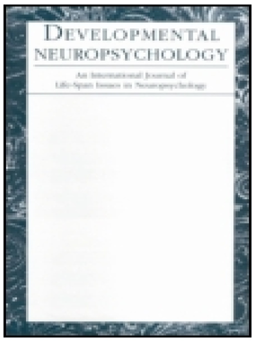

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Equiprobable and Oddball Paradigms: Two Approaches for Documenting Auditory Discrimination

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The oddball paradigm is frequently used to study auditory discrimination. However, due to its lengthy recording sessions, an alternative design may be considered when time constraints are paramount. In the current study, auditory event-related potentials (ERPs) were obtained in 10 typical adults in response to two speech sound contrasts (/ba/-/ga/, /ba/-/pa/) presented using the oddball and equiprobable (equal trial counts for all conditions) paradigms. Sound discrimination was evident within the 100–300 msec post-stimulus window in both paradigms. Therefore, the equiprobable design can be a reasonable alternative to the oddball paradigm in situations when recording length threatens the quantity of available data.

Psychophysiological measures of cortical responses such as event-related potentials (ERPs) are a frequent tool of choice for studying human auditory processing. Unlike behavioral paradigms, ERPs have the ability to measure such processing at the millisecond level and thus provide a fine-grained level of analysis needed for quantifying individual differences in sound processing and differentiation (Yoder, Camarata, Camarata, & Williams, 2006). Differences in cortical electrical brain responses evoked by auditory stimuli have been interpreted to reflect the brain's ability to discriminate the stimuli. Differences in such discrimination have been associated with specific developmental disability groups, including dyslexia (Guttorm, Leppänen, Richardson, & Lyytinen, 2001; Molfese, 2000; Stoodley, Hill, Stein, & Bishop, 2006), specific language impairment (Bishop & McArthur, 2004; McArthur, Atkinson, & Ellis, 2010), and autism spectrum disorders (Bomba & Pang, 2004; Ceponiene et al., 2003; Ferri et al., 2003; Whitehouse & Bishop, 2008).

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The choice of optimal stimulus presentation during ERP data collection is an important one. During the last two decades, oddball paradigms have been widely used to assess auditory stimulus discrimination (Cheour, Leppanen, & Kraus, 2000; Näätänen, Paavilainen, Rinne, & Alho, 2007). Oddball paradigms involve the frequent presentation of one stimulus (i.e., standard) interspersed with rare occurrences of different stimuli (i.e., deviants). If the participant is passively exposed to the stimuli while his or her attention is directed elsewhere, analyses focus on the Mismatch Negativity (MMN) response with a fronto-central distribution at 100–250 msec (Fabiani, Gratton, & Coles, 2000; Liebenthal et al., 2003; Näätänen, Gaiilard, Mantysalo, 1978) and/or a frontal P3a (Coull, 1998; Squires, Squires, & Hillyard, 1975). When the participant is asked to attend to the stimuli with the goal of actively detecting each occurrence of the deviant stimulus, analysis centers on the P3b peak maximal over centro-parietal scalp (Sutton, Tueting, Zubin, & John, 1965). Because the MMN response does not require active participation and occurs prior to P3a, it has been frequently used in developmental (Csepe, 1995; Friederici, Friedrich, & Weber, 2002; Kraus, McGee, Carrell, & Sharma, 1995; Kraus, Koch, McGee, Nicol, & Cunningham, 1999; Kraus et al., 1993; Kushnerenko et al., 2002), sleep (Alho, Saino, Sajaniemi, Reinikainen, & Naatanen, 1990; Campbell, Bell, & Bastien, 1991), and clinical research (e.g., Cone-Wesson & Wunderlich, 2003; Duncan et al., 2009; Oates, Kurtzberg, & Stapells, 2002) examining auditory discrimination across the lifespan, including persons unable to provide behavioral responses to the stimuli. The MMN response can be evoked by perceivable differences between auditory stimuli, such as changes in duration, frequency, or intensity of the sound, as well as variability in voice onset time or place of articulation (Cheour et al., 2000; Näätänen et al., 2007; Rosburg, 2003). MMN latency and amplitude is considered to be generally stable across the lifespan (Cheour et al., 2000; Courchesne, 1990; Csepe, 1995). Consequently, this passive oddball paradigm is a scientifically attractive model to obtain ERP measures of auditory discrimination due to its broad applications and consistency.

