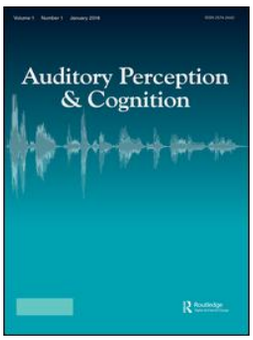

Routledge
Taylor & Francis Group

Auditory Perception & Cognition

ISSN: 2574-2442 (Print) 2574-2450 (Online) Journal homepage: https://www.tandfonline.com/loi/rpac20

Event-Related Potential and Behavioral Correlates of Deafness to Change in the Identity and Location of Objects in Auditory Scenes

Natalie J. Ball, Matthew G. Wisniewski, Nandini Iyer & Brian D. Simpson

To cite this article: Natalie J. Ball, Matthew G. Wisniewski, Nandini Iyer & Brian D. Simpson (2019): Event-Related Potential and Behavioral Correlates of Deafness to Change in the Identity and Location of Objects in Auditory Scenes, Auditory Perception & Cognition

To link to this article: https://doi.org/10.1080/25742442.2018.1561099

Published online: 28 Jan 2019.

AUDITORY PERCEPTION & COGNITION
https://doi.org/10.1080/25742442.2018.1561099

Routledge
Taylor & Francis Group

Event-Related Potential and Behavioral Correlates of Deafness to Change in the Identity and Location of Objects in Auditory Scenes

Natalie J. Ball[a], Matthew G. Wisniewski[b], Nandini Iyer[c] and Brian D. Simpson[c]

[a]Department of Psychology, University at Buffalo, Buffalo, NY, USA; [b]Department of Psychological Sciences, Kansas State University, Manhattan, KS, USA; [c]U.S. Air Force Research Laboratory, Wright-Patterson Air Force Base, Dayton, OH, USA

ABSTRACT

Failure to detect change in an auditory scene (i.e., *change deafness*) has been found to occur with alterations to object identities and the location of objects. Event-related potential (ERP) correlates of change deafness for object identity have been identified, but to our knowledge, ERP comparisons between spatial and identity change deafness are non-existent. We examined whether ERP differences exist between spatial and identity (ID) changes, and among levels of change detection accuracy (*correct change identified* vs. *wrong change identified* vs. *change deaf*). Within a trial, listeners were presented with two consecutive auditory scenes, each composed of four environmental sounds played simultaneously at separate azimuths on the horizontal plane. Scene 2 was either identical to the first ("no change"), had one sound replaced ("ID change"), or contained the same sounds at different locations ("space change"). Accuracy was similar for ID and space change trials (~60% correct), but error patterns differed. On space change trials, listeners made few ID change responses. However, on ID change trials listeners were nearly equal in their tendencies to make a no change and space change response. N1-P2 complexes locked to scene onsets were largest on trials where a change was indicated, but the wrong change type was chosen. P3b amplitudes locked to Scene 2 onset were monotonically related to accuracy (larger for correct and wrong change trials than change deaf trials). Effects were similar for space and ID changes, but scalp topography of P3b differed for change types (larger amplitudes for ID change trials at left temporal electrodes). Data indicate that P3b amplitude is a reliable indicator of successful change detection across different types of scene changes, showing different topography reflecting different "what" and "where" processing streams. N1-P2 complex effects suggest better encoding of scenes in relation to change detection, but unknown change type.

ARTICLE HISTORY
Received 15 January 2018
Accepted 27 November 2018

KEYWORDS
Change deafness; change detection; event-related potential; N1-P2; P3b

Introduction

The ability to perceive changes in our auditory environment has likely been crucial to the survival of our species. Hearing allows us to sense our changing environments from every direction, and serves as a monitoring and orienting system for the other senses

CONTACT Natalie J. Ball njball@buffalo.edu University at Buffalo, Buffalo, NY 14203, USA

(Arnott & Alain, 2011). However, laboratory examination has shown that we often fail at detecting changes. *Change deafness* refers to the inability to detect auditory changes, even if they are very apparent or intense (Gregg and Samuel (2008); for reviews on change deafness, see Snyder and Gregg (2011); Snyder, Gregg, Weintraub, and Alain (2012)). Event-related potential (ERP) studies of change deafness can be especially useful for our understanding of why it occurs, and how to deal with it in real-world situations where it can be a problem. Given the temporal precision of ERPs, they can yield insights into whether change deafness is related to errors in pre-change encoding and representation quality (Gregg, Irsik, & Snyder, 2014; Gregg & Samuel, 2008), attention (Backer & Alain, 2012; Eramudugolla, Irvine, McAnally, Martin, & Mattingley, 2005), or failures for changes registered at the sensory level to reach awareness at higher-level processing stages (Puschmann et al., 2013). This knowledge is then key to the development of methods that reduce it in applied settings. For example, pilot-error airplane accidents are often attributed to a failure to detect auditory alerts or alarms in the auditory scene (Dehais et al., 2014; Giraudet, St-Louis, Scannella, & Causse, 2015). If ERPs suggest that pre-change encoding is at fault, methods should aim to improve this aspect. Alternatively, it may be possible to use ERP methods online to mitigate change deafness (e.g., if the ERP indicates that a change was not detected, the signal could be presented again).

In the laboratory, humans have shown change deafness with semantics in discourse comprehension (Nieuwland & Van Berkum, 2005), talker identity (Fenn et al., 2011; Vitevitch, 2003), streams of simple stimuli (e.g., tones with varying pitch and rhythm; Puschmann et al. (2013); or chords; Demany, Trost, Serman, and Semal (2008)), and environmental sounds (Eramudugolla et al., 2005; Gregg et al., 2014; Gregg & Samuel, 2008; Gregg & Snyder, 2012; McAnally et al., 2010). Change deafness has also been found to occur with changes in the spatial location of objects in auditory scenes. Simpson, Brungart, Gilkey, Iyer, and Hamil (2007) had participants listen to auditory scenes comprising a varying number of sounds from different locations. A target sound was deleted at the end of the observation interval, and participants' task was to identify the location of the deleted sound source. As the complexity of the auditory scene increased (greater number of objects), longer exposures were needed to accurately judge individual location changes. Others have shown that listeners are increasingly change deaf to changes in the location of objects as the number of objects in a scene increases (Eramudugolla et al., 2005).

Given the findings of change deafness across change types, it may be that common processes are at play regardless of the type of change. Some theoretical work is consistent with this. For instance, neural network models have shown that distributed systems tuned to speaker sound location may utilize identity information as well, suggesting that these processes may overlap within the auditory cortex (Salminen, May, & Tiitinen, 2007). Also, the P3b component of the ERP (a well-established neural correlate of change deafness; Gregg et al. (2014); Gregg and Snyder (2012); Puschmann et al. (2013)) can be similar for changes in a number of different stimulus characteristics. These results may reflect the P3b being less sensitive to stimulus characteristics as it is to task-dependent categorization (e.g., target vs. non-target) defined by changes in stimulation and an individual's intentions (Luck & Hillyard, 1994). Despite theories that localization and identification overlap in the cortex, Clarke et al. (2002) found that some lesion patients can lose the ability to localize, while maintaining the ability to recognize sounds. The opposite can also be found. In this

work, damage to anterior temporal areas was associated with identification impairment, while damage to parietal regions was associated with localization dysfunction (Clarke, Bellmann, Meuli, Assal, & Steck, 2000). Functional magnetic resonance imaging (fMRI) has provided evidence that sound identification generates larger activation in the inferior frontal gyrus and auditory cortex, whereas localization generates more activation in the superior frontal sulcus and posterior temporal and parietal cortices (Alain, Arnott, Hevenor, Graham, & Grady, 2001). Notably, some human ERP studies have also supported differences between spatial and non-spatial tasks. When asked to identify or locate animal calls, Leavitt, Molholm, Gomez-Ramirez, and Foxe (2011) reported greater N1 amplitude during identification ("what") than during localization ("where"). Using source modeling of the auditory ERP, De Santis, Clarke, and Murray (2007) found common superior temporal and prefrontal cortical modulations in both "what" and "where" tasks using tones, with significantly higher activity in regions at or near the right temporoparietal cortices for the "where" condition (also, see Alain et al. (2001); Alain, McDonald, Kovacevic, and McIntosh (2009)).

