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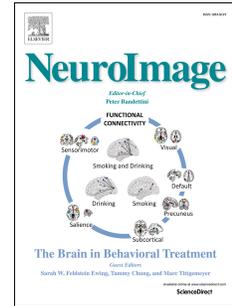
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Influence of talker discontinuity on cortical dynamics of auditory spatial attention

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Abstract

In everyday acoustic scenes, listeners face the challenge of selectively attending to a sound source and maintaining attention on that source long enough to extract meaning. This task is made more daunting by frequent perceptual discontinuities in the acoustic scene: talkers move in space and conversations switch from one speaker to another in a background of many other sources. The inherent dynamics of such switches directly impact our ability to sustain attention. Here we asked how discontinuity in talker voice affects the ability to focus auditory attention to sounds from a particular location as well as neural correlates of underlying processes. During electroencephalography recordings, listeners attended to a stream of spoken syllables from one direction while ignoring distracting syllables from a different talker from the opposite hemifield. On some trials, the talker switched locations in the middle of the streams, creating a discontinuity. This switch disrupted attentional modulation of cortical responses; specifically, event-related potentials evoked by syllables in the to-be-attended direction were suppressed and power in alpha oscillations (8-12 Hz) were reduced following the discontinuity. Importantly, at an individual level, the ability to maintain attention to a target stream and report its content, despite the discontinuity, correlates with the magnitude of the disruption of these

cortical responses. These results have implications for understanding cortical mechanisms supporting attention. The changes in the cortical responses may serve as a predictor of how well individuals can communicate in complex acoustic scenes and may help in the development of assistive devices and interventions to aid clinical populations.

Keywords: auditory attention | event-related potentials | neural oscillations | alpha lateralization

Abbreviations: electroencephalography (EEG); Event-related Potential (ERP); Consonant Vowel (CV); Interaural timing difference (ITD); Finite Impulse Filter (FIR); Attentional Modulation Index (AMI); Mismatch Negativity (MMN); Event-related Desynchronization (ERD)

1. Introduction

Attention plays a fundamental role in understanding complex auditory scenes, operating as a form of sensory gain-control that directly alters the representation of information in the cortex. Specifically, magnetoencephalography and electroencephalography (EEG) studies have shown that selective auditory attention directly modulates event-related potentials (ERPs) evoked by sounds and generated by neural activity in auditory cortex (Hillyard et al., 1973, Picton and Hillyard, 1974, Chait et al., 2010, Ding and Simon, 2012, Choi et al., 2014): ERPs of attended sounds are enhanced while the ERPs of distractor sounds are suppressed (Choi et al., 2014). The degree of modulation of ERPs correlates with individual differences in performance in auditory selective attention tasks (Choi et al., 2014, Dai and Shinn-Cunningham, 2016), suggesting a strong link to perception.

Selective auditory attention also influences ongoing neural alpha oscillations (8-12 Hz) (Strauß et al., 2014, Wöstmann et al., 2015, 2016), which are linked to inhibition of the processing of task-irrelevant information (Thut et al., 2006, Klimesch et al., 2007, Wöstmann et al., 2015). Attentive focusing to one side in auditory space leads to a relative decrease in alpha power in contralateral compared to ipsilateral brain regions (Frey et al., 2014) and governs success of selective attention, isolating one stimulus at a specific spatial location (Kerlin et al., 2010).

Although much effort has been put into studying the relationship between the neural processes controlling attention and auditory scene analysis, little work has gone into understanding how perceptual discontinuities in acoustic scenes affect the neural processing of sustaining auditory attention. In a classical "cocktail party", talkers can change location or a conversation may jump from one speaker to another. These perceptual discontinuities of acoustic features, such as in talker or location, have been shown to affect our behavioral ability

24 to maintain attention to sound streams, even when the discontinuous feature is not the focus
25 of attention (Best et al., 2008, 2010, Maddox and Shinn-Cunningham, 2012, Bressler et al.,
26 2014).

27 Here, we investigated how perceptual discontinuity of the talker affect the cortical pro-
28 cesses responsible for focusing auditory spatial attention. We analyzed changes in ERP mag-
29 nitudes and alpha power. EEG recordings showed that when listeners are attending to a
30 particular location, a switch in talker disrupts ERP modulation and decreases power in the
31 alpha band. In addition, the lateralization of alpha power with respect to the side of attention
32 is disrupted following the perceptual discontinuity in talker. Critically, at an individual level,
33 the magnitude of the suppression in ERPs and alpha power predicts how well a listener main-
34 tains attention and recalls the attended stimuli, showing a direct link between these neural
35 markers and perceptual outcome.

36 **2. Materials and Methods**

37 *2.1. Apparatus*

38 All measures were obtained with subjects seated in an acoustically and electrically shielded
39 booth (double-walled IAC booth, Lyngby, Denmark). A desktop computer outside the booth
40 controlled all aspects of the experiment, including triggering, sound delivery and storing data.
41 The stimuli were presented via Fireface UCX (RME, Haimhausen Germany) and triggers
42 were sent from a RME ADI-8 trigger box (RME, Haimhausen Germany). A headphone
43 driver presented sound through ER-2 insert phones (Etymotic, Elk Grove Village, IL). All
44 sounds were digitized at a sampling rate of 44.1 kHz. During the active portion of the EEG
45 experiment, the subjects responded using the numerical pad on a keyboard.

46 *2.2. Subjects*

47 Nineteen young (median = 25 y; range = 22-34 y; 5 females) right-handed listeners took
48 part in this study. All subjects had pure-tone thresholds below 20 dB hearing level (HL) at
49 octave frequencies between 0.25 and 8 kHz. The subjects provided written informed consent
50 and were financially compensated for their participation. Informed consent was obtained in
51 accordance with protocols established at Technical University of Denmark.

52 *2.3. Stimuli*

53 Stimuli consisted of consonant vowel syllables (CVs) of \ba\, \da\, or \ga\ spoken by a
54 native English male and female talker. CVs were recorded in a sound-proof booth with a large
55 diaphragm condenser microphone (AudioTechnica AT4033, Stow, OH, USA) through a Duet
56 analog-to-digital interface (Apogee Electronics Corp., Santa Monica, CA, USA) at a sampling

57 rate of 44.1 kHz at 16-bit resolution. Sound files were edited on the digital audio workstation,
 58 Digital Performer 7 (MOTU, Cambridge, MA, USA). Auditory materials were presented at
 59 an average intensity of ~ 70 dB sound pressure level (SPL).

60 For each trial, an initial 0.1 s broadband noise was presented diotically to serve as a
 61 normalization factor for inherent individual differences in overall ERP magnitude. The noise
 62 was ramped with a $0.02 \text{ s} \cos^2$ rise-decay to minimize the use of onset cues. Following the
 63 noise-burst, two spatially separated isochronous streams of CV syllables were presented: one
 64 from the left (ITD of -0.028 s , corresponding to roughly -30° azimuth), and one from the right
 65 (ITD of 0.028 s , $+30^\circ$). Five CV syllables were randomly chosen for each auditory stream with
 66 the constraint that the same CV could not be presented simultaneously across the two auditory
 67 streams. Each CV was zero-padded at the end such that the overall duration was 0.388 s .
 68 Additionally, each CV syllable was ramped with a $0.02 \text{ s} \cos^2$ rise-decay to minimize spectral
 69 splatter. As shown in Fig. 1C, by design, the timing of the CVs in the two locations was offset
 70 in time to allow isolation of the ERPs evoked by each CV. The leading stream, always the
 71 target in the experiment, started 0.6 s after the onset of the noise-burst. The lagging auditory
 72 stream started 0.18 s after the onset of the leading stream. The inter-stimulus interval (offset
 73 to onset) within each stream was 0.045 s . The initial talkers in the left and right auditory
 74 streams were randomly selected with equal probability from trial to trial.

75 *2.4. Procedure*

76 The experiment consisted of both passive and active listening conditions. Passive and
 77 active conditions were performed in separate blocks. In the passive listening condition, par-
 78 ticipants watched a silent, captioned movie of their choice, ignoring the acoustic stimuli.