However, like most methodological approaches, oddball paradigms also have some drawbacks (see Kujala, Tervaniemi, & Schröger, 2007 for a review). These drawbacks are only of concern under specific experimental circumstances but can be difficult to overcome. In case of the MMN paradigms, they typically require a large number of trials, often approaching or exceeding 1,000 trials (Duncan et al., 2009; Näätänen, Pakarinen, Rinne, & Takegata, 2004). Even when intertrial intervals are brief, the recording sessions can be lengthy, making it more difficult to obtain usable data in certain study populations, such as young children or persons with intellectual disabilities. Another challenge is the limitation of the number of discriminations that could be tested in a single session. Testing multiple pair-wise contrasts would typically require multiple recording sessions due to the need to provide sufficient numbers of trials for each contrast. To address this concern, Näätänen et al. (2004) introduced a multi-deviant oddball paradigm that allows testing of more than one auditory contrast in the same session. However, the total recording time could still remain prohibitive for participants with limited compliance periods.

Another drawback of the MMN oddball paradigm is due to balancing the need for reproducible MMNs, which requires a high number of stimulus presentations (e.g., a minimum of 150 deviant trials; Duncan et al., 2009), versus preventing habituation of response to deviant stimuli, which tends to occur when deviants are presented “too often” (McGee et al., 2001). Equally concerning is the fact that MMN oddball response is not always detectable (e.g., Cheour et al., 1998; Leppanen, Eklund, & Lyytinen, 1997), even when behavioral evidence of sound discrimination is present (e.g., Sharma et al., 2006; Wunderlich & Cone-Wesson, 2001). This could be partially explained by masking of the MMN response in the difference wave by temporally overlapping ERPs (e.g., N1 or P3; Duncan et al., 2009; Näätänen, Jacobsem, & Winkler, 2005; Rinne, Sarkka, Degerman, Schroger, & Alho, 2006). The inability to detect an MMN response can lead to exclusion of such data sets from the analysis and reduce the usable sample size. This is of particular concern to the study of rare or challenging populations, such as very young children, individuals with rare genetic syndromes, or persons at risk for atypical outcomes.

An attractive alternative when time constraints are paramount is the equiprobable paradigm, where trials for each stimulus condition are presented in random order an equal number of times. This paradigm is also well established and has been used in programmatic research (e.g., Key, Molfese, O'Brien, & Gozal, 2009; Key et al., 2007; Maitre, Lambert, Aschner, & Key, 2013; Molfese & Molfese, 1985, 1997; Lyytinen, Leppanen, Richardson, & Guttorm, 2003; Lyytinen et al., 2005; McArthur et al., 2010; Yoder et al., 2006). The equiprobable approach has also been utilized to assess speech and non-speech sound discrimination in infants (Guttorm et al., 2001; Molfese & Molfese, 1988; Molfese, Burger-Judisch, & Hans, 1991; Key et al., 2007; Key, Lambert, Aschner, & Maitre, 2012), children (Espy, Molfese, Molfese, & Modglin, 2004; Key, Bradham, & Porter, 2010; Key et al., 2009), and adults (Molfese, 1978, 1980; Eichele, Nordby, Rimol, & Hugdahl, 2005). Like the oddball paradigm in studies for which MMN is the focus, equiprobable stimulus presentation is often used as a passive task, which requires no behavioral response. In addition to the equal number of stimulus presentations across all conditions, equiprobable paradigms typically include fewer trials (less than 100 trials per stimulus) resulting in a shorter recording session. When applied to auditory discrimination, analyses of ERPs recorded using the equiprobable paradigm typically involve several peaks that occur within the MMN response window (e.g., N1, P2, and N2). Evidence of sound discrimination is inferred from differences in peak amplitudes. While the oddball paradigms allow for specific prediction regarding the directions of amplitude differences (the deviant stimuli are expected to elicit larger amplitudes than the standards), the direction of amplitude effects in the equiprobable paradigm is more varied and depends on the specific stimuli used.

Opinions on the functional interpretation of the stimulus-related differences in ERPs obtained in the equiprobable and oddball paradigms vary. In the latter, investigators usually attribute stimulus effects to change detection and memory processes such as preattentive sensory memory for the MMN (Näätänen, 2001) or working memory for P3 peaks (Donchin & Coles, 1988). Conversely, the N1 and P2 responses often used in the analyses of the equiprobable designs are interpreted to reflect discrimination of the acoustic properties of the individual stimuli and their initial identification (see Key, Dove, & Maguire, 2005, Näätänen et al., 2007 for reviews). However, recent studies challenge this distinction and suggest that there is a functional overlap between the MMN and N1 responses (May & Tiitinen, 2010).