Several studies have examined electrophysiological correlates of deafness to changes of object identity in auditory scenes (Gregg et al., 2014; Gregg & Snyder, 2012; Puschmann et al., 2013). Some correlates of change deafness have been observed in the auditory N1-P2 complex (for review on the N1-P2 complex, see Hyde (1997); Näätänen and Picton (1987)). Specifically, the N1 has larger amplitude on change detected trials compared to undetected change trials (Gregg and Snyder (2012); although, see Gregg et al. (2014)). P2 has been related to "implicit" change detection. This is suggested by data showing that P2 is larger in amplitude for change compared to no change trials, even when listeners indicate that they heard no change (Gregg & Snyder, 2012). These results have been interpreted to support the idea that errors in early perceptual processes lead to change deafness (e.g., McAnally et al. (2010); Gregg and Snyder (2012)). Puschmann et al. (2013) found evidence for change detection processing in both the middle latency Nb, and the amplitude of the P3b. They suggested that undetected changes may be successfully encoded in the sensory system and at least partially processed in the auditory cortex, but may fail to trigger further cortical responses that are related to the listener's awareness of a change. Enhancement of P3b has been an indicator of detection of identity changes in a number of other studies, and is the most consistent correlate of change deafness (Gregg et al., 2014; Gregg & Snyder, 2012; Puschmann et al., 2013). P3b effects may be taken to support a higher-level route to change deafness related to processing errors in the categorization or verbal labeling of multiple auditory objects (e.g., Demany et al. (2008)).

Though ERP work has explored change deafness to identity changes, examinations of spatial changes are lacking. We know of no study that has explored ERPs in a change deafness paradigm, where complex sounds are formed by simultaneously combining auditory objects that vary in location or identity from scene to scene. We aimed to characterize differences between successful and unsuccessful detection of spatial and identity changes in environmental auditory scenes, and assess whether the ERPs and behaviors associated with change deafness are similar or different across these types of changes. We employed a modified version of a common change deafness paradigm. Participants were asked to determine the type of change that occurred between two consecutively presented scenes, each of which was composed of four auditory objects played simultaneously. There were three trial types. "No change" trials contained identical scenes presented in Scenes 1 and 2. "Space change" trials

contained a change in the locations of auditory objects from Scene 1 to scene 2. "Identity (ID) change" trials contained a change in the identity of one of the objects, which was replaced with a new object in Scene 2. There are important insights that can be gained from this design. First, if there are differences in ERPs between types of changes, this would suggest that processing may diverge into different neural pathways, as typically suggested in the "what" vs. "where" literature. Additionally, the components affected by change type would give us information about whether the divergence happens early in sensory processing (in the N1-P2 complex) or later in higher-order processes related to decision-making (in the P3b). Similar ERPs between space and identify changes may instead indicate that common processes are at play in detecting both types of changes (cf. Salminen et al. (2007)). Secondly, the design allows us to relate the ERP and behavioral responses to graded accuracy of change perception. To this end, we compared trials in which listeners correctly reported the type of change (correct trials), reported the wrong type of change (wrong change trials), or reported no change when a change occurred (change deaf trials). The current paradigm is uniquely able to answer these questions. Based on previous work, we expected to see effects in the N1-P2 complex, as well as in the P3b component. Differences between space and ID changes, if present, were expected to be observable in the amplitudes and/or scalp distributions of one of these components. If differences between trial types were not present, but significant differences between correct and change deaf trials were still found, this would be a promising result that would support the use of the same ERP components to study both types of changes, and/or the applied use of ERPs in methods to mitigate change deafness.

Methods

Participants

Seventeen young adults (9 females, age 19–32 (M = 23.12, SD = 3.95) with normal hearing confirmed by audiometric testing (<20 dB HL, 0.25–8 kHz) participated for compensation. Two participants were dropped from analyses because their EEG data contained too few epochs corresponding to wrong change trials when there was a space change (one subject had 0 epochs, the other had only a single epoch). The study was approved by the Wright Site Institutional Review Board. All participants gave written informed consent.

Apparatus

Participants sat in a sound-attenuating booth during testing. Sounds were presented through insert earphones (ER-2; Etymotic Research, Elk Grove Village, IL, USA) at a level not exceeding 80 dB Sound Pressure Level (SPL). Timing of stimuli was controlled using a TDT System 3 real-time processor (RP2.1; Tucker-Davis Technologies, Alachua, FL). Experimental procedures were executed in MATLAB (Mathworks, Natick, MA).

Stimuli

The auditory objects used were 15 environmental sounds (Table 1) selected from a compilation of commercially available sound effects (Ghostwriters, 1998). Sounds were selected to promote similarity in bandwidth (and thus, presumably, localizability) and

Table 1. Sounds used along with percentages of normal sound recognition from Simpson et al. (2007).

Sound	Recognition accuracy
Coughing	97%
Harp	99%
Telephone	100%
Soda pouring	99%
Bees	99%
Dog bark	100%
Drums	99%
Firetruck	100%
Lawnmower	100%
Pig	99%
Ping Pong	100%
Rooster	100%
Sheep	99%
Snoring	99%
Teethbrushing	96%

Recognition accuracies reflect percent correct identification when a sound was presented by itself.

identifiability (as determined by behavioral testing, see Simpson et al. (2007)). All sounds were filtered to a bandwidth of 0.2 kHz–14 kHz and were level-normalized to the same Root Mean Square (RMS).

Scenes comprised of four of these objects were created. Scenes were presented for a duration of 1000 ms. If the duration of the sound object was not long enough to fill 1000 ms, it was looped during presentation without silent intervals. Objects were spatially separated along the horizontal plane and rendered at 45°, 10°, −10°, and −45° from center (see Figure 1). Head-related transfer function (HRTF) measurements from KEMAR dummy head recordings were used to simulate presentation at the desired azimuths. The methods for obtaining this HRTF are described elsewhere (see Brungart, Romigh, and Simpson (2009)).

Procedure

A two-interval, two-alternative forced-choice (2i-2afc) task was used. Examples of the different trial types are shown in Figure 1. On each trial, white noise was presented for 750 ms, then Scene 1, followed by 750 ms of white noise, and then Scene 2. White noise was used to separate the two scenes in order to limit impacts of echoic memory. Noise was presented prior to Scene 1 to balance any effects that noise may have had on the ERP following Scene 2. Scene 2 consisted of either: (a) the same four objects at the same spatial locations ("no change" from Scene 1), (b) the same four objects with locations randomly swapped ("space change"), or (c) replacement of one of the objects in Scene 1 with a new object ("ID change"). Participants were asked to make button press responses on a numeric keypad located on the desk directly in front of them, with adjacent keys (pressing (1) for no change, (2) for space change, (3) for ID change). For space change trials, new locations were selected randomly on each trial such that either 2, 3, or all 4 locations could be different. For ID change trials, an object was selected from Scene 1 at random and was replaced with a randomly selected object not already in the scene.

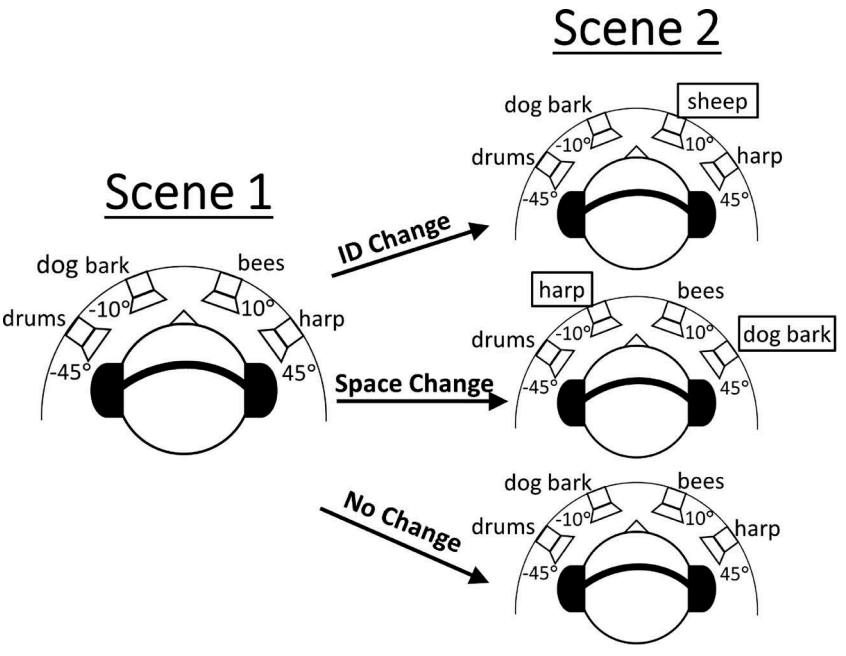

Figure 1. Examples of the three trial types. Scene 1 is presented first (left) and then Scene 2 consists of either an ID change, a space change, or no change.