79 In the active portion of the experiment, participants fixated on a centrally presented
 80 dot. As shown in Fig. 1A, at the start of each trial, a visual cue of a left or right arrow
 81 was presented, indicating the to-be-attended side; 0.5 s after the cue onset, there was a 1 s
 82 fixation period after which the stimulus was presented. Approximately 0.2 s after the offset
 83 of the last CV in the stimulus, a circle appeared around the fixation point, indicating the
 84 response period. After a 2 s long response time, the circle changed colors to provide feedback:
 85 green to indicate a correct response or red to indicate an incorrect response, respectively.
 86 Approximately 1 s (jittered $0.99\text{-}1.01 \text{ s}$) after the response period, the next trial began.

87 Subjects were instructed to count and report the number of /ga/ syllables they heard in
 88 the cued target stream, ignoring the switch in talker if it occurred in the trial. The number
 89 of /ga/ syllables on any trial could vary between 0-5. On average two /ga/ syllables were
 90 presented. More trials contained a lower number of /ga/ syllables (0-2); the percentage of the
 91 trials for 0-5 /ga/ syllables was approximately 14.7%, 34.5%, 31.6%, 15.7%, 3%, and 0.3%,
 92 respectively.

93 On half the trials, a discontinuity was introduced in the task-irrelevant acoustic feature:
 94 the talkers swapped locations in the third CV presentation. This is referred to as a “switch

95 trial”. On the other half of the trials, the talker in each location remained the same, referred
96 to as a “continuous trial”. Statistically identical stimuli were presented to participants during
97 the passive listening condition. Each participant performed 132 trials for each condition. The
98 trial order was fully randomized.

99 Including preparation time, the experiment lasted approximately 2h. Prior to the experi-
100 ment session, each subject had approximately an hour long training session. The training was
101 completed when listeners reached a performance score of 70% trial correct on the continuous
102 trials, well above the chance level of 17%. All but one of the participants were able to reach
103 this criterion; the remaining subject, who reached a performance level of 68%, did not perform
104 the main experiment.

105 *2.5. EEG Data Recording and Analyses*

106 Cortical responses were recorded using a 32-channel EEG system (Biosemi Active 165 II
107 system, Amsterdam, Netherlands) at a sampling rate of 2048 Hz. Two additional electrodes
108 were placed on the mastoids for reference and another four electrodes were placed around the
109 eyes to monitor eye movement.

110 For EEG data analyses, we used the Fieldtrip toolbox (Oostenveld et al., 2011), EEGLab
111 toolbox (Delorme and Makeig, 2004) and customized Matlab scripts. Continuous data were
112 re-referenced to the average mastoids, highpass-filtered at 1 Hz (1408th order windowed sinc
113 finite impulse response filter, FIR; zero-phase lag), and lowpass-filtered at 20 Hz (1408th
114 order windowed sinc FIR; zero-phase lag). Independent component analysis was used to
115 reject components corresponding to eye blinks and saccadic eye movements. For the ERP
116 analysis, data were down-sampled to 256 Hz and epoched from -0.2 to 3.2 s relative to the
117 onset of the initial noise burst in the trial. Epochs were rejected if the mean amplitude of a
118 trial was a standard deviation or more away from the mean of the distribution across trials.
119 Trials were grouped into two types, continuous and switch trials. To fairly compare across
120 listeners, we used the first 98 remaining trials after the rejection from each condition.

121 Spectral analysis ($t=0-3.2$ s) was performed using the original sampling rate (2048 Hz).
122 For each electrode, the induced (i.e., average evoked response subtracted from each trial) spec-
123 tral power and time-frequency content were estimated using the multi-taper method (Thom-
124 son, 1982). By removing the averaged evoked response in the spectral analysis, we could
125 analyze the effect of a switch on the spectral power independently from any effect observed
126 in the ERP. Three bi-orthogonal prolate-spheroidal sequences were used in this method to
127 minimize the spectral leakage outside of the bandwidth of 1.33 Hz (Slepian, 1978). A moving
128 window of 0.28 s with a step-size of 0.05 s was used for the computation of the time-frequency
129 representation of induced alpha power. Because alpha frequency varies from subject to sub-
130 ject (Nunez et al., 1978), we determined the individual alpha frequency on a subject basis,
131 defined as the frequency between 8-12 Hz with maximum power (Klimesch, 1999). Using this

132 subject-specific frequency, we defined each individual alpha band as 2 Hz above and below
 133 this peak. To compute the across-subject average induced alpha power, we averaged across
 134 these subject-specific alpha bands.

135 *2.6. Attention Indices*

136 Two indices of attentional modulation of neural responses were calculated: amplitude
 137 analysis of the N1 of the ERP and the attentional modulation index of induced alpha power
 138 (AMI α ; (Wöstmann et al., 2016)). For the ERP analysis, the amplitude of the N1 component
 139 was calculated from the individual-subject average ERPs for each electrode, computed by
 140 finding the local minimum within a fixed time window positioned from 0.1-0.2 s after each
 141 CV onset. For each listener, the N1 in the six front-central electrodes (F3, F4, FC1, FC2,
 142 Fz and Cz), which yielded the strongest auditory-evoked responses (Fig. 1D), were averaged
 143 together. Inherent individual differences in overall ERP magnitude were large on an absolute
 144 scale. We therefore normalized (division) each individual subject's ERPs with the amplitude
 145 of the N1 response to the noise-burst at the start of each trial, **averaged over all conditions**.
 146 We quantified how the N1 is modulated by attention by comparing the N1 peak amplitudes of
 147 each CV in the target stream across conditions (i.e., passive vs. active condition, continuous
 148 vs. switch trial).

149 The AMI α , [$AMI\alpha = (\alpha_{left} - \alpha_{right}) / (\alpha_{left} + \alpha_{right})$], revealed a spatially resolved mea-
 150 sure of attentional effects on alpha power (8-12 Hz) at each electrode. For each condition,
 151 trials were separated into attend left and right. The alpha power for each channel (32 chan-
 152 nels) in attend left and attend right trials were analyzed separately in two time windows to
 153 determine the alpha power before (t=0.6-1.466 s) and after a discontinuity (t=1.467-3.2 s).
 154 The AMI α was computed for each of these two windows.

155 *2.7. Statistical Testing*

156 Unless otherwise specified, statistical inference was performed by fitting linear regression
 157 models to the data and adopting a model comparison approach (Baayen et al., 2008). Fixed-
 158 effects terms were included for the various experimental factors whereas subject-related effects
 159 were treated as random. In order to not over-parameterize the random effects, models were
 160 compared with and without each term using the Akaike information criterion (Pineiro and
 161 Bates, 2000). All model coefficients and covariance parameters were estimated using restricted
 162 maximum likelihood as implemented in the lme4 library in R. An F approximation for the
 163 type-II scaled Wald statistic was employed to make inferences about the fixed effects (Kenward
 164 and Roger, 1997): this approximation is more conservative in estimating Type I error than the
 165 Chi-squared approximation and performs well even with complex random-effects covariance
 166 structures (Schaalje et al., 2002). The p-values and F-statistics based on this approximation
 167 are reported.

168 When testing for differences in mean results, we applied parametric t-tests when the
169 data conformed to normality assumptions ($p > 0.05$ in Shapiro-Wilk test) and non-parametric
170 Wilcoxon signed rank test otherwise. Z and P-values are reported for Wilcoxon rank test. For
171 correlation analyses we used the Spearman correlation. Multiple comparisons were corrected
172 using the false discovery rate to limit Type I error.

173 3. Results

174 3.1. Switching of talker reduces behavioral performance

175 Fig. 2A compares the percent correct responses in trials where the talker in the target
176 location remained the same (i.e., the continuous trials) and where it switched (i.e., the switch
177 trials). When the task-relevant feature (location) and the task-irrelevant feature (talker) were
178 both continuous in the target stream, average performance across subjects was 86.6% cor-
179 rect. However, when the talkers at the target and distractor locations switched, performance
180 dropped significantly, to 71.4% correct (Wilcoxon signed-rank test; $z = 3.82$; $p < 0.001$).