In sum, both MMN oddball and equiprobable paradigms indicate that auditory ERPs in largely the same temporal window can vary as a function of sound input and reflect sound discrimination. The major difference between the paradigms is the number of trials presented and analyzed and therefore, the recording time necessary for generation of accurate results. The need exists for alternatives to the oddball paradigm in producing valid usable data in situations of extreme time constraints. However, no study to date has investigated the results of the equiprobable and oddball paradigms in the same participants, using the same stimuli, equipment, and referencing procedures. Thus, the purpose of this exploratory study was to examine stimulus discrimination effects using the two paradigms of stimulus presentation recorded in the same session and in the same group of participants.

METHOD

Participants

Ten healthy adults (5 females), age 21–30 years (*M* age = 26.23 years, *SD* = 4.36 years) provided informed consent and participated in the study. Three participants were left-handed (*M* LQ = –.61, *SD* = .39), the rest were right-handed (*M* LQ = .66, *SD* = .37) as determined by the Edinburgh Handedness Inventory (Oldfield, 1971). All participants reported normal hearing. This research received prior approval by the Institutional Review Board of Vanderbilt University.

Stimuli

The stimuli included three computer-synthesized consonant–vowel syllables (/ba/, /ga/, /pa/). The chosen syllables are common in English language and represent commonly investigated speech contrasts: differences in place of articulation (POA; /ba/-/ga/) and voice onset time (VOT; /ba/-/pa/). All stimuli were matched in intensity, rise and decay times (40 msec), formant number (5), and duration (250 msec). The stimuli were synthesized on a Klatt (cascade) synthesizer, so that the amplitudes of individual formants were modulated as a function of the respective formant frequencies, as in natural speech. The central frequencies of the steady-state portion of the formants were kept constant across different consonants.

Electrodes

A high-density array of 128 Ag/AgCl electrodes embedded in soft sponges (Geodesic Sensor Net GSN200, EGI, Inc., Eugene, OR) was used to record the ERPs. Electrode impedance levels were below 40 kOhm before and after testing. Data were sampled at 250 Hz, with filters set to 0.1–30 Hz. During data collection all electrodes were referred to Cz (vertex) and then re-referenced offline to an average reference.

Procedure

Each participant was tested individually in a sound-attenuated room. ERPs were obtained using two stimulus presentation paradigms, an oddball (MMN) paradigm and the equiprobable paradigm. The order of the two stimulus presentation paradigms was counterbalanced across the participants. The syllables were presented at 75 dB SPL(A) as measured at the participant’s ear through a speaker positioned approximately one meter above the midline of the head. In both paradigms, participants were instructed to sit quietly and watch a movie presented on a TV monitor 80 cm in front of them. The decision to use a movie during electroencephalogram (EEG) data collection was motivated by frequent use of videos in studies utilizing both paradigms, especially when testing young children.

Recording of the brainwaves was controlled by Net Station software (v. 4.1; EGI, Inc.). Stimulus presentation was controlled by E-Prime (PST, Inc., Pittsburgh, PA). During the entire test session, the participant's EEG and behavior were continuously monitored. For the equiprobable paradigm, stimulus presentation was suspended during periods of motor activity.

Oddball (MMN) paradigm. All sounds were presented in random order following the initial 10-trial presentation of the standard stimulus. Syllable /ba/ was selected as the standard stimulus and presented 70% of the time (560 trials), while /ga/ and /pa/ served as the POA and VOT deviants with the probability of 15% (120 trials) each. Interstimulus interval was set to 800 msec. The recording session lasted 18–20 min with a total number of 800 trials.

Equiprobable paradigm. The same three sounds were presented in random order, 30 times each. Intertrial interval varied randomly between 700–1300 msec to prevent habituation to stimulus onset. The recording session lasted 6–8 min with a total of 90 trials.

Data Analysis

Individual ERPs were derived by segmenting the ongoing EEG based on each stimulus onset to include a 100-msec prestimulus baseline and a 500-msec post-stimulus interval. Resulting segments were screened for artifacts using computer algorithms included in NetStation and then followed by a manual review. The automated screening criteria were set as follows: for the eye channels, voltage in excess of 140 μV was interpreted as an eye blink and voltage above 55 μV was considered to reflect eye movements. Any channel with voltage exceeding 200 μV was considered bad. Trials contaminated by eye or movement artifacts or containing more than 15 bad channels (12% of the electrodes) were excluded from the analysis. Following artifact rejection, remaining trials were averaged, baseline corrected, and referenced to an average reference.[1]

In order to better relate the results of the oddball and equiprobable paradigms to existing literature, only the electrodes corresponding to the following 10–20 system locations over frontal (Fp1/Fp2, F3/F4, F7/F8), central (C3/C4), and temporal (T3/T4, T5/T6) areas were included in analyses (see Figure 1 for specific electrode correspondence between the EGI net and the 10–20 system). Also, in line with the typical MMN analyses and the typical timing of adult N1, P2, and N2 components in equiprobable paradigms, subsequent analyses were focused on the interval between 100–300 msec.