Electrophysiology

EEG data (70 channels) were collected at a 2048 Hz sampling rate, 24-bit A/D resolution, and were referenced to the common-mode-sense driven-right-leg (CMS/DRL) reference of the BioSemi Active II system (BioSemi, Amsterdam, the Netherlands). Caps comprised of 64 scalp electrode locations arranged according to the international 10–20 system were fit on to subjects' heads accordingly. Six additional electrodes were placed lateral to eyes, underneath the eyes, and on each mastoid.

Data were re-sampled offline at 256 Hz (after applying and anti-aliasing filter), re-referenced to the average of the mastoids, and digitally bandpass filtered (0.25–20.25 Hz half amplitude cutoff, 1691 point zero-phase FIR filter) using EEGLAB (Delorme & Makeig, 2004). Excessively noisy portions of continuous data and visibly noisy channels were manually removed from the data. The remaining data were run through independent component analysis (ICA). Independent components (ICs) determined to be related to eye-movements or muscle-related artifacts using IC scalp projection, time course, and spectra were removed from the data (for review, see Jung et al. (2000)). Epochs were extracted from −0.2 s to 1.5 s surrounding onsets of Scene 1 and Scene 2. Baselines were subtracted from each data epoch (−.2 s to 0 s). Epoch voltage time-courses were then averaged to make ERPs.

N1, P2, and P3b (Scene 2 only) component amplitudes were extracted from the ERPs using mean voltages within specified time windows post Scene 1 and Scene 2 onsets. Time windows were selected based on grand average ERP waveforms (averaged across all participants and conditions). The N1 window was 100–140 ms, P2 was 180–220 ms,

and P3b was 600–1100 ms after each scene onset. Five different clusters of electrodes were used to simplify the analysis of scalp topography effects with statistics. These clusters were labeled according to their scalp locations as: anterior, central, posterior, left temporal, and right temporal (exact locations are highlighted later). Mean amplitudes were taken as mean voltage across time points in the select time-window and channels in the select cluster. For the N1-P2 complex, we further simplified analyses using a difference in mean amplitude between N1 and P2 (P2 minus N1). Larger values indicate a larger amplitude N1-P2 complex (cf. Hyde (1997); Lightfoot (2016)).[1] The difference measure for the N1-P2 complex also serves as a measure of the response that is relatively unaffected by baseline distortions that can sometimes be caused by the types of high-pass filtering we used to reduce artifacts in the data (for review, see Acunzo, Mackenzie, and van Rossum (2012); Widmann, Schröger, and Maess (2015)). Amplitudes were entered into standard parametric statistical analyses with an alpha level of .05. Alpha was adjusted for post-hoc tests using Bonferroni corrections. Corrected p-values are reported. All error bars in figures represent within-subject standard errors of the mean (Cousineau, 2005).

Results

Change Deafness Occurs for Both Changes in Space and Identity, but Error Patterns Differ

Accuracies across trial types are shown in Figure 2(a). Participants correctly responded "same" in 93.19% (SD = 9.85) of no change trials, showing a low rate of falsely indicating a change. Accuracy for space change and ID change trials was 63.06% (SD = 16.35) and 58.42 (SD = 11.18), respectively. This means that on around 40% of all change trials participants exhibited change deafness, or did not accurately perceive the type of change. A 1-way repeated measures ANOVA revealed significant differences among means, $F(2, 28) = 64.57$, $p < .001$, $\eta_p^2 = .82$. Post-hoc tests showed that accuracy on no change trials was significantly higher than both space change trials, $t(14) = 7.46$, $p < .001$, Cohen's $d = 1.69$, and ID change trials, $t(14) = 12.43$, $p < .001$, Cohen's $d = 3.02$. Participants were slightly more accurate on the space change trials than on ID change trials, but this difference failed to reach significance, $t < 1.5$.

Figure 2(b) shows the proportion of trials in which a wrong change was indicated (e.g., a space change response on an ID change trial) or change deafness occurred. Errors are split up by trial type. For space change trials, an incorrect "ID change" response was made only ~10% of the time. In contrast, an incorrect "space change" response was made on ~21% of ID change trials. This was similar to the proportion of ID change trials in which change deafness occurred. To statistically analyze this apparent bias, a 2 (Error Type) × 2 (Trial Type) repeated measures ANOVA was conducted. The ANOVA revealed a significant main effect of Error Type, $F(1, 14) = 4.98$, $p = .042$, $\eta_p^2 = .26$, reflecting a lower proportion corresponding to wrong change responses compared to change deaf responses. There was also a significant interaction, $F(1, 14) = 18.51$, $p = .001$, $\eta_p^2 = .57$. The main effect of Trial Type was not significant, $F < 2.39$. Supporting the visual interpretation, post-hoc paired comparisons revealed that the proportion of wrong change space trials was significantly

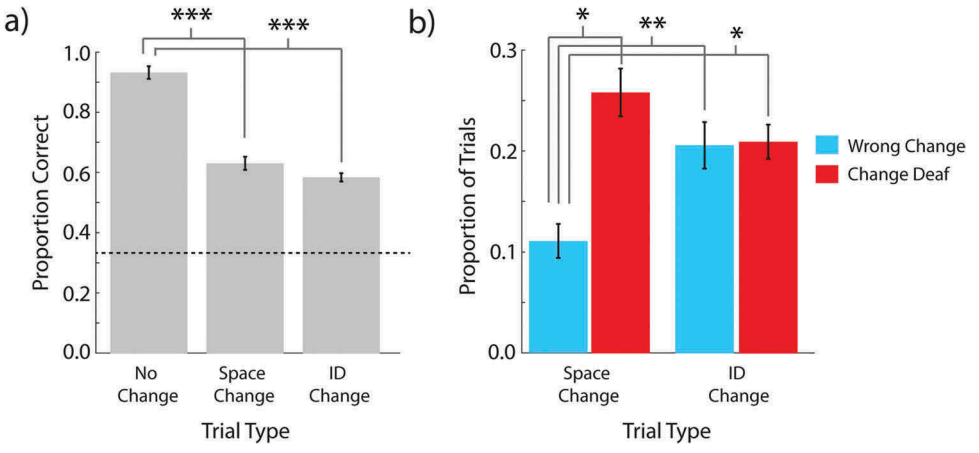

Figure 2. (a) Accuracy for each trial type; (b) proportions of trials on which a wrong change and no change (i.e., change deaf) response was given for space and ID change trial types. Error bars represent within-subject standard errors of the mean. Asterisks mark significance after Bonferroni correction for multiple comparisons (*$p < .05$, **$p < .01$, ***$p < .001$).

lower than change deaf space trials, $t(14) = 3.88$, $p = .01$, Cohen's $d = .78$, wrong change ID trials, $t(14) = 4.38$, $p = .004$, Cohen's $d = 1.00$, and change deaf ID trials, $t(14) = 3.39$, $p = .026$, Cohen's $d = .61$. Thus, though change deafness rates may be similar for space and ID changes, the willingness to give a space change response on ID change trials appears to be more likely than the opposite.