181 To determine whether target position influenced error rate, we computed the percentage of
182 errors made as a function of target CV position in trials with only a single target (Fig. 2B). We
183 limited our analysis to trials with only single target CVs because the error rates in trials with
184 multiple targets are not independent from one position to another. There was a non-significant
185 trend of which the largest errors in the switch trials occurred when the trial contained the
186 target /ga/ CV at the time of the switch (Fig. 2B, red). Linear mixed-effect regression model
187 of the error rates, with both trial type and CV position and their interaction as regressors,
188 showed significant main effect of position of the target CV ($F_{(4,162)} = 3.65$, $p = 0.007$).
189 There was no significant main effect of trial type or its interaction with target position. The
190 lack of effect of trial type on behavioral performance does not suggest that the switch has
191 no significant effect on the performance because only 34.5% of overall trials were included in
192 this analysis. It is likely that trials with > 1 target CV are more demanding and the switch
193 has more of a detrimental effect. Indeed, within the switch trials, about 35% of the errors
194 occurred in the trials with 2 target CVs compared to the single target CV trials that had
195 an error rate of 25%. Nevertheless, when pooled across all trials, the effect of the switch is
196 apparent as shown in Fig. 2A.

197 3.2. Attention modulates ERPs

198 The normalized ERP N1 amplitudes, typically occurring ~ 0.1 - 0.15 s after syllable onsets,
199 were calculated separately for each subject, CV, and attentional condition (Fig. 3C). For
200 the same physical stimuli, N1 magnitudes differ between active (Fig. 3C, filled boxes) and
201 passive listening conditions (Fig. 3C, open boxes). Specifically, compared to the evoked
202 responses in the passive listening condition, in the active listening conditions, N1s for CVs

203 in the to-be attended target stream are enhanced (i.e., increased negativity; see Table 1 for
 204 statistical summary). A linear-mixed effect regression model of the ERP amplitudes with
 205 CV position and attentional condition (passive vs. active) as regressors yields a significant
 206 effect of attentional condition ($F_{(1,313.15)} = 26.69, p < 0.001$) and CV position ($F_{(4,307.94)} =$
 207 $42.9, p < 0.001$). There was no significant interaction. We also observed a suppression of the
 208 N1s for the CVs in the distractor stream. However, a statistical analysis was not performed
 209 on the distractor stream because the N1s were difficult to identify in the active listening
 210 condition, even though they were clearly identifiable in the passive condition.

211 3.3. Talker discontinuity disrupts attentional modulation of ERPs

212 As expected, comparison of the N1s for the continuous (Fig. 3A, black trace) and switch
 213 active trials (Fig. 3A, red trace) showed no significant difference in N1 amplitude before the
 214 switch in talker. At the time of the switch (yellow highlighted region in Fig. 3A), there was an
 215 enhancement of the N1 response relative to when there was no switch in talker. Immediately
 216 following this discontinuity, there was an observed suppression of the N1 to the subsequent
 217 target CV, as seen in the blue highlighted region in Fig. 3A and C ($z=2.73, p=0.003$). This
 218 observation is confirmed with a linear-mixed effect regression model of the ERP amplitudes
 219 with CV position and trial type (continuous vs. switch) as regressors. The model yields a
 220 significant effect of position ($F_{(4,131.79)} = 22.56, p < 0.0001$) and interaction of position and
 221 trial type ($F_{(4,131.16)} = 3.22, p = 0.015$). There was no significant main effect of trial type.
 222 The suppression of the N1 following the switch was transient; the N1 to the last CV (i.e., ~1
 223 s after the switch) did not show this suppression.

224 To confirm that the observed reduction in the N1 following the discontinuity is linked to
 225 attention, we compared continuous and switch trials in the passive condition (Fig. 3B). The
 226 corrected multiple comparisons showed a significant enhancement of the N1 at the time of
 227 the switch ($z=2.82, p=0.02$), the mismatch negativity (MMN), indicating the deviance in the
 228 stream. However, we found no notable difference in the N1 of the leading stream following
 229 the switch (Fig. 3B). This suggests that the reduction observed following the switch in the
 230 active listening condition was likely related to attention as it was not observed in the passive
 231 condition.

232 3.4. Change in alpha power with talker discontinuity

233 We computed how talker discontinuity affected induced alpha neural oscillations, which
 234 are thought to play a functional role in inhibiting processing of task-irrelevant informa-
 235 tion (Klimesch et al., 2007, Wöstmann et al., 2016). As seen in Fig. 4, an across-condition
 236 comparison of all 32 channels showed a significant reduction of induced alpha power following
 237 a switch in talker (t-test with false discovery rate correction, $t=3.39, p<0.05, df=18$). De-
 238 creased power in the alpha band occurred between the time window of 1.79-2.37 s, coinciding

239 with the reduced N1 amplitude. The decrease in power was largest in the parietal and occipital
 240 channels, as shown in the scalp topography in Fig. 4, consistent with a parietal generator.

241 The effect of talker discontinuity on the neural representation of attended location was
 242 quantified by calculating the attentional modulation index of induced alpha power (AMI α) for
 243 all 32 channels during stimulus presentation. Trials for each condition were separated into at-
 244 tend left and attend right trials. AMI α was computed as a response $(\alpha_{left} - \alpha_{right}) / (\alpha_{left} + \alpha_{right})$
 245 for time windows before and after the switch. A positive AMI α indicates larger neural re-
 246 sponses for attention-left trials and negative AMI α indicates larger responses for attention-
 247 right trials. A difference of the AMI α between the left and the right hemispheres indicates a
 248 hemispheric lateralization of neural responses due to focus of spatial attention.

249 As shown in Fig. 5, in the time window before the switch, the mean AMI α was positive
 250 at channels over the left hemisphere but not significantly different from zero over the right
 251 hemisphere. This asymmetry is likely related to the asymmetric representation of spatial in-
 252 formation in brain regions, including parietal cortex. Specifically, regions in the left cortex
 253 primarily represent contralateral (right) exocentric space, while regions in the right hemi-
 254 sphere dominantly represent left (contralateral) exocentric space, but also right exocentric
 255 space (Kaiser et al., 2000, Huang et al., 2014).

256 Within the continuous and switch trials, AMI α was significantly different between left
 257 and right hemispheres before a potential switch in talker (Fig. 5A and B; one-tailed paired
 258 t-test, $t=2.97$, $p=0.004$; $t=3.47$, $p=0.001$, $df=18$). As expected, there was no significant
 259 difference in the lateralization of alpha across trial types (i.e., continuous vs. switch trials) in
 260 this time window ($t=-0.03$, $p=0.513$, $df=18$). However, we found that the lateralization of the
 261 AMI α was significantly higher in the continuous than in the switch trials in the time window
 262 following a potential switch ($t=2.27$, $p=0.018$, $df=18$): in the continuous trials, where the
 263 talker in the attended location stayed the same, AMI α remained significantly lateralized (Fig.
 264 5A; $t=1.88$, $p=0.039$, $df=18$) but the lateralization of the AMI α was disrupted when the
 265 talker switched location (see the topography in Fig. 5B; $t=0.37$, $p=0.358$, $df=18$).

266 3.5. Changes in neural response correlate with behavioral performance

267 We observed individual differences not only in behavioral performance but also in the
 268 magnitude of N1 modulation and alpha power changes with a discontinuity in talker. We
 269 tested whether the differences observed in the neural responses predicted a listener's ability
 270 to maintain attention on a sound stream when the talker is discontinuous. We compared the
 271 magnitude of the decrease in both N1 and induced alpha power following a discontinuity in
 272 talker to the degree to which this discontinuity affected behavioral performance (i.e., the differ-
 273 ence in performance between switch and continuous trials). We found significant correlations
 274 between the behavioral cost and both the suppression of the N1 (Fig. 6A; $r=-0.61$, $p=0.005$)
 275 and the decrease in alpha power (Fig. 6B; $r=0.53$, $p=0.02$) following the switch in talker.

276 Specifically, listeners whose performance was degraded more by talker discontinuity showed a
277 larger decrease in both neural responses following the switch.