For each paradigm, averaged data for the selected electrodes were submitted to two temporal principal components analyses (PCAs) with Varimax rotation using the SPSS v.13. One PCA used individual sound averages as the input, which is typical of analyses of ERP data when stimuli are presented using an equiprobable paradigm. The second PCA used difference waves based on the POA or VOT contrasts. The latter was used because the MMN response is typically identified in a difference wave calculated by subtracting the ERP elicited by the standard sound (/ba/) from that of the deviant stimulus (/ga/ or /pa/). The PCAs reduced 200 msec of data to small sets of non-correlated components accounting for the maximum variance. These components corresponded to the intervals (i.e., temporal windows) of organized (i.e., correlated) variability in the ERP waveform. These temporal windows were defined as a minimum of five consecutive

[1]Although MMN paradigms often utilize a nose or mastoid reference, the use of an average reference is acceptable (see Kujala et al., 2007) and is generally recommended for analyses of ERPs obtained with high-density electrode arrays (e.g., Dien, 1998).

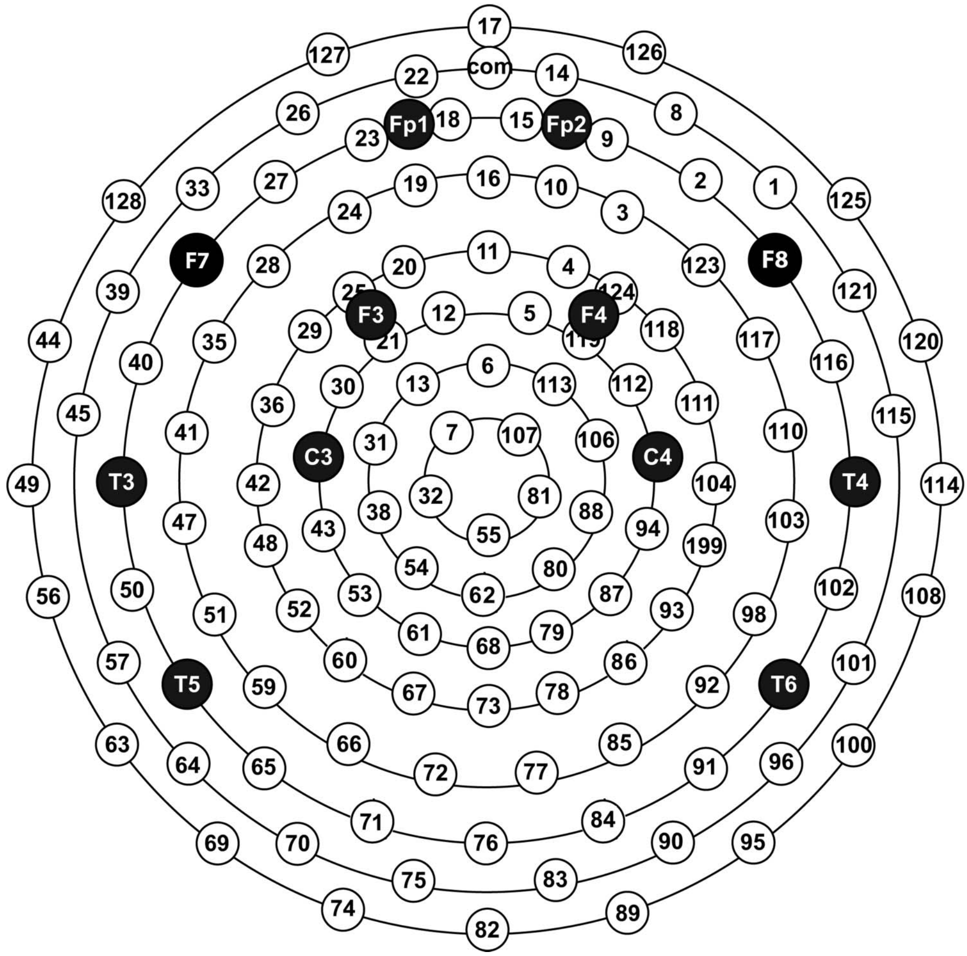

FIGURE 1 A diagram of the 128-channel net layout. Circular markers indicate locations corresponding to the 10–20 electrode system.