Scene 1 ERPs Distinguish Wrong Change Trials from Correct and Change Deaf Trials

Scene 1 ERPs split up by trial type, response accuracy (correct, wrong change, or change deaf), and electrode cluster are shown in Figure 3.[2] All ERPs showed clear N1-P2 complexes. Some conditions showed slightly noisier ERPs than others. For example, the ERPs for space change trials where a wrong change was indicated show oscillations in the alpha range (8–13 Hz) that were not removed via averaging of single-trials (see Luck (2005)). This is likely related to there being fewer trials in which an ID change was indicated on space change trials (see behavioral results above). However, note that the mean amplitude measure used for statistics is resistant to differences in trial counts between conditions (see Luck (2005)). A 5 (electrode cluster) × 3 (accuracy) × 2 (trial type) repeated measures ANOVA was run on the difference between P2 and N1 amplitudes (see methods). The ANOVA revealed a main effect of electrode cluster, $F(4, 56) = 4.29$, $p = .004$, $\eta_p^2 = .24$. This is unsurprising as the N1 and P2 are known to vary in amplitude among electrode locations (Hyde, 1997). There was also a significant main effect of accuracy, $F(2, 28) = 6.46$, $p = .006$, $\eta_p^2 = .32$ (see Figure 4). Post-hoc paired comparisons revealed that wrong change trials showed a significantly larger amplitude than change deaf trials, $t(14) = 2.89$, $p = .036$, Cohen's $d = 1.04$. The difference between correct and wrong change trials failed to reach significance after correction, $t(14) = 2.44$, $p = .087$, Cohen's $d = 1.43$, and the difference between correct and change deaf trials was also non-significant, $t < 1$. No other main effects or

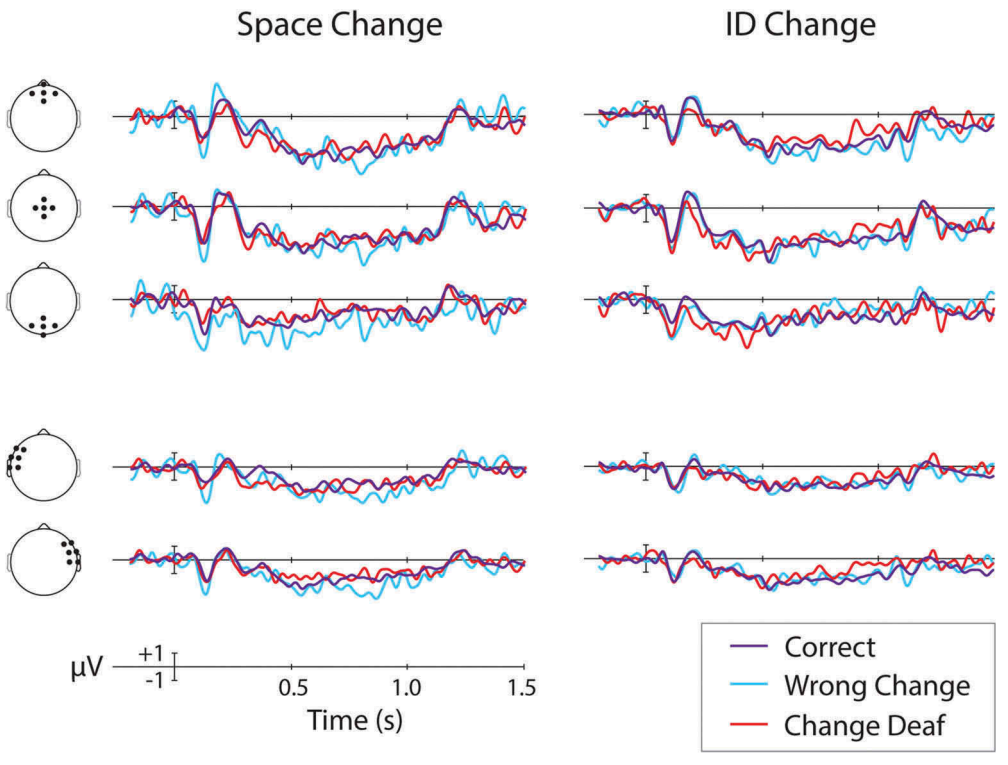

Figure 3. Scene 1 ERPs for the different electrode clusters, trial types, and accuracies. Points plotted on top of scalp images represent electrode locations within a cluster. ERPs associated with clusters are arranged in rows.

interactions were significant, *F*s < 2. These analyses suggest that a larger N1-P2 complex to the onset of Scene 1 is not associated with being correct to the type of change to come, but rather to indicating a change of the wrong type.

Scene 2 ERPs Distinguish Levels of Accuracy and Spatial from ID Changes

Scene 2 ERPs are shown in Figure 5. As with Scene 1 ERPs, all conditions showed N1-P2 complexes. ERPs for space change and ID change trial types also showed clear P3b components. Repeated measures ANOVAs as run above for Scene 1 were replicated for Scene 2 components. For the difference in N1 and P2 amplitudes, there was a significant main effect of electrode cluster, $F(4, 56) = 10.34$, $p < .001$, $\eta_p^2 = .43$. There was also a significant main effect of accuracy, $F(2, 28) = 5.18$, $p = .012$, $\eta_p^2 = .27$, indicating differences in the N1-P2 complex across different accuracies. Finally, there was a significant 3-way interaction, $F(8, 112) = 3.37$, $p = .002$, $\eta_p^2 = .19$. No other main effects or interactions were significant, *F*s < 2.75.

The 3-way interaction likely resulted partially from the differences between trial types and levels of accuracy occurring at the frontal and central electrode clusters where the N1-P2 complex showed the largest amplitudes. Figure 6 shows the mean differences in N1 and P2 amplitude for trial type and levels of accuracy at the central electrode

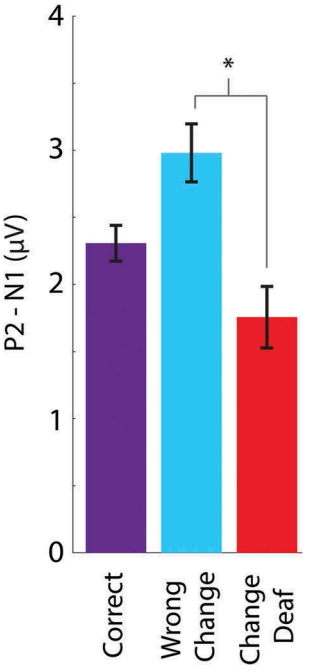

Figure 4. P2 minus N1 amplitude for correct, wrong, and change deaf trials (averaged across trial types and electrode clusters). Error bars show within-subject standard errors of the mean. Asterisks mark significant differences (*$p < .05$).

cluster. A 2 (trial type) × 3 (accuracy) repeated measures ANOVA was run using this data. This ANOVA revealed a significant main effect of accuracy, $F(2, 28) = 8.95$, $p = .001$, $\eta_p^2 = .39$. Post-hoc paired comparisons conducted on levels of accuracy revealed that wrong trials showed a significantly larger N1-P2 amplitude compared to both the correct, $t(14) = 5.89$, $p < .001$, Cohen's $d = 5.37$, and change deaf trials, $t(14) = 3.25$, $p = .018$, Cohen's $d = 1.88$. The difference between correct and change deaf trials was not significant, $t < 1$. Note that this pattern is similar as reported above for the N1-P2 complex to Scene 1. The interaction failed to reach significance, $F(2, 28) = 6.19$, $p = .063$, $\eta_p^2 = .18$, but may have been attributable to differences between the space change and ID change trial types in the difference between correct and change deaf trials. That is, on ID change trials, the N1-P2 complex was larger in amplitude for correct compared to change deaf trials, whereas the opposite was true for space change trials.

