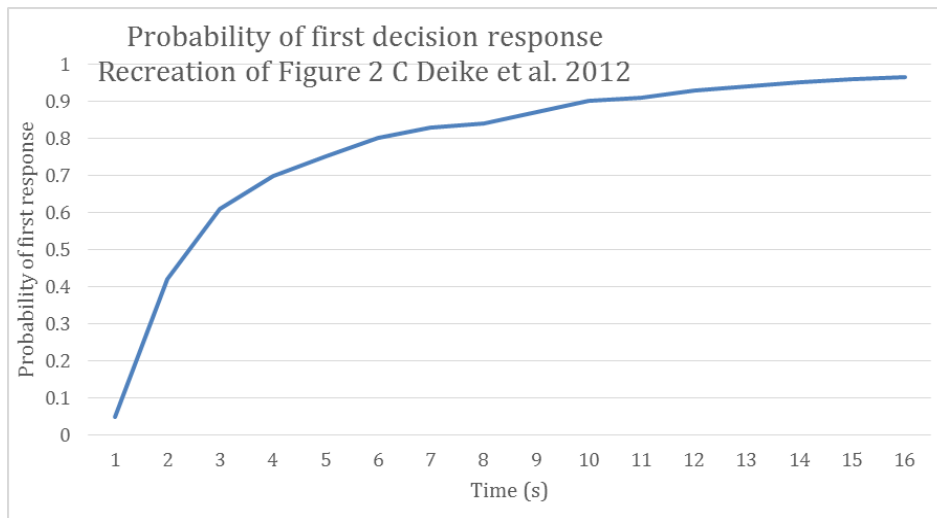


reported. These discrepancies could potentially be due to the variety of testing methods used in studies. For example, amplitude-modulation based (Hong & Turner, 2006) and spectral-cue based stream segregation (Cooper & Roberts, 2009) have been evaluated. Other experiments have implemented tasks in which performance is reduced (Cooper & Roberts, 2007, 2009) or promoted (Hong & Turner, 2009) by stream segregation. Segregation has been measured using self-reported perception (subjective paradigm) (Chatterjee et al., 2006; Deike et al., 2012; Böckmann-Barthel et al., 2014; Marozeau et al., 2013) and performance-based (objective paradigm) tasks (Hong & Turner, 2006, 2009; Cooper & Roberts, 2007; Micheyl & Oxenham, 2010a; Nie & Nelson, 2015). Experiments have also used stimuli presented acoustically (Hong & Turner, 2006) and electrically (Chatterjee et al., 2006). Such fundamental differences in methodology complicate the formation of conclusions regarding stream segregation for both NH and CI listeners.

The presence of a build-up effect, one of the main proposed necessary characteristics of stream segregation (Bregman, 1990), is unclear in CI users. Chatterjee et al. (2006) and Cooper and Roberts (2009) did not observe a build-up of stream segregation in CI users based on spectral cues, and Cooper and Roberts thus concluded CI users are unable to form auditory streams. Other research has indicated that a build-up effect may not be present in NH listeners either (Deike et al., 2012; Micheyl & Oxenham, 2010b). Böckmann-Barthel et al. (2014) found that, like NH listeners, CI users perceived auditory streams as segregated within a few seconds post-onset of the stimuli when the streams were sufficiently different, suggesting stream segregation in the absence of build-up. They further noted that, when the difference between the auditory streams were ambiguous, a build-up did occur in the CI users, as it did in the NH

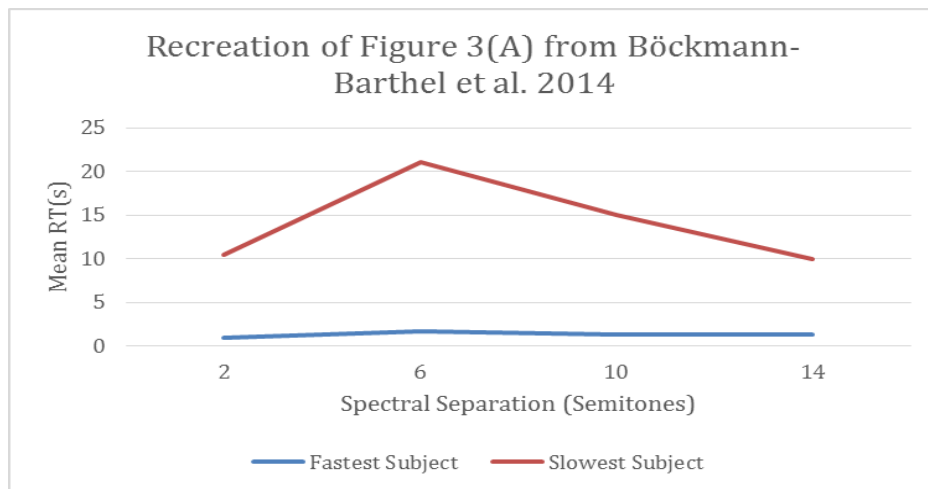
listeners (Deike, et al 2012). Consequently, Böckmann-Barthel et al. concluded that both CI users and NH listeners likely experience a similar quality of stream segregation.