time samples loading on the same factor with the same algebraic sign and the loading value of .60 or greater. The use of the data-driven objective temporal PCA approach reduces the risk of experimenter bias influencing the identification of individual peaks, which is arguably present when visual analysis is used. The number of factors to be used in later analyses was chosen using the Scree Test (Cattell, 1966). Data from both stimulus presentation paradigms were analyzed using two approaches: a repeated measures ANOVA for single sound averages and a series of one-group *t*-tests for the difference waves.

For single sound averages, rotated factor scores served as dependent variables in a repeated measures ANOVA with Huynd-Feldt correction to address violations of sphericity. As is typical for analyses of equiprobable paradigms, Consonant (3) × Electrode (6) × Hemisphere (2) within-subject design was used. Because data from equiprobable and oddball paradigms are typically interpreted to reflect differences in sound discrimination, post-hoc analyses of significant effects involving the Consonant variable were limited to the POA (/ba/ vs. /ga/) and VOT (/ba/ vs. /pa/) comparisons, where within-subject *t*-tests were used to identify (a) which stimuli, (b) at what electrode site(s), and (c) in which hemisphere elicited differences in ERP amplitudes. For significant results as indicated by *p*-values that are unadjusted for multiple significance testing, we also report the *p*-values that were adjusted for multiple significance testing using the multivariate permutation testing approach (MPT). Unlike Bonferroni-adjusted alpha, MPT-adjusted *p*-values do not assume that all dependent variables in a "family" of significance tests are independent (i.e., uncorrelated). Simulation studies have demonstrated that MPT for paired comparisons retain a family-wise error rate of .05 while being more statistically powerful than Bonferroni adjustment (Blair & Karniski, 1994).

For the difference waves, an ANOVA was not run as the goal was not to compare differences between the two sound contrasts but to demonstrate presence of amplitude differences for each of the contrasts. Instead, a series of one-group *t*-tests were used to examine whether the mean factor scores for /ga/-/ba/ and /pa/-/ba/ contrasts were different from zero within each of the PCA-identified temporal windows. For significant results as indicated by *p*-values that are unadjusted for multiple significance testing, we also report the *p*-values that were adjusted for multiple significance testing using the MPT approach. This approach was taken to better resemble analysis of difference wave data from oddball designs when MMN is the response of interest.

RESULTS

There were no differences between the two stimulus presentation paradigms in the proportion of trials retained for analyses after artifact rejection (88.4% vs. 87.8% of total trials were retained for the equiprobable and oddball tasks, respectively). Individual condition averages were based on 27.30+/–1.83 (ba), 25.60+/–3.57 (pa), and 26.70+/–3.59 (ga) trials in the equiprobable paradigm. For the oddball task, there were 506.80+/–37.47 (ba), 105.00+/–9.90 (pa), and 104.30+/–9.36 (ga) trials per condition. Mean amplitudes for temporal intervals of interest for each paradigm are presented in Tables 1 (oddball/MMN paradigm) and 2 (equiprobable paradigm).

Individual Stimulus Data

ERP data collected in the equiprobable paradigm. The temporal PCA identified four factors accounting for 87.3% of the total variance. Sound discrimination effects were present for two of the four PCA factors. For the PCA component on which time samples between 148–180 msec had the largest loadings (i.e., weighting), there was a Consonant × Electrode interaction ($F(10,90) = 2.47$, $p = .039$, partial *eta sq.* = .22). Post-hoc analyses indicated that over the posterior temporal (T5/6) locations, which typically demonstrate evidence of sound discrimination in equiprobable paradigms (e.g., Guttorm et al., 2001; Molfese & Molfese, 1985, 1997), /pa/ sounds elicited more positive amplitudes compared to /ba/ ($t(9) = 4.26$, unadjusted $p = .002$, adjusted $p = .02$, $d = 1.35$; Figure 2). As is typical, the direction of these differences was reversed at frontal (F3/4) sites ($t(9) = 3.995$, unadjusted $p = .003$, adjusted $p = .025$, $d = 1.26$). For the PCA component on which time samples between 188–236 msec had the largest