The ANOVA on P3b amplitudes revealed a main effect of electrode cluster, $F(4, 56) = 11.02$, $p < .001$, $\eta_p^2 = .44$. There was also a significant electrode cluster × accuracy interaction, $F(8, 112) = 5.20$, $p < .001$, $\eta_p^2 = .27$, likely owing to mean amplitudes in the P3b time window being larger at the central and posterior electrode clusters on correct trials, while having a smaller effect at other electrode clusters, and very little difference across electrode clusters on change deaf trials. Figure 7 plots P3b amplitude for the different accuracies at the posterior electrode cluster where the P3b amplitude was largest. Paired comparisons revealed a significant difference between

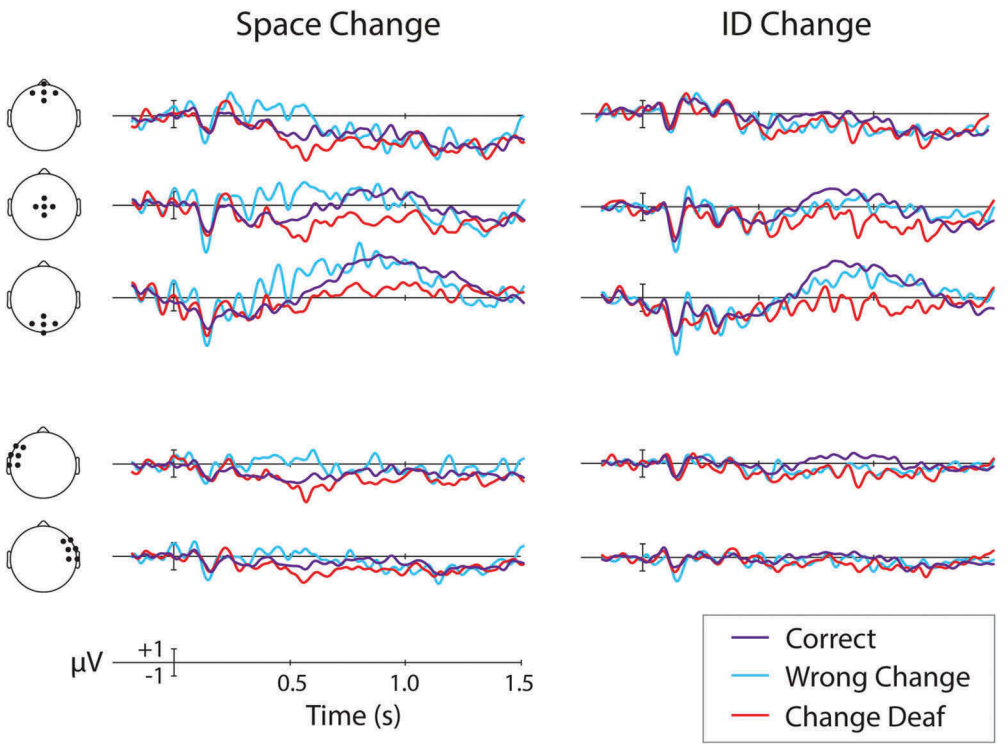

Figure 5. Scene 2 ERPs for the different electrode clusters, trial types, and accuracies. Points plotted on top of scalp images represent electrode locations within a cluster. ERPs associated with clusters are arranged in rows.

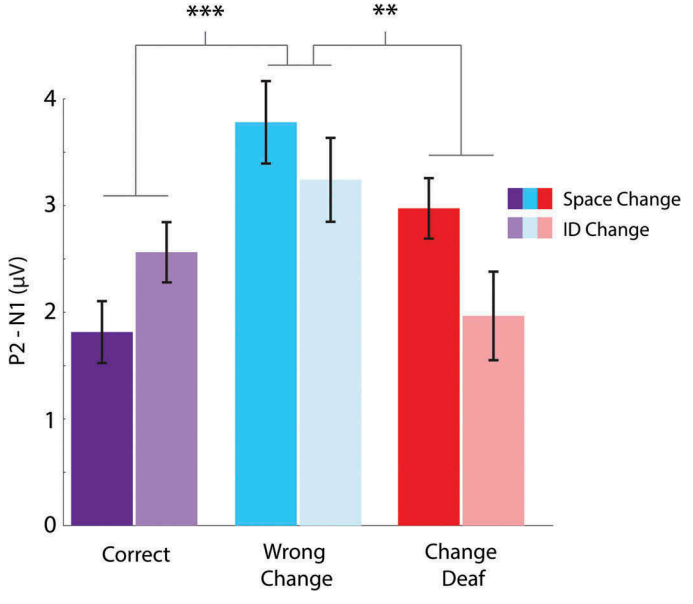

Figure 6. P2 minus N1 amplitude for correct, wrong, and change deaf trials on space change and ID change trials at the central electrode cluster. Error bars show within-subject standard errors of the mean. Asterisks mark significant differences (**$p < .01$, ***$p < .001$).

correct and change deaf trials, $t(14) = 4.53$, $p = .001$, Cohen's $d = 1.32$. It was also the case that wrong trials showed a significantly larger P3b amplitude than change deaf trials, $t(14) = 2.91$, $p = .033$, Cohen's $d = .77$. The difference between correct and wrong trials was non-significant, $t < 1$. Unlike the N1-P2 complex, the P3b appeared to show a clearer monotonic relationship with accuracy such that amplitude was largest for correct trials, and lowest for change deaf trials.

There was also a significant electrode cluster × trial type interaction, $F(4, 56) = 7.41$, $p < .001$, $\eta_p^2 = .35$. Figure 8(a) shows P3b amplitudes for space change (filled markers) and ID Change trials (open markers) for each electrode cluster on correct trials (i.e., trials where a P3b was clearly observable). Figure 8(b) shows a scalp map of the trial type difference in P3b amplitude (space change minus ID change). Consistent with prior work (e.g., Alain et al. (2001)), changes in ID were associated with more positive amplitudes at frontal and temporal electrodes (reflected by "cool" coloring in Figure 8(b)), while space changes were associated with more positive amplitudes at posterior electrode sites ("hot" coloring in Figure 8(b)). We ran post-hoc paired comparisons (space vs. ID) for each electrode cluster.[3] The left temporal electrode cluster showed a significantly larger P3b amplitude for ID change trials, $t(14) = 3.37$, $p = .025$, Cohen's $d = 1.04$. Other clusters failed to reach significance after multiple comparisons correction, ts < 2.02. Thus, in the P3b time window there does appear to be a difference between space and ID change trials located over left temporal areas such that the amplitude is more positive for ID changes.

Discussion

In the present study, we examined behavioral and ERP correlates of change detection for object identity and object location in auditory scenes comprised of environmental sound stimuli. Our goals were to compare and contrast levels of change detection accuracy (i.e., correct, wrong change, or change deaf) for these two types of auditory scene changes. These goals were motivated by a gap in the literature regarding levels of change deafness (deaf to any change versus deaf to type of change), a need to test whether or not the ERP features associated with changes in identity in auditory scenes are also related to changes in space, and conflicting theories on the processing of spatial and identity information in sound yet to be addressed in the change deafness literature (e.g., Clarke et al. (2002); Salminen et al. (2007)). Main findings were as follows. Behaviorally, participants showed similar accuracies when there was a change in the spatial location of objects as when there was a change in one of the object identities. However, error patterns differed. For space change trials, participants were more likely to incorrectly respond with no change than ID change, whereas for ID change trials, errors were equally distributed between reports of space change and no change. In ERPs, the amplitude of the N1-P2 complex locked to both the onset of Scene 1 and Scene 2 was largest for "wrong change" trials. This finding was not predicted, as we are the first to test types of change, and requires further research. In contrast, the later P3b locked to the onset of Scene 2 showed a monotonic relationship with levels of change detection accuracy, having a larger amplitude for correct and wrong change trials compared to change deaf trials. The clearest difference between space change and ID change trials was in the scalp distribution of this P3b. P3b was more positive in

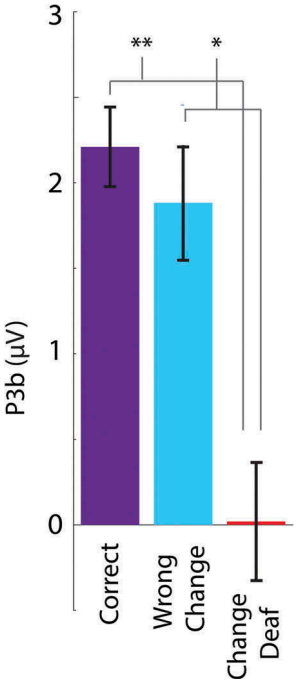

Figure 7. P3b amplitude for correct, wrong, and change deaf trials (averaged across trial types) at the posterior electrode cluster. Error bars show within-subject standard errors of the mean. Asterisks mark significant differences after Bonferroni correction (*$p < .05$, **$p < .01$).

amplitude for ID change than for space change trials at a left lateralized temporal cluster of electrodes.