The current study was conducted to examine further the presence of a build-up of auditory stream segregation, particularly through defining earlier response times for perception in a subjective paradigm that studies such as Böckmann-Barthel et al. (2014) and Deike et al. (2012) had not. If, as proposed by Bregman (1978) and Anstis and Saida (1985), build-up of auditory stream segregation occurs somewhere within the initial few seconds of stimuli presentation, this data requires accounting for. **Figure 1** displays a recreation of Figure 2C from Deike et al. (2012), and shows that their NH listeners often had rather late first response times, reaching a 0.8 cumulative probability of first response at approximately 6 seconds. However, these results seemed unlikely, and possibly due to instruction, testing, or training error, as NH listeners rapidly assess auditory input and should have displayed markedly short latencies for perceptual responses.



**Fig. 1.** A recreation of Figure 2 (C) from Deike et al. (2012) showing the cumulative probability of first perceptual response over time amongst normal-hearing listeners.

**Figure 2**, a recreation of Figure 3(A) from Böckmann-Barthel et al. (2014) shows similar issue with response times, their CI user with the slowest responses averaging approximately 15 seconds for a first perceptual response across all conditions, not to mention half of their participants averaged greater than 5 seconds. Even in accounting for delays in response time due to transmission of signals through a CI device, these responses seem to miss the window during which first perception would actually occur. As a result, this experiment followed detailed instruction and training procedures, outlined later, to account for possibilities of why these delays may have occurred in both studies.



**Fig. 2.** A partial recreation of Figure 3 (A) from Böckmann-Barthel et al. (2014) showing the average first response time at various spectral conditions from different subjects. This image displays only the fastest and slowest of their 8 CI users, but displays the variability in response time.

The current study inspected in NH listeners an auditory experience similar to that of CI users, with degraded spectral difference cues and intact AM-rate cues through use of amplitude-modulated, narrowband noise stimuli, as well as comparing results to CI user results. Build-up of stream segregation was explored based on reaction times and perceptual response in correlation to spectral separation and/ or AM-rate separation. A subjective testing paradigm was used to assess stream segregation strength. In this test, listeners were played an extended

window (24.7 s) of un-altering stimuli; where perception would presumably be allowed to experience any shifts it would naturally undergo (Anstis & Saida, 1985; Cooper & Roberts, 2007; Böckmann-Barthel et al., 2014), and allowed to respond over the time course whether they were experiencing a 1 or 2-stream perception.

## Materials and Methods

### *Participants*

Five normal-hearing adult listeners between the ages of 19 and 22, all female, and one adult unilateral cochlear-implant wearing listener, a 22-year old female, participated in this study. All NH listeners had symmetric (no greater than 10dB discrepancy between across ears) hearing thresholds no greater than 20 dB HL at 250, 500, 1000, 2000, 4000, 6000, and 8000 Hz. The CI-using participant was confirmed to have no residual hearing. The Institutional Review Board at James Madison University approved the research procedure to conduct the experiment on human participants. Informed consent was obtained from all participants.

### *Apparatus*

For all experiments, stimuli were generated via a customized Matlab (R2013a) script, which, in conjunction with PsychToolbox (version 3) (Brianard, 1997; Pelli, 1997), controlled stimulus presentation and response recording. An RTbox (Li et al., 2010) was used as the hardware interface to record participants' responses. The computer that was used was a Dell Optiplex 9010, with a Lynx 22 soundcard, which then ran through a DAC1 device, and was finally presented through a Klipsch RB-51 II bookshelf speaker.

### *Stimulus Sequences*

The stimuli, digitally synthesized at a sampling rate of 44,100 Hz in Matlab, were narrowband noise bursts, with bandwidths determined by methods described later in this section. The noise bursts were presented in ABAB sequences, where the full sequence duration was 24.7 seconds, each burst lasting 80 s, and having a 50 ms gap between bursts. Bursts had onset and