278 4. Discussion

279 Here we showed that discontinuities that may be encountered in everyday acoustic scenes
280 disrupt cortical processing involved in selecting and maintaining attention, thereby affecting
281 perception. Specifically, a change in talker from an attended location reduced behavioral
282 performance. Following this change, there was a reduction in N1 amplitude evoked by a
283 subsequent target syllable and a decrease in alpha power, associated with suppression of dis-
284 tractor syllables. The magnitude of the decreases in both N1 amplitude and induced alpha
285 power predicted the behavioral cost associated with the perceptual discontinuity. Ordinarily,
286 focused spatial attention is associated with strong lateralization of alpha power (enhanced
287 alpha contralateral to the distractor stimuli) (Frey et al., 2014, Wöstmann et al., 2015). Inter-
288 estingly, following the switch in talker, the hemispheric lateralization of alpha was disrupted,
289 yielding a diffuse pattern across the scalp. To our knowledge, this is the first study that has
290 demonstrated this neural correlate of disruption of auditory attention.

291 Past behavioral studies have shown that discontinuity of an unattended/task-irrelevant
292 feature impairs one's ability to selectively attend to a sound stream (Maddox and Shinn-
293 Cunningham, 2012, Bressler et al., 2014). In these studies, when the unattended feature was
294 discontinuous (e.g., switching talkers in the attended location), listeners were more likely to
295 report content from a competing syllable that matched the preceding target in its irrelevant
296 feature (i.e., report information from the same talker but from the wrong location rather
297 than the information from the new talker in the to-be-attended target location; Maddox and
298 Shinn-Cunningham (2012)). These results show that even when a feature should be ignored to
299 perform the task as instructed, its continuity has an obligatory influence on selective auditory
300 attention. Consistent with this previous work, we found a significant decrease in performance
301 when listeners were supposed to attend to location regardless of talker identity, but the talker
302 at the attended location switched identities. It may be more natural to attend to a talker rather
303 than a location; however, the same behavioral effects have been observed when attending to
304 a talker that moves in space (Maddox and Shinn-Cunningham, 2012).

305 While there is an effect of perceptual discontinuity on behavioral performance, until now,
306 it was not clear how this affects the cortical control of attention. When listeners need to
307 analyze the spectrotemporal content of a sound source in the presence of simultaneous, com-
308 peting sources, they must sustain selective attention on the target source. In such situations,
309 attention has a substantial effect on the sensory representation of the sound mixture in the
310 cortex. Consistent with past work, we found that attention enhanced N1s evoked by CVs
311 in the target stream (Picton and Hillyard, 1974, Choi et al., 2013, 2014). We also observed
312 that the N1s evoked by CVs in the distractor/unattended stream were suppressed (relative

313 to the passive condition), suggesting that auditory attention operates as a form of sensory
314 gain-control (see also Choi et al. (2014)).

315 When the talkers at the attended and ignored locations switched, the effects on the neural
316 response were two-fold: there was 1) an enhancement of the N1 evoked by the first CV
317 following the switch and 2) a suppression of the N1 evoked by the subsequent CV following
318 the change (Fig. 3A). The enhancement of the N1 evoked by the third CV in the target
319 stream is consistent with the MMN response associated with a deviance in the stream (i.e., a
320 change in talker). Consistent with the fact that mismatch negativities are pre-attentive, the
321 MMN was also observed in the passive condition (Fig. 3B). Thus, the enlarged response to
322 the third CV response is likely not linked to attention, but rather represents an automatic
323 response to deviations from expectations in sound streams (Näätänen et al., 1978). In contrast,
324 following this enhancement, the N1 evoked by the fourth target CV had a significantly reduced
325 amplitude (Fig. 3A). This was not observed in the passive trials (Fig. 3B), suggesting that this
326 effect reflects a disruption of cortical mechanisms of attention that lead to target enhancement.
327 Although we cannot infer much about the N1 at the time of the switch, as it overlaps with
328 the MMN, the suppression of the N1 following the switch seems to reflect a degradation of
329 the sensory representation of that target CV in the cortex, which interfered with extracting
330 target content. The attentional modulation of N1 recovered about 1 s after the discontinuity,
331 as seen in the N1 amplitude evoked by the last CV in the target stream. Future work may
332 utilize this ERP method to investigate whether the recovery of attention is prolonged in
333 older and/or hearing-impaired listeners following perceptual discontinuities, as some evidence
334 suggests longer neural recovery times and slowing of cognitive processing associated with
335 age (Schneider and Pichora-Fuller, 2001, Lu et al., 2011).

336 Along with the suppression of the N1 following the talker discontinuity, the power in the
337 alpha band (8-12 Hz) decreased (Fig. 4). This event-related desynchronization (ERD) per-
338 sisted through several cycles of the alpha oscillations and occurred around the time at which
339 the third CV in the target stream was presented. It is possible that the alpha desynchroniza-
340 tion and N1 effects are linked: previous work has found that phase-locked alpha and theta
341 oscillations generate the ERP N1-P2 complex (Klimesch et al., 2004). However, we analyzed
342 induced alpha power (averaged evoked response removed). Although one might expect that
343 the magnitude of alpha power, which is associated with suppression of distractors, is related
344 to the degree to which the N1 amplitude is modulated by attentional state, we found no
345 significant relationship between these neural measures. Although this negative result cannot
346 be interpreted as support for the null hypothesis (that alpha modulation and N1 modulation
347 are independent), this negative result calls for further investigation into whether or not there
348 is a direct relationship between alpha strength and N1 suppression. Our interpretation of
349 the ERD in the alpha band is based on its functional role in the inhibition of task-irrelevant
350 information (Thut et al., 2006, Klimesch et al., 2007, Wöstmann et al., 2015): following the

351 discontinuity in talker, the suppression of power in the alpha band suggests that the cortical
352 mechanisms responsible for inhibiting the distractor stream were disrupted.

353 Alternatively, this desynchronization of alpha may reflect the increase in attentional de-
354 mand following the discontinuity (Dujardin et al., 1993). However, if the change in the alpha
355 power was indeed reflecting task engagement, we would not expect to see differences in the
356 lateralization of induced alpha across continuous and switch trials (Fig. 4), where the effect
357 of task engagement is removed through the difference metric used here. Moreover, although
358 this condition was not included here, we did not observe a decrease in induced alpha power
359 following a discontinuity when listeners are instructed to attend to the talker, regardless of the
360 location (See supplementary material). If the effect we observe in Fig. 4 was due to task en-
361 gagement, it should be present in both attend-talker (not reported here) and attend-location
362 conditions.

363 In this spatial attention task, alpha power lateralization depended on the direction to
364 which attention was directed (Fig. 5; Kerlin et al. (2010), Wöstmann et al. (2016)): alpha
365 power tended to increase in the hemisphere ipsilateral to the exogenous locus of attention
366 and decrease in the hemisphere ipsilateral to the side that subjects ignored. This pattern was
367 most obvious in the posterior channels, consistent with activity in parietal regions (Colby and
368 Goldberg, 1999, Smith et al., 2010, Michalka et al., 2015). The pattern unlikely reflects the
369 effects of visuospatial attention to the visual cue, as the cue onset occurred long before (1 s)
370 the AMI α analysis window and the visual cue was at a central fixation point, not co-localized
371 with the target. Instead, as with absolute alpha power, alpha lateralization likely reflects
372 inhibition of neural activity related to ignored stimuli, mediated by high alpha power in the
373 hemisphere ipsilateral to the locus of attention (Jensen and Mazaheri, 2010, Wöstmann et al.,
374 2016).