Factors Contributing to Different Levels of Change Deafness

Some researchers posit that change deafness is related to verbal memory, in that deafness occurs because of a failure to name sounds. Based on findings that the detection of changes in simple tonal stimuli outperforms that of environmental sounds, Demany et al. (2008) have argued that change detection is limited by capacities in verbal memory. Others have argued that there is at least some route to change deafness in perceptual processes. For instance, Gregg et al. (2014) found higher levels of change deafness to occur with unrecognizable compared to recognizable sounds. Those authors argued that if change deafness was related to failures of verbal memory, deafness should have been rare when labels could not be used (e.g., when sounds are unrecognizable). We see consistencies between our findings and both views. Spatial location is not as easy to verbalize as identity (cf. Baddeley and Hitch (1974)), yet change deafness still occurred here. Further, note that this change deafness showed many similar correlates in the ERP across trial types (i.e., in the amplitudes of the N1-P2 complex and the P3b). Other than a left lateralized difference in P3b amplitude, the ease to which identity can be verbalized compared to spatial information did not appear to drastically impact these features, and a significant

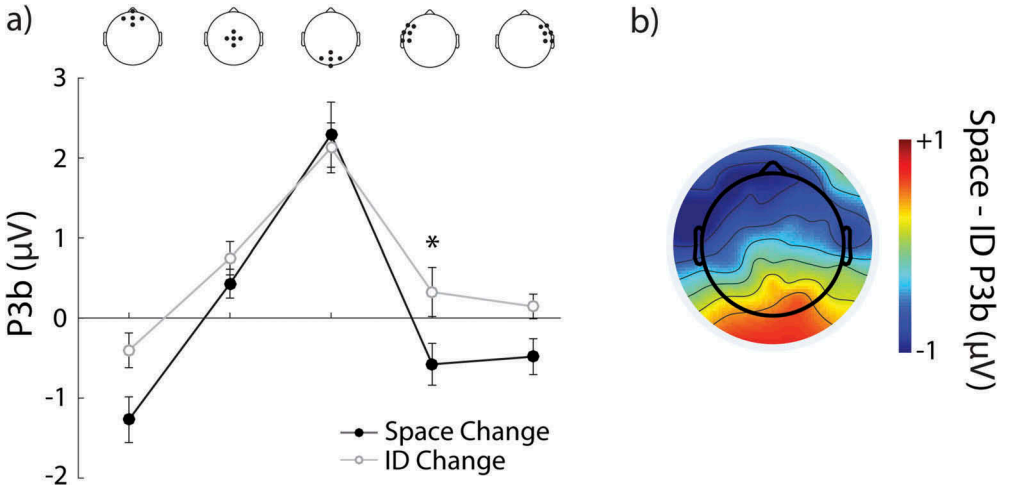

Figure 8. (a) Space change and ID change P3b amplitudes at each electrode cluster (for correct trials). Error bars show within-subject standard errors of the mean. Asterisks mark significant differences after Bonferroni correction (*p < .05). (b) Scalp map of the difference between space and ID trials in regard to P3b amplitude. Cool coloring indicates that the P3b was larger in amplitude for ID compared to the space change trials. Hot coloring indicates the opposite.

relationship between these ERP features and change deafness was observed for both trial types. This could be taken as evidence against the idea that change deafness is related to errors in higher-level categorization or verbal labeling processes. On the other hand, our unique paradigm revealed that under the more commonly studied ID change scenario, a failure to indicate an ID change does not necessarily mean that an individual did not detect a change at all. It may be that they are unwilling to indicate an ID change unless they are able to categorize and/or label the new or missing object. Relatedly, Eramudugolla et al. (2005) found that individuals were more likely to indicate change in an experiment containing spatial (their Experiment 3) compared to an experiment containing identity changes (their Experiment 1). One potential reason for this could be that when the perceptual impressions of Scene 1 and Scene 2 differ, either due to an actual difference or variable encoding (cf. Macmillan and Creelman (1991)), a spatial change makes more sense as a response. If the change cannot be verbalized, participants may be less willing to make an ID change response. If this is the case, a dual-process account of change detection in scenes may be more feasible. Deafness to some types of changes (e.g., spatial) may be strictly related to errors in perceptual processing, whereas other types of changes (e.g., identity) may be related to both verbal and perceptual processing errors.

An interesting new finding that comes out of this study is a non-monotonic relationship between the amplitude of the N1-P2 complex and change detection accuracy (correct < wrong change > change deaf). This trend was apparent for the N1-P2 complex locked to Scene 1 (although, see correct vs. wrong change post-hoc comparison) and Scene 2. There has been some disagreement as to whether or not pre-change encoding is related to change deafness (for review, see Gregg et al. (2014)). That effects were present for Scene 1 suggest that pre-change encoding can be related to change

deafness, but maybe not in the manner proposed. N1-P2 complex amplitude is often presumed to be related to encoding accuracy (e.g., Hyde (1997)). Given this, our data suggest that better encoding of Scene 1, not worse encoding, is related to being deaf to the type of change. The mirroring of this trend in Scene 2 may be related to what others have called an "implicit" change detection (Gregg & Snyder, 2012). That the N1-P2 complex is largest in amplitude on wrong change trials may be because listeners have adequately perceptually processed the first scene, and a change, but this information did not lead to knowing what type of change actually occurred.

There is some disagreement in the field of neural correlates of consciousness (NCC) about the nature of P3b regarding consciousness. Some have argued that the P3b is a neural marker of consciousness as an all-or-none phenomenon (Dehaene & Changeux, 2011). In the visual literature, Shafto and Pitts (2015) found that early visual processing was present in their inattentional blindness study when subjects were aware of changes, but not when they were inattentionally blind. Later positive activity (P3b) was only present when stimuli were task relevant, regardless of whether stimuli were consciously perceived. This data supports neural correlates of NCC occurring earlier than the P3b. Here, the P3b was enhanced for trials where a change was detected regardless of whether or not the exact type of change was known. This result can be seen as fitting somewhere in between these two views. P3b was only observed on those trials where individuals were aware of a change, but at the same time, that awareness was not full in that the type of change was not always indicated. Future work aimed at investigating "implicit" or less aware change detection in either the N1-P2 complex or P3b may yield novel insights from paradigms that investigate different levels of change deafness as we did.

Differences in the Processing of "What" and "Where" Changes in Auditory Scenes

Though there is a large literature on processing "what" and "where" information from sound (Clarke et al., 2002; De Santis et al., 2007; Leavitt et al., 2011) and the neural correlates of proposed differential processing pathways (Alain et al., 2001, 2009; Clarke et al., 2000; Kraus & Nicol, 2005), to our knowledge, we are the first to explore this in a scene change detection task with ERPs. We believe our data supports both views of distinct (e.g., Clarke et al. (2002)) and overlapping (Salminen et al., 2007) theories of processing regarding "what" and "where" information. There is considerable evidence that "what" and "where" information is processed differently both cortically (De Santis et al., 2007; Leavitt et al., 2011) and sub-cortically (Rees & Palmer, 2010). Our data showed differences in later processing of spatial and ID changes; specifically, larger P3b amplitudes were seen over the left temporal cortical areas for ID changes. This is consistent with previous neurophysiological work showing differences in spatial and ID processing (Alain et al., 2001, 2009; Du et al., 2015), particularly with work showing that these differences can arise as late as 300 ms post-stimulus onset, with larger amplitudes in temporal regions (Alain et al., 2001). Taken together, these data support differentiation in later processing stages during the post-change scene. Our data did not provide clear differences between early sensory evidence of differential encoding pathways of spatial and ID changes. Notably, others have observed differences between processing of spatial and identity information in the N1 time range (e.g., Leavitt et al. (2011)). It is possible that we did not replicate "what" versus "where" effects in the N1-

P2 complex because of paradigm differences. For instance, spatial and identity tasks were separate in the Leavitt et al.'s (2011) study. In the current study, they were integrated into the same task and the listener did not know ahead of time whether they were listening for spatial or identity changes. The effects previously reported could be related to effects of differences in the intentions of the listener (perhaps related to attentional effects on the N1; Choi, Rajaram, Varghese, and Shinn-Cunningham (2013); Hillyard, Hink, Schwent, and Picton (1973)) Still more, it is possible that such differences in the N1-P2 complex are either not observable during the processing of scenes with multiple objects, or differences exist at an earlier processing stage which were not assessable with the current methods (Kraus & Nicol, 2005).