offset ramps of 8ms. “B” noise bursts were centered at 1803Hz, the equivalent of the center frequency of electrode 10 on an Advanced Bionics cochlear implant device. “B” bursts were presented at an amplitude-modulation (AM) rate of either 0 or 50 Hz. “A” noise bursts were presented at 1803, 3022, or 6665Hz, the equivalent of an Advanced Bionics device’s 10<sup>th</sup>, 13<sup>th</sup>, and 16<sup>th</sup> electrodes, and had AM-rates of either 0, 50, 100, 200, or 300Hz. Bandwidths of the bursts were determined based upon the center frequency, resulting in bandwidths of 162Hz for 10<sup>th</sup> and 13<sup>th</sup> electrode conditions, and 216Hz for 16<sup>th</sup> electrode conditions, as outlined by Walker et al. (1984), to create a relatively uniform intensity in soundfield. In the conditions with AM, to eliminate spectral “splatter”, following the superimposition of AM, the narrowband noise was reprocessed through the identical bandpass filter that was used to create the unmodulated narrowband noise. **Table 1** displays all stimuli conditions that were examined in this experiment. Amplitude modulation rates for stimuli were based upon prior research determining elicitation of nonspectral pitch for sinusoidal amplitude modulation (SAM) between frequencies of 40 and 850Hz (Burns & Viemeister, 1976; Burns & Viemeister, 1981; Fitzgerald & Wright, 2005). To account for perceived loudness difference in presentation of varied-frequency stimuli, adaptive procedures from Jesteadt (1980) were adopted, approximating the loudness for A bursts at the 13<sup>th</sup> (A13) and 16<sup>th</sup> (A16) electrode equivalents to the loudness for the 10<sup>th</sup> (A10 and/or B10) electrode equivalent, registered at 60dB A within the soundfield.

**Table 1.** Displays all possible test conditions through a matrix of parameters. B AM-Rates are displayed in the left column, and A rates in the top row. B-bursts were always presented at 10<sup>th</sup> electrode equivalent, and either 0 or 50Hz AM-rate, whereas A-bursts could be presented at one of 5 AM-rates and one of the 3 electrode equivalent frequencies.

	A AM-Rate: 0Hz	A AM- Rate: 50Hz	A AM-Rate: 100Hz	A AM-Rate: 200Hz	A AM-Rate: 300Hz
B10 AM-Rate: 0Hz	A10, A13, A16				
B10 AM-Rate: 50Hz	A10, A13, A16	A10, A13, A16	A10, A13, A16	A10, A13, A16	A10, A13, A16

### *Procedure*

To begin testing, each subject performed adaptive loudness balancing procedures, outlined by Jesteadt (1980), to eliminate loudness as a confounding variable between conditions with spectral difference (i.e., B at 1803Hz and A at 3022 or 6665Hz). In this procedure, subjects sat at a meter’s distance from a single loudspeaker, were presented two consecutive noise bursts, and were tasked to press either 1 or 2 on a keyboard depending on whether the first or second bursts was perceived to be louder. The intensity of the target noise burst was adaptively adjusted based on the participant’s response. In conditions in which subjects did not perceive any loudness difference, they were told that they were allowed to guess which burst was louder. This test continued until noise bursts were loudness matched. The first set of tasks in loudness balancing were 13<sup>th</sup> electrode equivalent against 10<sup>th</sup> electrode equivalent conditions, where a 10<sup>th</sup> electrode equivalent burst and a 13<sup>th</sup> electrode equivalent burst would be presented, the participant would respond which was louder, and this would continue until loudness matching was achieved. Next, the subject would repeat the same task, balancing the loudness of 16<sup>th</sup> electrode equivalent against 10<sup>th</sup> electrode equivalent.

The next step, initial training, consisted of presenting stimuli outlined earlier. Subjects would then receive the following prompt:

“You are going to hear a sequence of noise bursts, alternating between an A and B burst, over and over. The A and B may differ in some characteristics, which will cause you to hear them as either one or two sound streams, this will not be the same as just recognizing the sounds as being different (allow them to experience during training). As soon you have a perception of whether you hear one or two, respond with your perception by pressing the 1 or 2 button on the Response box, you should not hold the button. Do not wait to be sure of what you hear; there is no correct response that is being looked for. Over the time that you are hearing the sound sequence, if how many streams you hear changes, just press the appropriate Response box button once to indicate the change.”

Furthermore, a computer screen within the booth displayed a visual progress bar to inform subjects of progression through each individual trial sequence. This measure was implemented to encourage self-awareness of the amount of time subjects were requiring to make their first responses. After completing approximately 12-18 sequences of stimuli, response files would be viewed, and if initial responses approximated 700 ms or less, data collection would begin. For subjects with later response times, inquiry was made as to their perception, and often they replied something to the effect of, “I think I know what I’m hearing, but I’m not quite certain, so I wait a little bit to respond.” In these instances, it was re-emphasized that there was no correct response for these tasks, and that if upon perception subjects believed it to be one way or the other, that was how they ought to respond at that time. Following this repetition of prompting, all subjects would respond within more appropriate windows for initial response. During data collection (post-training) subjects were presented, in random order, each possible



condition sequence a total of 10 times (not grouped together), with 3-second gaps between presentation of sequences, and 6 sequences per group before a break or continuation was offered to subjects. Subjects were prompted to take restroom or water breaks as needed, to allow them to remain attentive.