375 In the time window before a potential switch in talker, the alpha power was strongly lat-
376 eralized in both continuous and switch trials (Fig. 5), reflecting suppression of the distraction
377 CVs and selection of the auditory object in the attended direction (Kerlin et al., 2010). When
378 the talker switched location in the second half of the trial, the hemispheric lateralization of
379 alpha power was disrupted, but not when there was no switch. This may reflect spatial con-
380 fusion: auditory selective attention may begin with allocating spatial attention and binding
381 an auditory object to a location in space to assist in streaming (Kerlin et al., 2010). When
382 a talker suddenly switches location, the system has to disassociate this auditory object with
383 the location and associate the new talker with the target location. Our results thus appear
384 to reflect the interactions between bottom-up discontinuity and top-down switching of atten-
385 tion (Desimone and Duncan, 1995). Future work should investigate this topographical pattern
386 using imaging methods with higher spatial resolution (i.e., high-density EEG).

387 Task performance has been previously shown to relate to some variation of enhancement
388 of N1 amplitudes (Choi et al., 2014) and change in alpha power during stimulus presenta-

389 tion (Kerlin et al., 2010, Wöstmann et al., 2015, 2016). However, we do not yet understand
390 how the disruption of auditory attention is reflected in cortical responses, or how this relates
391 to behavioral performance. Here, we find that the suppression of the N1 evoked by the CV
392 following the switch in talker predicts the behavioral cost associated with the discontinuity
393 (Fig. 6): a subject with a larger suppression of N1 shows a greater behavioral cost of the
394 switch. We find a similar relationship with the ERD in the alpha band and behavioral perfor-
395 mance: a larger desynchronization of alpha is associated with a larger decrease in behavioral
396 performance. This pattern is inconsistent with previous work that shows that a larger ERD is
397 associated with correct trials and better performance (Dimitrijevic et al., 2017). The changes
398 in alpha power observed here presumably play a different role than in such previous tasks.
399 Specifically, the ERD we report is induced involuntarily by talker discontinuity; it is not
400 the result of a voluntary, top-down control of processing. Further investigation is needed to
401 understand the generators and the many roles of alpha oscillations. It is also important to
402 investigate whether similar effects (and of the same magnitude) are observed when the speaker
403 switches to a new third speaker in the attended location rather than the two speakers flipping
404 location, as was done in this study. It may be that the involuntary interruption of attention
405 would be reduced. Regardless, we can conclude that the relative suppression of alpha and N1
406 caused by the perceptual discontinuity of the target talker limits one’s ability to successfully
407 attend to a sequence of syllables from a particular direction.

408 5. Conclusions

409 In summary, it is important not only to understand how cortical processing of attention
410 enhances the sensory representation of sound mixtures, but also to understand the limitation
411 of the system and when and how it fails. We show that perceptual discontinuities, which
412 are common in acoustic settings, disrupt the neural mechanisms that facilitate sustained
413 auditory spatial attention. The changes observed here demonstrate that talker continuity has
414 an obligatory influence on selective auditory attention and affects listening in multi-source
415 environments.

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530 Insert Supplementary Figure 1 here.

ACCEPTED MANUSCRIPT

Figure 1: (A) Trial design. Each trial started with a visual cue to indicate the side to be attended. The cue was followed by a fixation dot at the center of the screen, then the stimulus presentation. Following the stimulus, the response screen was shown, prompting the listener for a response. Feedback was provided on each trial. (B) Two streams of CV were presented on each trial, one spoken by a male and the other by a female speaker. The streams were separated using interaural time differences corresponding to approximately $\pm 30^\circ$. In the continuous trials, the talker at each location remained the same. In contrast, in the switch trials, the two talkers swapped locations in the third CV presentation. (C) The stimulus timing was designed to allow isolation of the ERPs for each CV. The trial began with a noise-burst, indicated in black, followed by the start of the leading/target stream. The lagging/masker stream began 0.18 s after the leading stream, creating an asynchrony in the CV onsets. The colored envelope superimposed on the plot represents the talker at that location. (D) Scalp topography of the N1 response to the first target CV. White circles indicate the electrodes used for ERP analysis.

Figure 2: (A) Behavioral performance for each condition. The black whisker plots show population results with horizontal lines indicating across-subject medians; error bars depict the maximum and minimum percent correct observed in each condition. Results for individual listeners are indicated by circles, with gray lines connecting results in the two conditions. *** $P < 0.001$. (B) Error rates as a function of target CV position in trials with only a single target.

Figure 3: (A) Grand average epoched EEG response for the active listening continuous (black) and switch (red) trials along with example topographies for each trial type. Vertical grey lines indicate the N1 of CVs in the leading/target stream, while the orange lines indicate the N1s of the CVs in the lagging/distractor stream. The yellow highlighted region indicates the time of the CVs following the switch in talkers, while the light blue highlighted region shows the time of the CVs after the switch. Topographies present the scalp distribution of N1 amplitude for the fourth CV in the leading stream in the to-be-attended continuous, and to-be-attended switch trials. (B) Grand average epoched EEG response for the passive continuous (dashed black) and switch (dashed red) trials. Topographies represent the scalp distribution of N1 amplitude for the third CV in the leading stream in the passive listening continuous and switch trials. (C) Average peak N1 amplitude across subjects for each CV in the target stream for the passive (open box) and active (filled box) conditions. A more negative value on the ordinate indicates a larger N1. Lines in each box plot indicate the median. Highlights correspond to the switch and post-switch CVs, as in panel A and B. * $P < 0.05$, ** $P < 0.01$.

Figure 4: Power in the alpha band, as a function of time, compared across conditions. The highlighted region in blue represents the time window in which the alpha power was significantly reduced in the switch trials relative to the continuous trials. $*P < 0.05$ after adjustment for multiple comparisons. Dashed lines indicate the onset of CVs in the target stream. The scalp topography of the average difference in alpha power between switch and continuous trials is shown on the right over the blue-highlighted time window where the difference reached statistical significance.

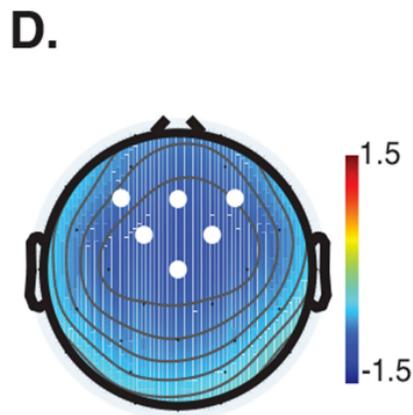
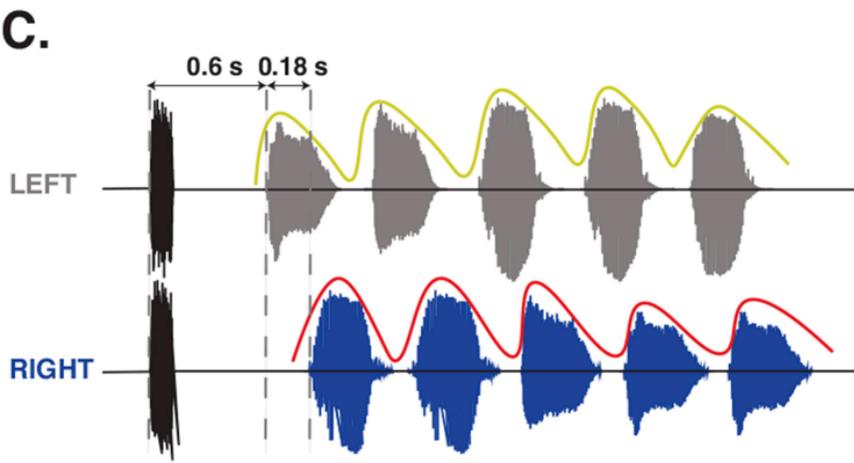
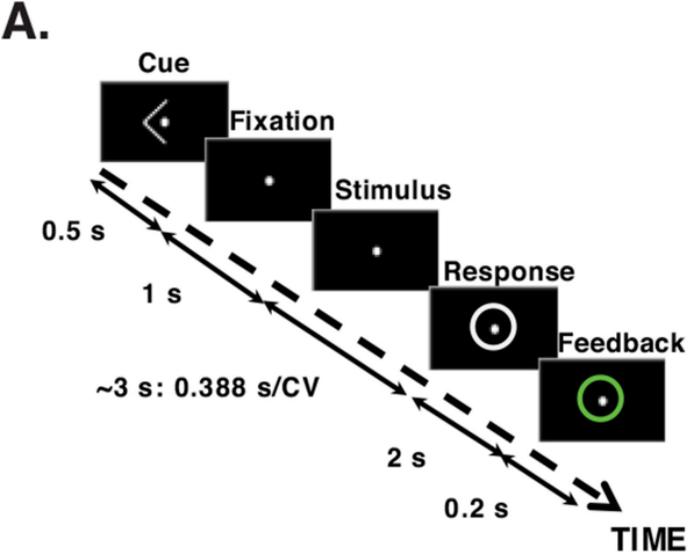
Figure 5: Topographic maps of the $AMI\alpha$ in two time periods (before and after a potential switch in talker) for continuous (A) and switch (B) trials. Bar graphs show mean across the posterior half of channels (excluding frontal channels) on the left hemisphere (LH) and right hemisphere (RH). Error bars indicate ± 1 SEM. $AMI\alpha$ showed a significant hemispheric lateralization (LH > RH) in both conditions before a potential switch. This lateralization remained significant in the second time window in the continuous trials where the talker remained in the same location (A: right panel). In contrast, when the talker switched location in the switch trials, the lateralization pattern was disrupted and was no longer significant. $*P < 0.05$; $**P < 0.01$; n.s., not significant.