TABLE 1
Mean (*SD*) ERP Amplitudes (μV) Measured Across Temporal Windows in the Oddball (MMN) Paradigm at C3/4 and T5/6

	ba	*ga*	*pa*	*ga-ba*	*pa-ba*
110–140 msec					
C3/4				0.24 (.52)	0.44 (.60)
T5/6				0.01 (.49)	−0.11 (.68)
156–220 msec					
C3/4				0.26 (.55)	−0.29 (.46)
T5/6				−0.07 (.63)	0.32 (.88)
220–300 msec					
C3/4				0.36 (.77)	0.21 (.50)
T5/6				−0.09 (.56)	0.02 (.72)
172–228 msec					
C3/4	0.3 (.12)	0.55 (.08)	0.12 (.32)		
T5/6	0.17 (.10)	0.08 (.12)	0.43 (.07)		

Note. ERP = event-related potentials; MMN = Mismatch Negativity.

TABLE 2
Mean (SD) ERP Amplitudes (μV) Measured Across Temporal Windows in the Equiprobable Paradigm at C3/4 and T5/6

	ba	*ga*	*pa*	*ga-ba*	*pa-ba*
108–148 msec					
C3/4				0.29 (1.47)	0.55 (1.21)
T5/6				−0.08 (1.40)	0.46 (1.55)
148–188 msec					
C3/4				0.28 (1.23)	−0.18 (1.18)
T5/6				−0.49 (2.07)	0.54 (1.48)
188–228 msec					
C3/4				0.39 (1.55)	−0.12 (1.35)
T5/6				−0.44 (2.02)	0.32 (1.74)
148–180 msec					
C3/4	−0.50 (.71)	−0.19 (.77)	−0.63 (.63)		
T5/6	0.03 (.38)	−0.49 (.35)	0.58 (.42)		
188–236 msec					
C3/4	1.03 (.11)	1.45 (.18)	0.98 (.32)		
T5/6	−0.60 (.03)	−1.04 (.05)	−0.32 (.15)		

Note. ERP = event-related potentials.

weighting, there was a main effect of Consonant ($F(2,19) = 4.85$, $p = .021$, partial *eta sq.* = .350). This effect was due to the POA contrast where /ga/ elicited more positive amplitudes than /ba/ ($t(9) = 3.343$, unadjusted $p = .009$, adjusted $p = .02$, $d = 1.06$).

ERP data collected in the oddball (MMN) paradigm. Temporal PCA identified four factors accounting for 91.7% of the total variance. Evidence of speech sound discrimination in the form of a Consonant × Electrode interaction ($F(10,90) = 4.03$, $p = .02$, partial *eta sq.* = .31) was

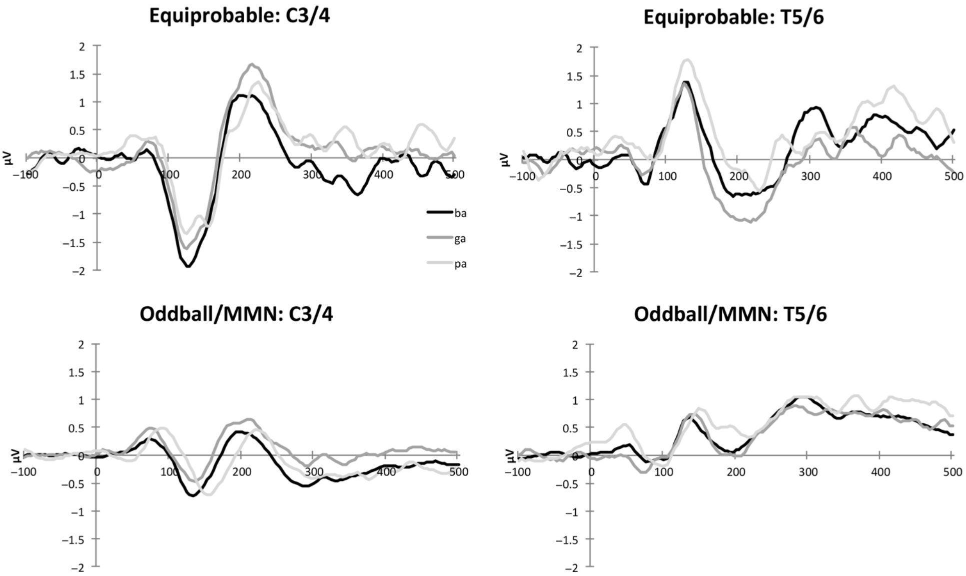

FIGURE 2 Event-related potential (ERP) waveforms at conventional electrode locations evidencing speech sound discrimination in equiprobable (T5/T6) and oddball (C3/C4) paradigms.

present only for the PCA component on which time samples between 172–228 msec had the largest weighting. The effect was due to the VOT contrast where the deviant stimulus /pa/ elicited more negative amplitudes than the standard stimulus /ba/ over central (C3/4) locations ($t(9) = 3.621$, unadjusted $p = .006$, adjusted $p = .04$, $d = 1.15$; Figure 2). As is typical, the direction of differences was reversed over lateral frontal (F7/8) and anterior temporal (T3/4) sites ($t(9) = 3.872$, unadjusted $p = .004$, adjusted $p = .03$, $d = 1.22$ and $t(9) = 4.394$, unadjusted $p = .002$, adjusted $p = .01$, $d = 1.39$). There were no significant findings involving the POA contrast.