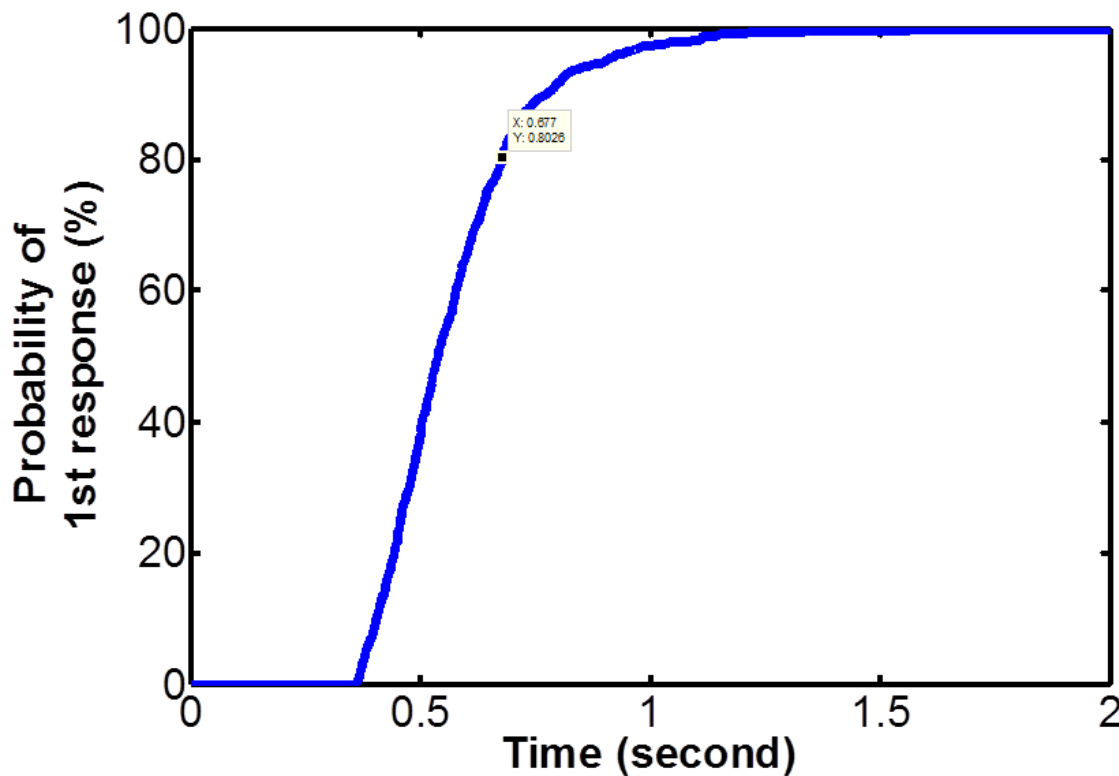
## **Data Analysis**

IBM SPSS statistics version 21 was used for data analysis, means, and errors reported within results. Data were analyzed using the univariate analysis tool, and a Bonferroni correction was applied.

## Results and Discussions

In this experiment, all responses for a condition sequence in which the initial response occurred prior to 360 ms were discarded. This is because these results could not have been valid, as it takes 260 ms for the beginning of the second AB burst set to occur, and approximately 100 ms response time, thus neither integration nor segregation would have rationally occurred beforehand.

Compared to the earlier results from **Figure 1**, initial responses were shown to occur much earlier in this experiment, **Figure 3** below shows the probability of a first response having occurred over the initial time course, averaged over all 5 NH listeners. Unlike in Deike et al.