Implications for Applied Work

Audition provides us with information about objects in the entirety of our nearby surroundings, not just that which is in our field of view. The honking of a car horn for a pedestrian, the sound of moving gunfire for a soldier, and the sound of a patient's cardiac monitor for a nurse, all provide crucial information through a change in the auditory scene. Both spatial and identity information is important. For example, appropriate behaviors to execute after hearing gunfire are different than the appropriate behaviors to execute after hearing a honking car horn. At the same time, spatial information may guide one to orient attention and actions to the appropriate location. The idea of implementing man–machine interfaces that use EEG/ERPs to enhance real-world human performance has increased in popularity in recent years (Hramov et al., 2017; Lotte et al., 2018; Müller et al., 2008). Many types of computational models are able to take single-trial EEG responses to stimulation (presumably carrying some of the same information in ERPs; Luck (2005)) and classify participant accuracies, attentional states, and confidence (e.g., Choi et al. (2013); Gherman and Philiastides (2015)). That we observed similar ERP correlates of change detection accuracy for space and ID changes is promising in this regard. That is, the ERP may indicate whether or not a change was detected regardless of the type of change. If P3b amplitude is low after a change occurs, an interface could present that information a second time. If P3b amplitude is high, an interface could avoid repeated presentations.

That we observed a strong correlate of change deafness in the amplitude of the P3b is especially promising. The finding that Scene 2 P3b amplitude showed a monotonic relationship with change detection accuracy (correct > wrong change > change deaf) is consistent with previous change blindness (Eimer & Mazza, 2005) and change deafness (Gregg et al., 2014; Gregg & Snyder, 2012; Puschmann et al., 2013) studies. The P3b appears to be associated with change detection accuracy in scenes across a variety of sensory modalities and change types within a modality. P3b is generally large enough in amplitude and low enough in frequency that it can be measured on single-trials (for review, see Sajda, Philiastides, and Parra (2009)). There is already a large breadth of work demonstrating the P3b's use in man–machine interfaces (for review, see Lotte et al. (2018)). Further, work on mobile brain imaging has shown that the P3b is readily observable in scenarios were an individual is actively moving (walking on a treadmill; Gramann, Gwin, Bigdely-Shamlo, Ferris, and Makeig (2010)). This is especially important for any man–machine interface employed in a real-world application. Though the N1-P2 complex showed a relationship with

change detection accuracy here, it may not be the most promising component to use in applied work as it may require averaging more stimulus presentations (Hyde, 1997).

Conclusions

We observed several novel findings in this study of ERP and behavioral correlates of change deafness to identity and spatial changes in auditory scenes. These included: (1) greater proportion of errors of the wrong change type on ID change trials compared to space change trials, (2) an association between N1-P2 complex amplitude and indicating the wrong type of change (e.g., a space change on an ID change trial), and (3) a larger P3b amplitude for trials responded to with greater accuracy. Results also demonstrate that ERP correlates of change deafness previously reported using changes in object identity (e.g., enhanced N1-P2 complex and P3b amplitudes for change detected trials), also exist for changes in object location. Our paradigm presents a way to examine degrees of change deafness (e.g., failures to detect any change vs. failures to know what changed). The results suggest that more work along these lines will serve to inform theories that vary in the separation of "what" and "where" processing. Further, they suggest a promising P3b correlate of change detection across various change types that could potentially be used to enhance change detection performance in real-world scenarios.

Notes

1. Analyses of N1 and P2 components of the N1-P2 complex separately yielded no main effects or interactions with the factors of accuracy or change type.
2. There was also an apparent sustained negativity with a frontal distribution (cf., Picton, Woods, and Proulx (1978)). However, an unplanned analysis of this sustained negativity with a 5 (electrode cluster) × 2 (accuracy) × 2 (trial type) repeated measures ANOVA found only a main effect of electrode cluster, $F(4,56) = 15.19$, $p < .001$, $\eta_p^2 = .52$. All other main effects and interactions were non-significant, Fs < 2.
3. A 5 (electrode cluster) × 2 (trial type) repeated measures ANOVA confirmed a significant electrode cluster × trial type interaction when using only correct trials, $F(4, 56) = 3.42$, $p = .014$, $\eta_p^2 = .20$.

Acknowledgments

This research was supported in part by an appointment of N.J.B. and M.G.W. to the Student Research Participation Program at the U.S. Air Force Research Laboratory, 711th Human Performance Wing administered by the Oak Ridge Institute for Science and Education through an interagency agreement between the U.S. Department of Energy and USAFRL.

Disclosure statement

No potential conflict of interest was reported by the authors.

References

Acunzo, D. J., Mackenzie, G., & van Rossum, M. C. W. (2012). Systematic biases in early ERP and ERF components as a result of high-pass filtering. *Journal of Neuroscience Methods*, *209*(1), 212–218.

Alain, C., Arnott, S. R., Hevenor, S., Graham, S., & Grady, C. L. (2001). "What" and "where" in the human auditory system. *Proceedings of the National Academy of Sciences of the United States of America*, *98*(21), 12301–12306.

Alain, C., McDonald, K. L., Kovacevic, N., & McIntosh, A. R. (2009). Spatiotemporal analysis of auditory "what" and "where" working memory. *Cerebral Cortex*, *19*(2), 305–314.

Arnott, S. R., & Alain, C. (2011). The auditory dorsal pathway: Orienting vision. *Neuroscience and Biobehavioral Reviews*, *35*(10), 2162–2173.

Backer, K. C., & Alain, C. (2012). Orienting attention to sound object representations attenuates change deafness. *Journal of Experimental Psychology: Human Perception and Performance*, *38*(6), 1554–1566.

Baddeley, A. D., & Hitch, G. J. (1974). Working memory. In G. H. Bower (Ed.), *The psychology of learning and motivation* (Vol. 8, pp. 47–89). New York, NY: Academic Press.

Brungart, D. S., Romigh, G. D., & Simpson, B. D. (2009). Rapid collection of HRTFs and comparison to free-field listening. *IEEE Workshop on Applications of Signal Processing to Audio and Acoustics*, New Paltz, NY.

Choi, I., Rajaram, S., Varghese, L. A., & Shinn-Cunningham, B. G. (2013). Quantifying attentional modulation of auditory-evoked cortical responses from single-trial electroencephalography. *Frontiers in Human Neuroscience*, *7*.

Clarke, S., Bellmann, A., Meuli, R. A., Assal, G., & Steck, A. (2000). Auditory agnosia and auditory spatial deficits following left hemispheric lesions: Evidence for distinct processing pathways. *Neuropsychologia*, *38*(6), 797–807.

Clarke, S., Bellmann Thiran, A., Maeder, P., Adriani, M., Vernet, O., Regli, L., … Thiran, J.-P. (2002). What and where in human audition: Selective deficits following focal hemispheric lesions. *Experimental Brain Research*, *147*(1), 8–15.

Cousineau, D. (2005). Confidence intervals in within-subject designs: A simpler solution to Loftus and Masson's method. *Tutorials in Quantitative Methods for Psychology*, *1*, 42–45.

De Santis, L., Clarke, S., & Murray, M. M. (2007). Automatic and intrinsic auditory "what" and "where" processing in humans revealed by electrical neuroimaging. *Cerebral Cortex*, *17*(1), 9–17.

Dehaene, S., & Changeux, J.-P. (2011). Experimental and theoretical approaches to conscious processing. *Neuron*, *70*(2), 200–227.

Dehais, F., Causse, M., Vachon, F., Régis, N., Menant, E., & Tremblay, S. (2014). Failure to detect critical auditory alerts in the cockpit: Evidence for inattentional deafness. *Human Factors*, *56*(4), 631–644.