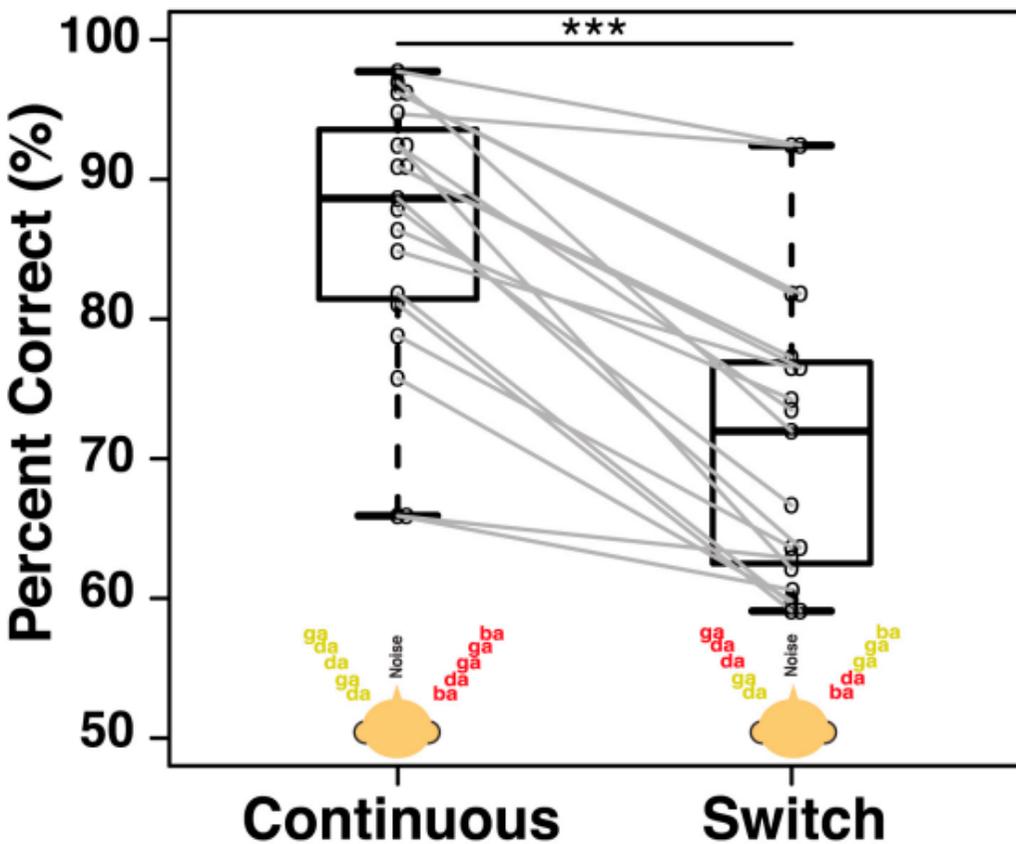
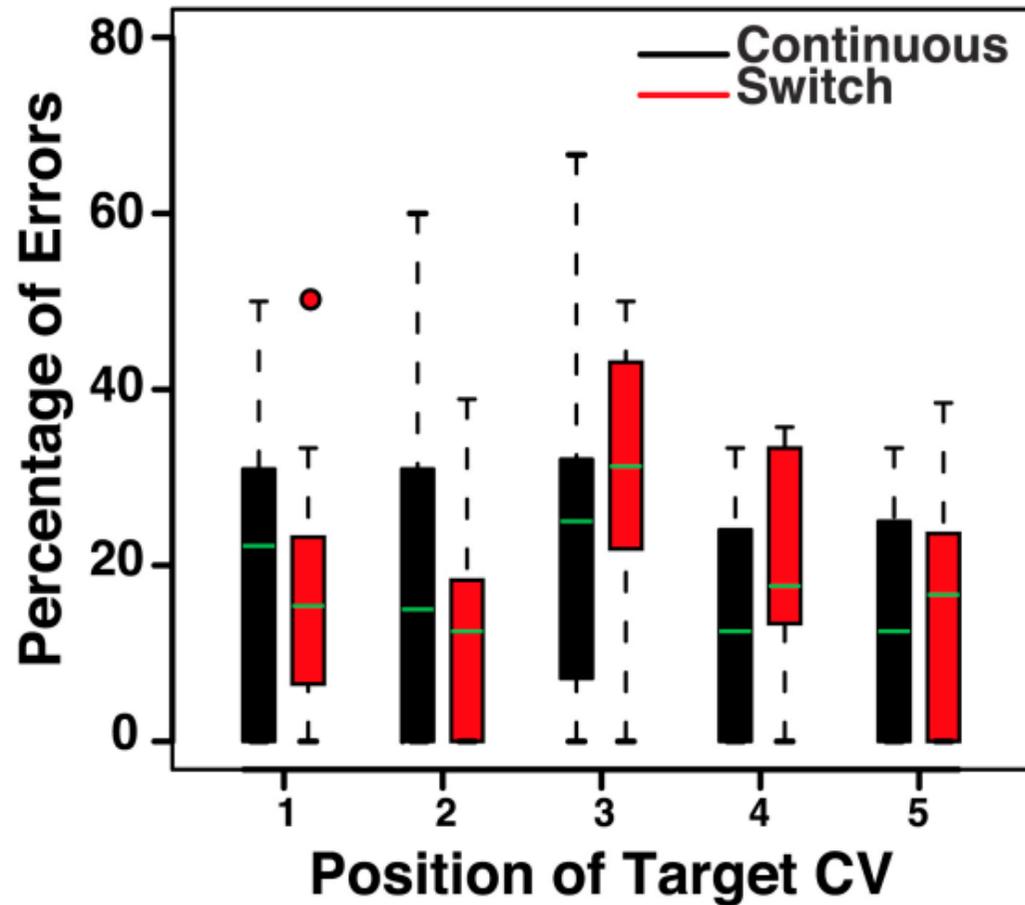
Figure 6: Relationship between the behavioral cost of talker discontinuity, defined as (% correct in Continuous - % correct in Switch trials), and (A) the difference in the N1 in continuous vs. switch (larger negative values indicate larger suppression of the N1 in the switch trials, corresponding to greater neural disruption of attention) and (B) the decrease in power in the alpha band, both calculated in a time window immediately following the switch in talker. Dashed lines represent 90% confidence intervals. $*P < 0.05$.