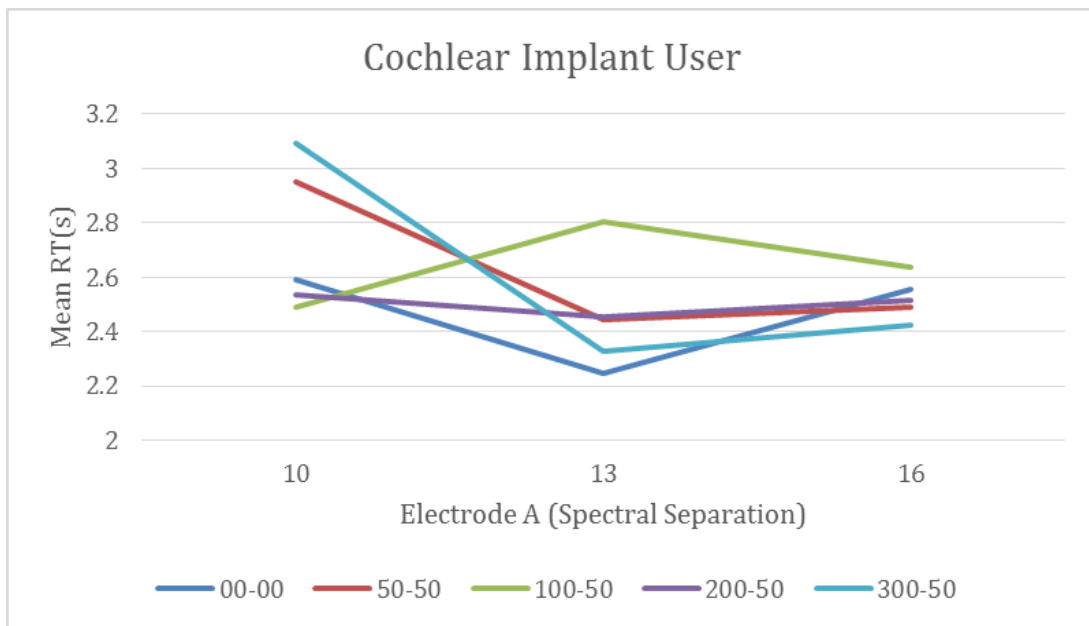


**Fig. 3.** Probability of a first perceptual response having occurred across the 5 NH listeners.

(2012), where a 0.8 cumulative probability of first response having occurred was registered at

approximately 6 seconds, this experiment showed 0.8 cumulative probability at only 0.67 seconds.

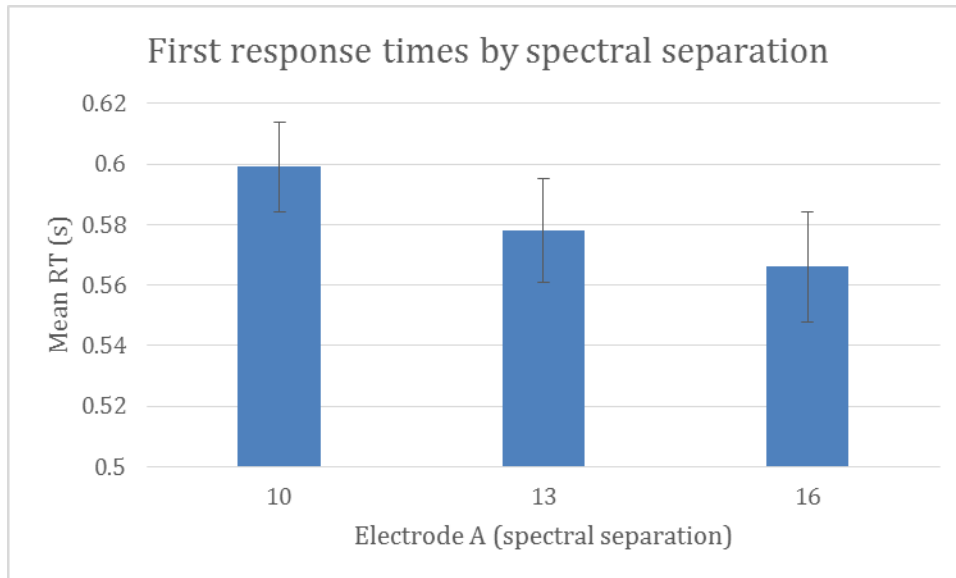
In comparison to Böckmann-Barthel et al. (2014), results from one CI user in the present study thus far cannot show significant results. However, by adhering to testing procedures outlined earlier, the one CI user which has been examined displayed initial response times comparable to the quickest of results from CI users in Böckmann-Barthel et al. (2014), shown in **Figure 4** below.



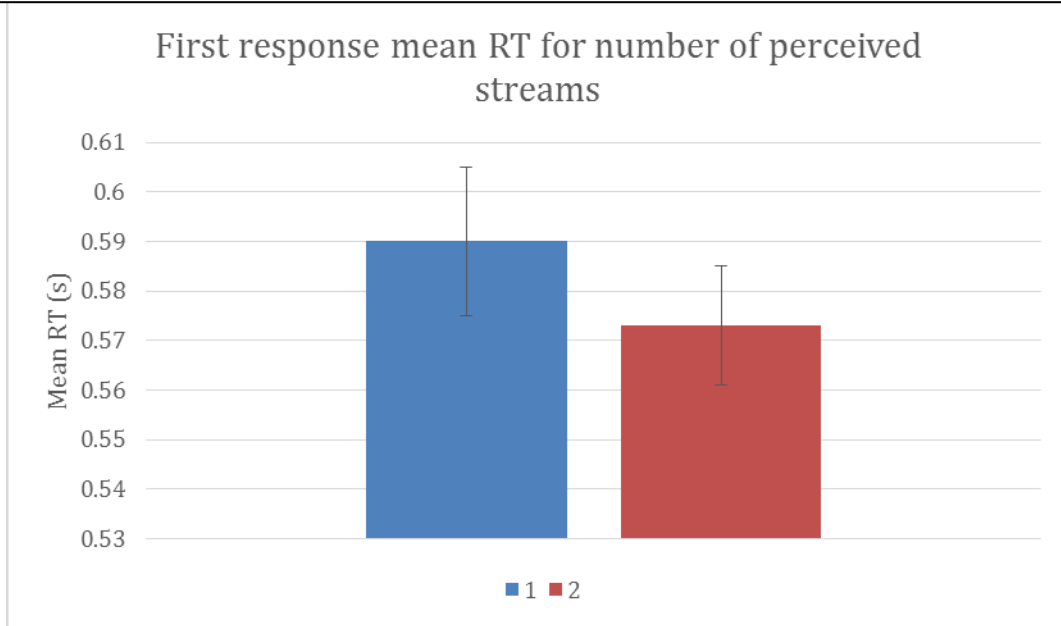
**Fig. 4.** A chart displaying the probability of a CI user’s first perceptual response having occurred, divided by each spectral separation and AM-rate condition.