Stimulus Contrast Data (Difference Wave)

ERP data collected in the equiprobable paradigm. Temporal PCA identified four factors accounting for 85.387% of the total variance. One-sample t-tests (two-tailed) identified significant differences from zero for the VOT contrast (/pa/-/ba/) over right central scalp locations at the 108–148 msec interval ($t(9) = 2.759$, unadjusted $p = .022$, adjusted $p = .26$, $d = .872$) and at the 188–228 msec interval ($t(9) = 2.925$, unadjusted $p = .017$, adjusted $p = .27$, $d = .925$). Additionally, within 148–188 msec interval, VOT difference waves were significantly different from zero over bilateral frontal and posterior temporal sites (F3: $t(9) = 2.652$, unadjusted $p = .026$, adjusted $p > .08$, $d = .839$; F4: $t(9) = 3.269$, unadjusted $p = .010$, adjusted $p > .08$, $d = 1.034$; T5: $t(9) = 3.931$, unadjusted $p = .003$, adjusted $p = .08$, $d = 1.241$; T6: $t(9) = 2.570$, unadjusted $p = .030$, adjusted $p > .08$, $d = .813$). A significant POA contrast difference (/ga/-/ba/) was also present in this time interval over left posterior temporal scalp (T5: $t(9) = 2.738$, unadjusted $p = .023$, adjusted $p > .08$, $d = .866$).

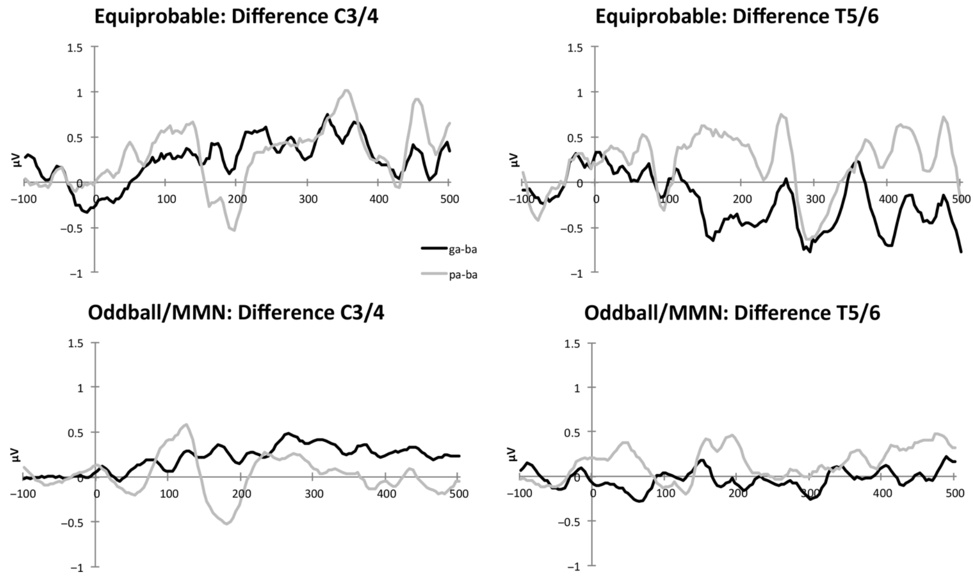

FIGURE 3 Difference waveforms evidencing speech sound discrimination in equiprobable (T5/T6) and oddball (C3/C4) paradigms.