Delorme, A., & Makeig, S. (2004). EEGLAB: An open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *Journal of Neuroscience Methods*, *134*(1), 9–21.

Demany, L., Trost, W., Serman, M., & Semal, C. (2008). Auditory change detection: Simple sounds are not memorized better than complex sounds. *Psychological Science*, *19*(1), 85–91.

Du, Y., He, Y., Arnott, S. R., Ross, B., Wu, X., Li, L., & Alain, C. (2015). Rapid tuning of auditory "what" and "where" pathways by training. *Cerebral Cortex*, *25*(2), 496–506.

Dave Dworkin's Ghostwriters. (1998). Sound Effects Toolkit [CD]. Minneapolis, MN: Radio Mall.

Eimer, M., & Mazza, V. (2005). Electrophysiological correlates of change detection. *Psychophysiology*, *42*(3), 328–342.

Eramudugolla, R., Irvine, D. R. F., McAnally, K. I., Martin, R. L., & Mattingley, J. B. (2005). Directed attention eliminates "change deafness" in complex auditory scenes. *Current Biology*, *15*(12), 1108–1113.

Fenn, K. M., Shintel, H., Atkins, A. S., Skipper, J. I., Bond, V. C., & Nusbaum, H. C. (2011). When less is heard than meets the ear: Change deafness in a telephone conversation. *The Quarterly Journal of Experimental Psychology*, *64*(7), 1442–1456.

Gherman, S., & Philiastides, M. G. (2015). Neural representations of confidence emerge from the process of decision formation during perceptual choices. *NeuroImage*, *106*, 134–143.

Giraudet, L., St-Louis, M.-E., Scannella, S., & Causse, M. (2015). P300 event-related potential as an indicator of inattentional deafness? *PloS one*, *10*(2), 1–18.

Gramann, K., Gwin, J. T., Bigdely-Shamlo, N., Ferris, D. P., & Makeig, S. (2010). Visual evoked responses during standing and walking. *Frontiers in Human Neuroscience*, *4*. doi:10.3389/fnhum.2010.00202

Gregg, M. K., Irsik, V. C., & Snyder, J. S. (2014). Change deafness and object encoding with recognizable and unrecognizable sounds. *Neuropsychologia*, *61*, 19–30.

Gregg, M. K., & Samuel, A. G. (2008). Change deafness and the organizational properties of sounds. *Journal of Experimental Psychology*, *34*(4), 974–991.

Gregg, M. K., & Snyder, J. S. (2012). Enhanced sensory processing accompanies successful detection of change for real-world sounds. *NeuroImage*, *62*(1), 113–119.

Hillyard, S. A., Hink, R. F., Schwent, V. L., & Picton, T. W. (1973). Electrical signs of selective attention in the human brain. *Science*, *182*(4108), 177–180.

Hramov, A. E., Maksimenko, V. A., Pchelintseva, S. V., Runnova, A. E., Grubov, V. V., Musatov, V. Y., … Pisarchik, A. N. (2017). Classifying the perceptual interpretations of a bistable image using EEG and artificial neural networks. *Frontiers in Neuroscience*, *11*, 674.

Hyde, M. (1997). The N1 response and its applications. *Audiology and Neurotology*, *2*(5), 281–307.

Jung, T. P., Makeig, S., Lee, L. W., McKeown, M. J., Brown, G., Bell, A. J., & Sejnowski, T. J. (2000). Independent component analysis of biomedical signals. *Proceedings of the 2nd International Workshop on Independent Component Analysis and Blind Signal Separation*, Helsinki, Finland.

Kraus, N., & Nicol, T. (2005). Brainstem origins for cortical "what" and "where" pathways in the auditory system. *Trends in Neurosciences*, *28*(4), 176–181.

Leavitt, V. M., Molholm, S., Gomez-Ramirez, M., & Foxe, J. J. (2011). "What" and "where" in auditory sensory processing: A high-density electrical mapping study of distinct neural processes underlying sound object recognition and sound localization. *Frontiers in Integrative Neuroscience*, *5*. doi:10.3389/fnint.2011.00023.

Lightfoot, G. (2016). Summary of the N1-P2 cortical auditory evoked potential to estimate the auditory threshold in adults. *Seminars in Hearing*, *37*(1), 1–8.

Lotte, F., Bougrain, L., Cichocki, A., Clerc, M., Congedo, M., Rakotomamonjy, A., & Yger, F. (2018). A review of classification algorithms for EEG-based brain-computer interfaces: A 10 year update. *Journal of Neural Engineering*, *15*(3), 031005.

Luck, S. J. (2005). *An introduction to the event-related potential technique*. Cambridge, MA: MIT Press.

Luck, S. J., & Hillyard, S. A. (1994). Electrophysiological correlates of feature analysis during visual search. *Psychophysiology*, *31*(3), 291–308.

Macmillan, N. A., & Creelman, C. D. (1991). *Detection theory: A user's guide*. New York, NY: Cambridge University Press.

McAnally, K. I., Martin, R. L., Eramudugolla, R., Stuart, G. W., Irvine, D. R. F., & Mattingley, J. B. (2010). A dual-process account of auditory change detection. *Journal of Experimental Psychology*, *36*(4), 994–1004.

Müller, K.-R., Tangermann, M., Dornhege, G., Krauledat, M., Curio, G., & Blankertz, B. (2008). Machine learning for real-time single-trial EEG-analysis: From brain-computer interfacing to mental state monitoring. *Journal of Neuroscience Methods*, *167*(1), 82–90.

Näätänen, R., & Picton, T. (1987). The N1 wave of the human electric and magnetic response to sound: A review and an analysis of the component structure. *Psychophysiology*, *24*(4), 375–425.

Nieuwland, M. S., & Van Berkum, J. J. A. (2005). Testing the limits of the semantic illusion phenomenon: ERPs reveal temporary semantic change deafness in discourse comprehension. *Cognitive Brain Research*, *24*(3), 691–701.

Picton, T. W., Woods, D. L., & Proulx, G. B. (1978). Human auditory sustained potentials: The nature of the response. *Electroencephalography & Clinical Neurophysiology*, *45*(2), 186–197.
Puschmann, S., Sandmann, P., Ahrens, J., Thorne, J., Weerda, R., Klump, G., … Thiel, C. M. (2013). Electrophysiological correlates of auditory change detection and change deafness in complex auditory scenes. *NeuroImage*, *75*, 155–164.
Rees, A., & Palmer, A. L. (2010). *The oxford handbook of auditory science: The auditory brain*. New York, NY: Oxford University Press.
Sajda, P., Philiastides, M. G., & Parra, L. C. (2009). Single-trial analysis of neuroimaging data: Inferring neural networks underlying perceptual decision-making in the human brain. *IEEE Reviews in Biomedical Engineering*, *2*, 97–109.
Salminen, N. H., May, P. J. C., & Tiitinen, H. (2007). Overlapping "what" and "where" in a model of auditory cortical processing. *International Congress Series*, *1300*, 81–84.
Shafto, J. P., & Pitts, M. A. (2015). Neural signatures of conscious face perception in an inattentional blindness paradigm. *The Journal of Neuroscience*, *35*(31), 10940–10948.
Simpson, B., Brungart, D., Gilkey, R., Iyer, N., & Hamil, J. (2007, June 26–29). Localization in multiple source environments: Localizing the missing source. *Proceedings of the 13th International Conference on Auditory Display*, Montréal, Canada.
Snyder, J. S., & Gregg, M. K. (2011). Memory for sound, with an ear toward hearing in complex auditory scenes. *Attention, Perception, & Psychophysics*, *73*(7), 1993–2007.
Snyder, J. S., Gregg, M. K., Weintraub, D. M., & Alain, C. (2012). Attention, awareness, and the perception of auditory scenes. *Frontiers in Psychology*, *3*. doi:10.3389/fpsyg.2012.00015.
Vitevitch, M. S. (2003). Change deafness: The inability to detect changes between two voices. *Journal of Experimental Psychology*, *29*(2), 333–342.
Widmann, A., Schröger, E., & Maess, B. (2015). Digital filter design for electrophysiological data – A practical approach. *Journal of Neuroscience Methods*, *250*, 34–46.