Having achieved earlier response times in NH listeners, the Analysis of Variance (ANOVA) was performed to examine the effect of spectral separation and amplitude-modulation rate upon the time and perceptual decision of the first response. **Figure 5** shows the relation between average first response time and spectral separation. Spectral separation was not shown

to have any significance in relation to first response time [ $F(2, 89) = 1.087, p = 0.342$ ], though further testing could reveal otherwise. **Figure 6** shows no significant effect of initial stream perception (1 or 2-stream) on first response time [ $F(1, 89) = 0.780, p = 0.380$ ]. AM-rate similarly showed no significant effect on first response time [ $F(4, 89) = 0.813, p = 0.520$ ], though not displayed in the figures.

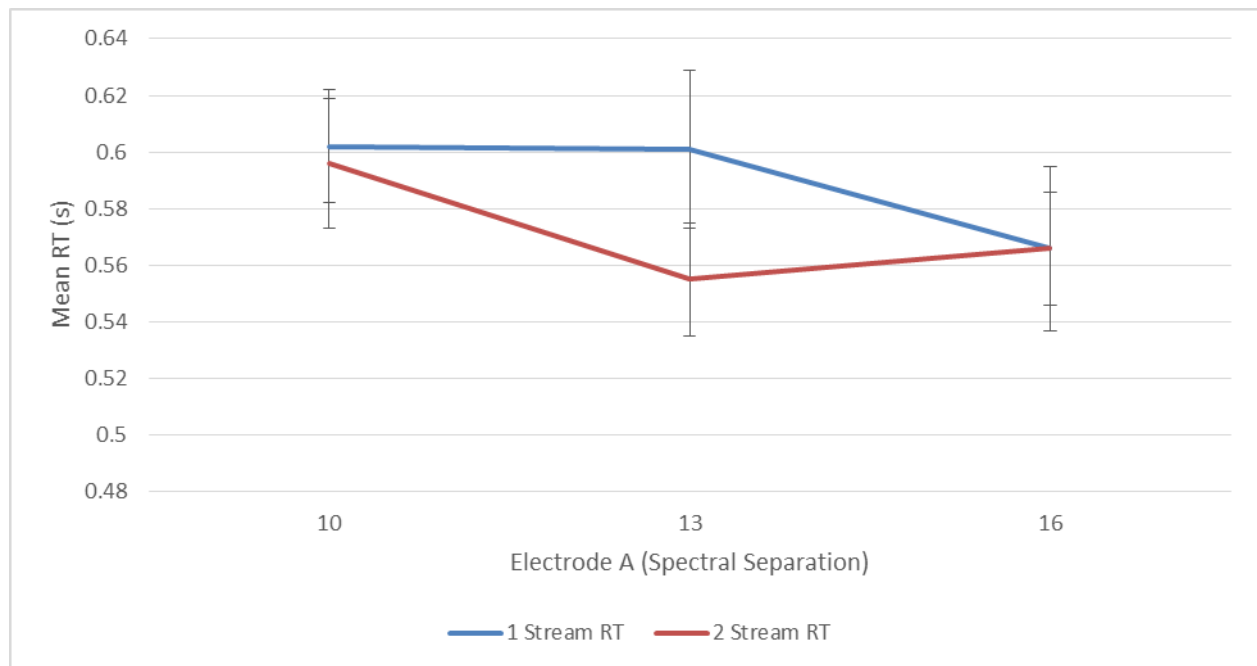


**Fig. 5.** displays the average first response time across all 5 NH subjects for each spectral separation condition. Conditions did not show significant difference from one another.



**Fig. 6.** displays the average first response time across all 5 NH subjects for each perceptual response. Lack of significance shows that subjects were not delaying responses to gain confidence in a 2-stream response.