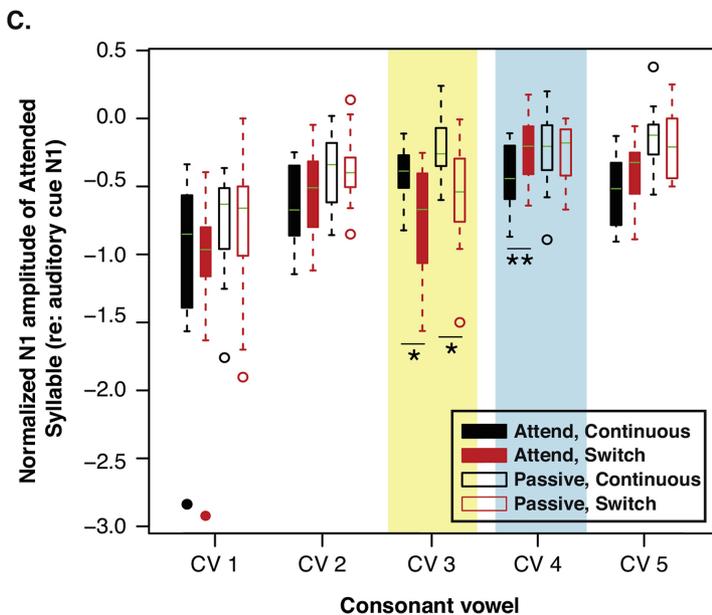
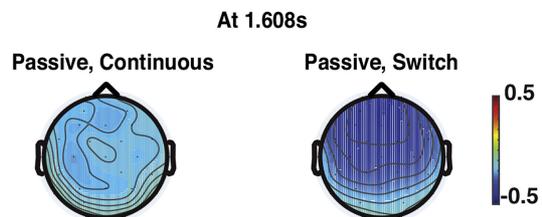
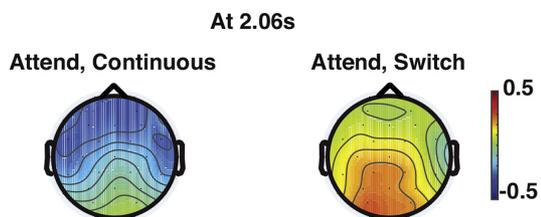
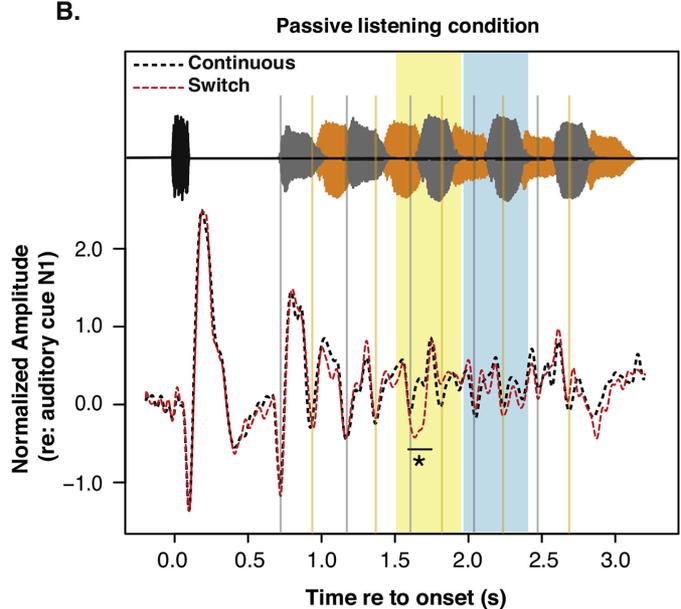
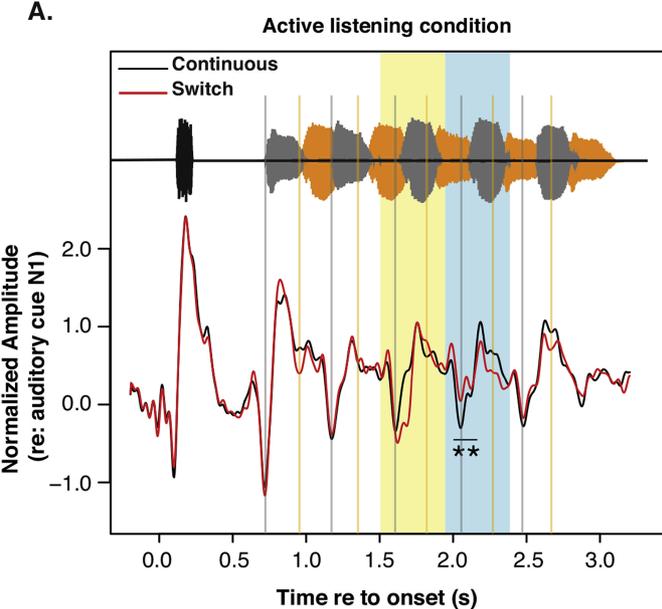
Figure S1: Power in the alpha band, as a function of time, when listeners are instructed to attend to a talker, regardless of location. The stimuli presented were the same as those in the data reported in the manuscript. In the switch trials, the talkers swapped location. The yellow highlighted region represents the time window in which the target and masker talker swap locations. Dashed lines indicate the onset of CVs in the target stream. We find no significant difference in alpha power between the continuous and switch trials, in contrast to when listeners are instructed to attend to a location (Fig. 4 in manuscript).

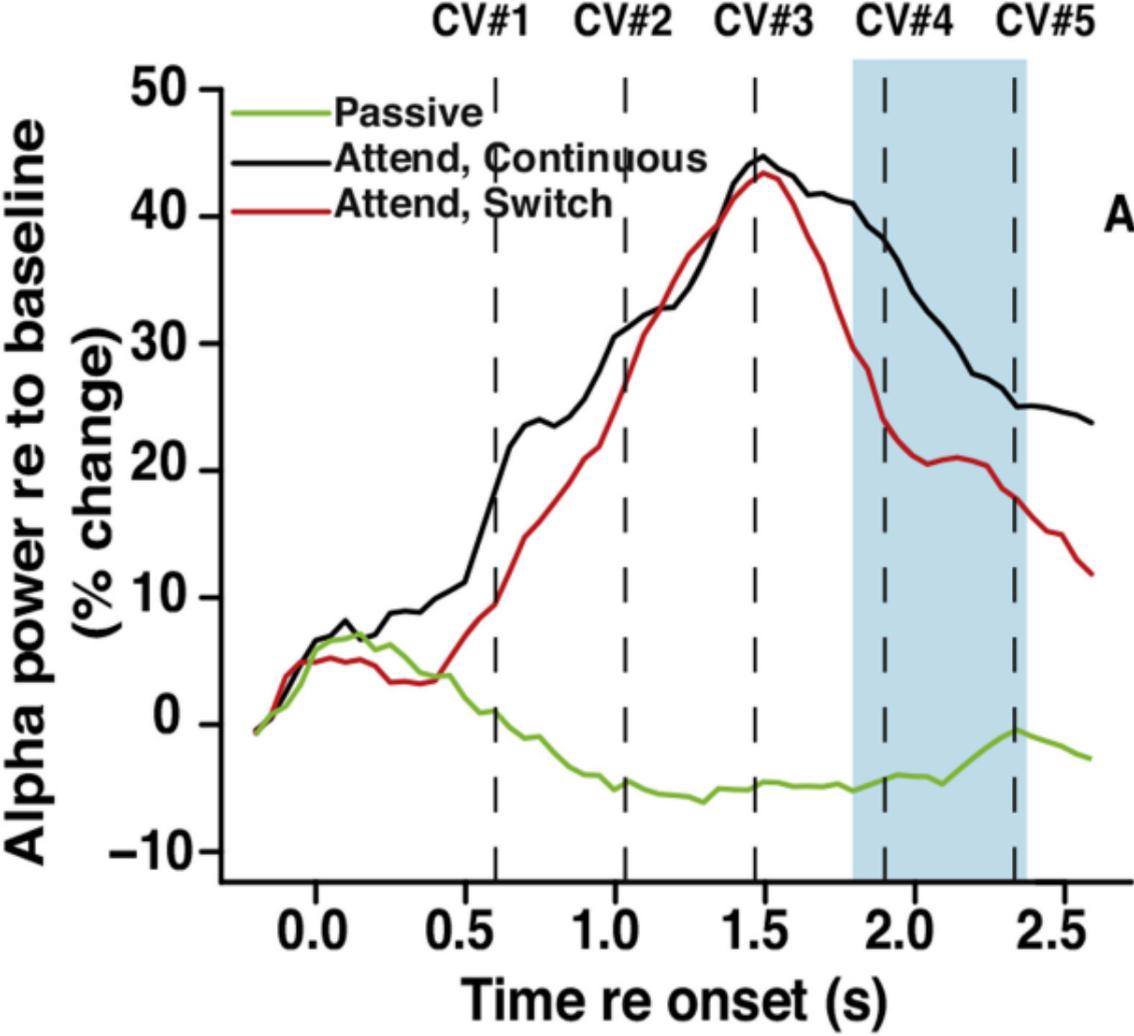
Table 1: Attentional modulation of N1 analysis, * $p < 0.05$, ** $p < 0.01$