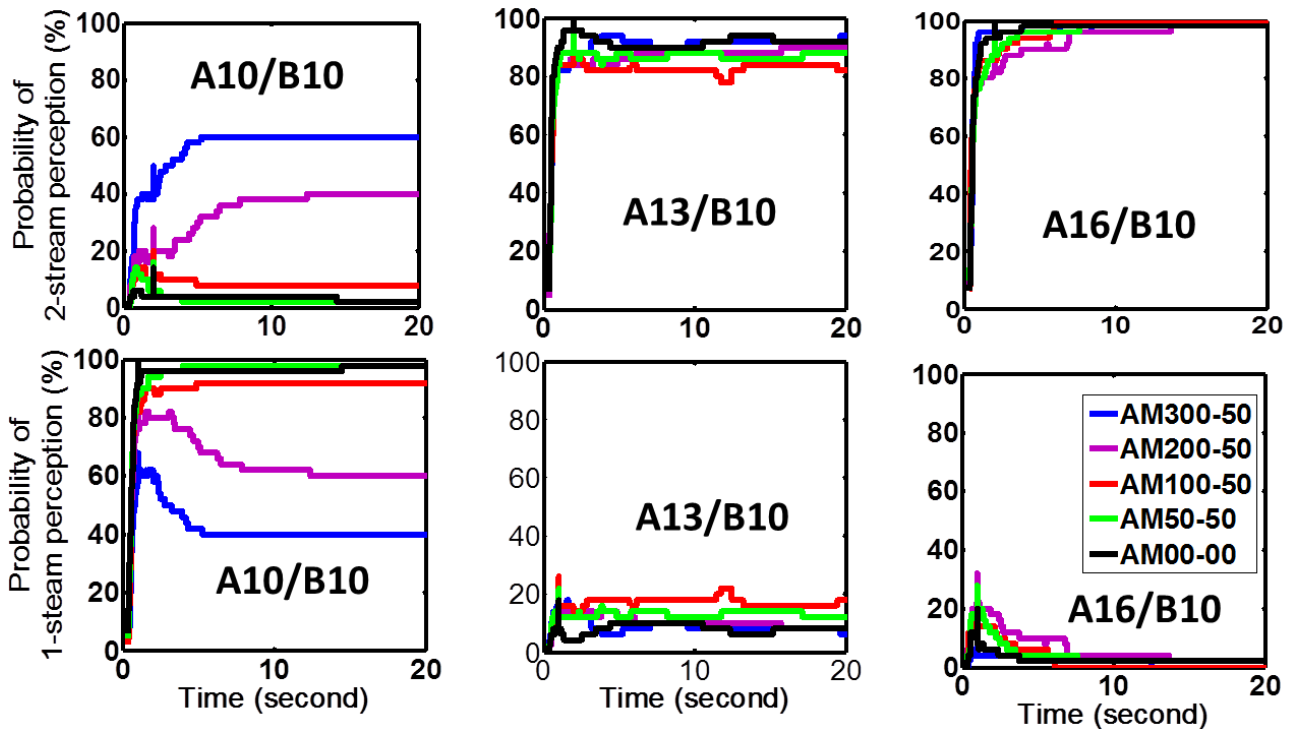
No statistical interaction existed between spectral separation and the initial response of perceived stream [F (2, 89)= 0.522, p= 0.595], showing that for each condition of spectral separation, subjects would respond initially at the same time with perceptual responses, whether the perception was segregated or integrated (**Figure 7**).



**Fig. 7.** Average first response time as a function of spectral separation for 1 and 2-stream perception. No interaction on response time between spectral separation and initial stream perception was shown.

**Figure 8**, an analysis of the probability of 1 or 2-stream perception over the entire time course of each condition, averaged across trials and NH participants show mostly results which would be expected. In conditions with spectral separation (i.e., 10<sup>th</sup> to 13<sup>th</sup> and 10<sup>th</sup> to 16<sup>th</sup> electrode equivalent), initial responses showed high probability of two-stream perception, experienced a small increase of probability, and remained fairly static for the remaining time course. This finding indicates absence of build-up. In the condition lacking spectral separation (i.e., 10<sup>th</sup> to 10<sup>th</sup> electrode equivalent), conditions without large AM-rate cues all initiated and

remained at a high probability of 1-stream perception. However, in instances with AM-rate difference greater than two octaves, a build-up effect was present. In these instances of build-up, initial response tended towards 1-stream, and then 2-stream perception gained approximately .2 probability above initial probability over the first 6 seconds of stimuli presentation.

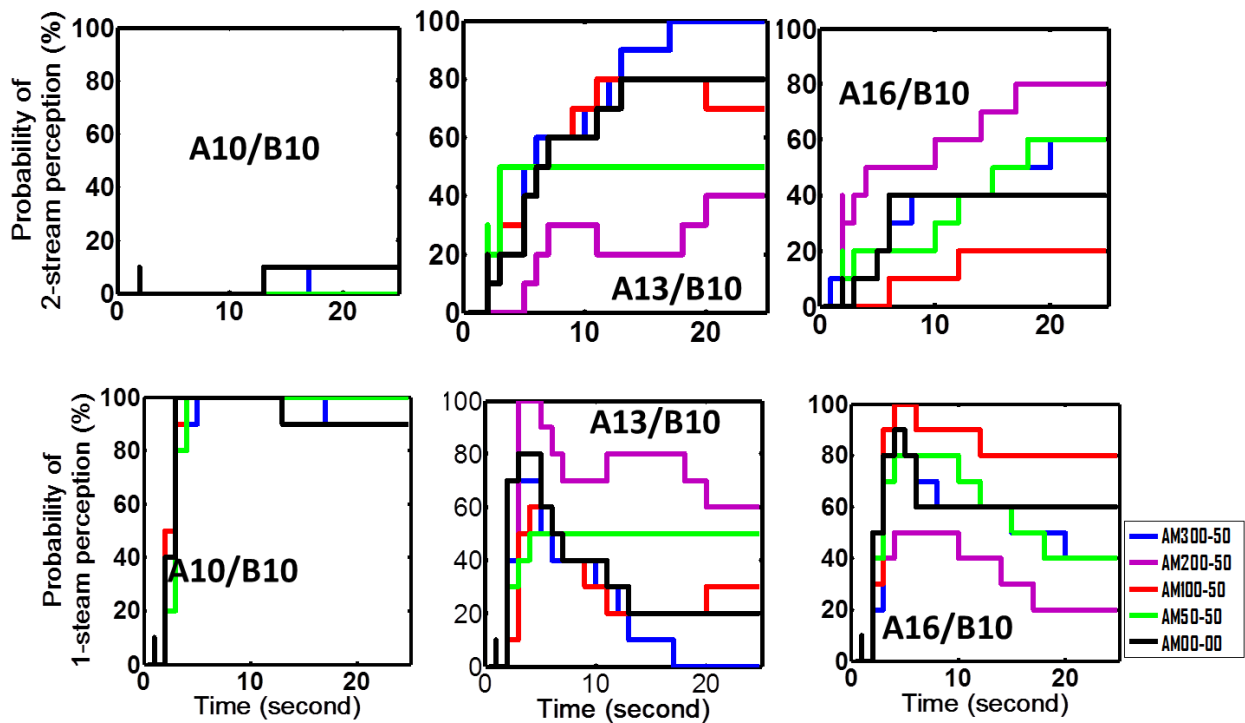


**Fig. 8.** displays the probability of perceptual response per each condition over the time course of stimuli presentation, collapsed across all five NH subjects.

Though requiring further collection of data from CI users, **Figure 9** displays results in the same manner as **Figure 8** for the sole CI user tested in this experiment. While conditions with spectral separation (13<sup>th</sup> to 10<sup>th</sup> and 16<sup>th</sup> to 10<sup>th</sup> electrode equivalent) did not show a tendency towards rapid 2-stream perception comparable to that of NH listeners, a trend was seen with an increasing probability of 2-stream perception over time. In other words, the preliminary data suggest that even with large spectral separations between the A and B burst sequences, it takes approximately 6 seconds for a CI user to start perceptually segregating them, manifesting build-



up stream segregation with large spectral separations. This implies that CI users may not be able to make use of the cues that are salient for normal hearing immediately, although over time they are likely to make use of these cues to some extent. With respect to the effect of AM-rate separation upon perceptual likelihood, unlike NH listeners, no clear trend can be seen, as no consistent effect of a given AM-rate separation is observed across the three spectral separation conditions. In addition, the preliminary observation of the sole build-up stream segregation is inconsistent with Böckmann-Barthel et al. (2014), where build-up was absent in some conditions. Further data will be collected to examine this inconsistency.



**Fig. 9.** displays the probability of perceptual response per each condition over the time course of stimuli presentation, for the CI-user.

## Summary

Addressing the methodological limitations in previous studies, our study has revealed interesting trends. Consistent with the previous studies, our preliminary data in NH listeners showed that salient spectral separation cues elicited stream segregation with an absence of build-up (Deike et al., 2012; Nie et al., 2014), and that weak cues such as AM-rate separation (Nie & Nelson, 2015) elicited stream segregation with the presence of build-up (Deike et al., 2012). Given the presence of this phenomenon prior to response times elicited from subjects amongst similar experiments, implementation of prompting and training similar to this experiment would likely yield further interesting results. Systematic statistical analysis will be performed to achieve a conclusion.

Though current observation indicates discrepancy with prior research findings (Roberts et al., 2007; Böckmann-Barthel et al., 2014) amongst CI listeners, additional data are needed before conclusive claims can be made. However, if these findings were to be supported, it would indicate that CI users are not using available cues that promote stream segregation in normal-hearing listeners. This inability may partly account for difficulties CI users face in noisy environments, as well as poor speech comprehension scores.

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