CV	Continuous trials, passive vs. active	Switch trials, passive vs. active
1	$z = -2.32^*$	$z = -1.7^*$
2	$z = -1.76^*$	$z = -1.4^*$
3	$z = -1.68^*$	$z = -1.03$
4	$z = -2.13^*$	$z = -0.23$
5	$z = -3.18^{**}$	$z = -1.75^*$



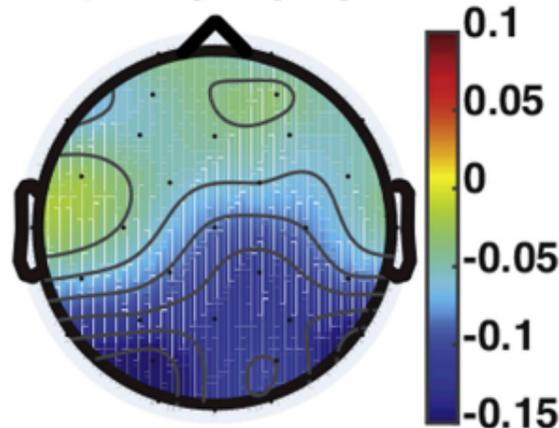
A.**B.**





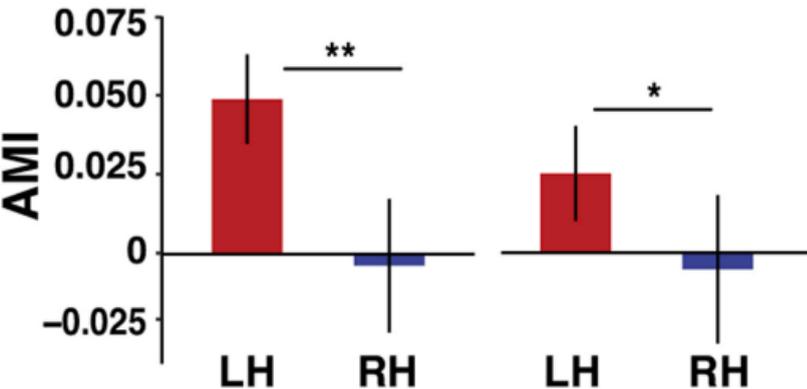
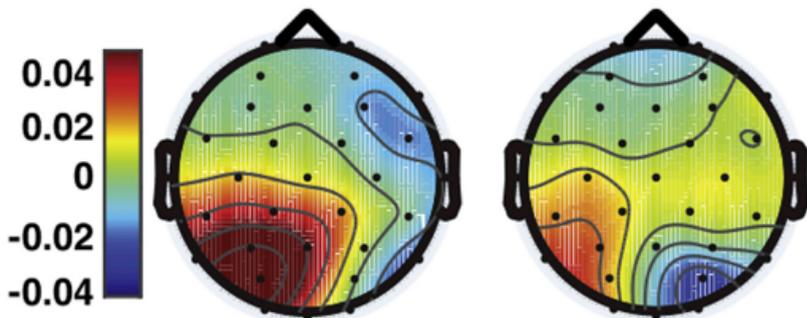
Alpha power difference

$t=1.79-2.37$ s

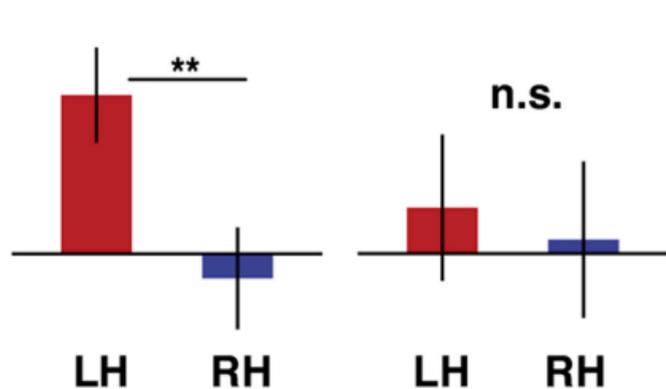
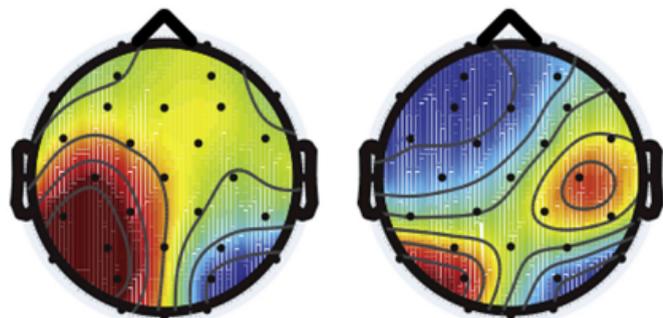


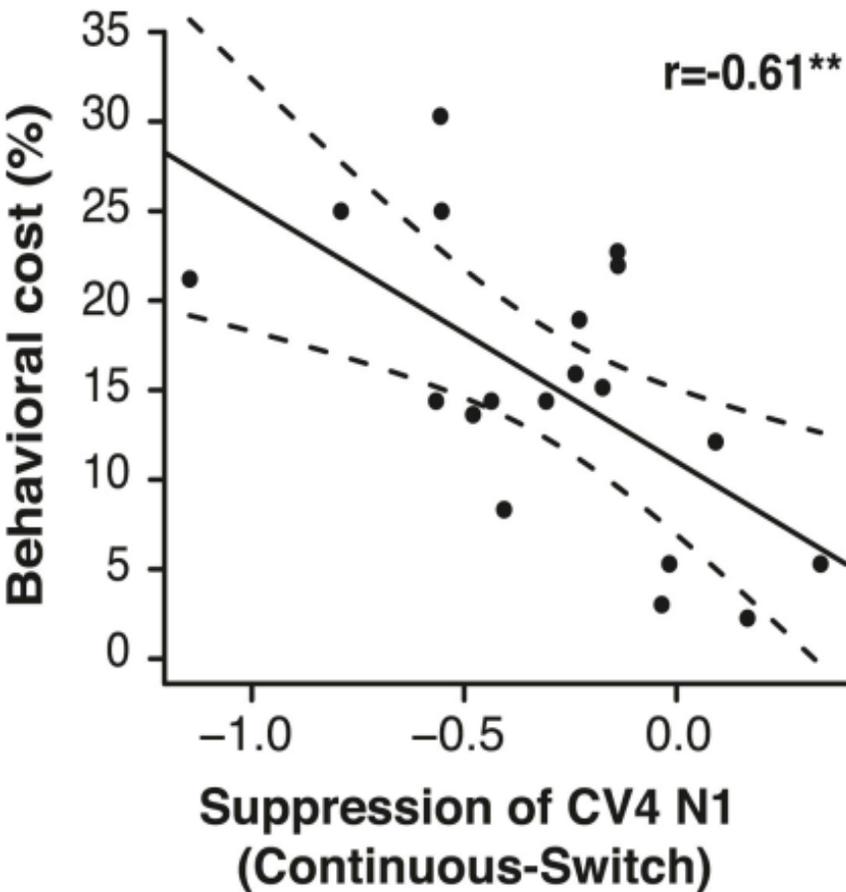
A.**Attend, Continuous**

Time: 0-1.466 s Time: 1.467-3.2 s

**B.****Attend, Switch**

Time: 0-1.466 s Time: 1.467-3.2 s



A.**B.**