ERP data collected in the oddball (MMN) paradigm. Temporal PCA identified three factors accounting for 85.302% of the total variance. One-sample t-tests (two-tailed) revealed that significant differences from zero for the VOT contrast (/pa/-/ba/) were present throughout the analysis window (Figure 3) and were detected over bilateral central, right frontal, and left temporal scalp locations (100–140 msec: C4 - $t(9) = 3.081$, unadjusted $p = .013$, adjusted $p = .21$, $d = .974$; 156–220 msec: C3 - $t(9) = 4.580$, unadjusted $p = .001$, adjusted $p = .03$, $d = 1.448$; C4 - $t(9) = 2.980$, unadjusted $p = .015$, adjusted $p > .15$, $d = .942$; F4 - $t(9) = 2.338$, unadjusted $p = .044$, adjusted $p > .15$, $d = .739$; F8 - $t(9) = 2.350$, unadjusted $p = .043$, adjusted $p > .15$, $d = .743$; T3 - $t(9) = 3.306$, unadjusted $p = .009$, adjusted $p = .15$, $d = 1.045$; 220–300 msec: C3 - $t(9) = 2.322$, unadjusted $p = .045$, adjusted $p > .09$, $d = .734$). A significant difference from zero was present in the POA contrast difference wave (/ga/-/ba/) at left frontal pole location between 156–220 msec (Fp1: $t(9) = 3.021$, unadjusted $p = .014$, adjusted $p = .15$, $d = .955$) and right central scalp at 220–300 msec intervals (C4: $t(9) = 3.890$, unadjusted $p = .004$, adjusted $p = .09$, $d = 1.230$).

DISCUSSION

Psychophysiological measures of auditory processing, especially in speech sound discrimination, are frequently used to document typical and atypical development, characterize group differences in brain functioning, and predict future outcomes. Consequently, implementing an ERP testing procedure that would target between-stimulus differences while minimizing data loss due to artifacts and participant noncompliance is very important. Our results demonstrate that in situations when recording time limits threaten the quantity of available data, an equiprobable paradigm is a reasonable alternative to the oddball design. These issues are of particular concern to researchers working with very young participants or persons with disabilities.

The main goal of this exploratory study was to examine stimulus discrimination effects using the equiprobable and oddball paradigms under the same conditions in the same group of participants. The tasks were designed to resemble the prototypical oddball and equiprobable paradigms, including the numbers of trials and intertrial intervals. Using the same participants, the same equipment, the same data collection parameters, the same syllables, the same analysis approach, and the same test environment increased the probability that any differences in results between paradigms could be interpreted as intrinsic to the paradigms (e.g., relative number of trials per stimulus). Each paradigm produced results similar to those reported in previously published studies using that stimulus presentation approach, supporting the relevance of the current data to the paradigm in general. In the oddball task, sound discrimination effects were observed in the usual fronto-central locations (see Näätänen et al., 2007 for review). In the equiprobable paradigm, stimulus-related effects were present over frontal and temporal areas (see Molfese, Fonaryova Key, Maguire, Dove, & Molfese, 2005 for review).

Analyses of the ERPs at the level of the individual sounds revealed that both equiprobable and oddball paradigms evidenced VOT discrimination (148–180 msec and 172–228 msec, respectively). The equiprobable paradigm also provided evidence of the POA discrimination in the 188–236 msec window. While this effect was not clearly observed in the oddball paradigm when single sound averages were used as the dependent measure, it was present when using difference waves as the input. Utilizing difference waves also mitigated a relative weakness of the equiprobable paradigm associated with the interpretability of the results. Although there is equivocal data concerning which stimulus should produce the larger amplitude when individual stimuli are presented equally often (e.g., Guttorm et al., 2001; Molfese et al., 1991), the value of the difference in amplitudes between the contrasting syllables is interpretable in the same way as the difference waves from an oddball paradigm—larger difference (in absolute values) implies greater stimulus differentiation (Cheour et al., 1998; Key et al., 2012; Näätänen et al., 2007; Yoder et al., 2006).

The underlying processes contributing to ERP amplitude differences observed in each of these stimulus presentation options are currently under rigorous debate. While both paradigms elicited brain responses that varied between stimuli, some researchers, but not all, consider the between-stimulus differences in ERP response obtained using an oddball paradigm to indicate a different process than that obtained using an equiprobable design. Proponents of the MMN paradigms often argue that the MMN and N1 responses reflect different stages of auditory processing (Näätänen et al., 2004, 2007). Specifically, the MMN is considered to result from a memory-based stimulus comparison and change detection process while stimulus-related modulation of the N1 response is thought to reflect acoustic features of the individual stimuli without additional stimulus comparisons. However, a recent review and simulation studies by May and Tiitinen (2010) offer compelling arguments that both responses reflect neuronal adaptation and spatial representation of sound in the auditory cortex. While acknowledging the different interpretations of functional significance of MMN and N1 currently debated in the field, we respectfully posit that accepting one interpretation or the other is not critical to deciding whether to choose the oddball or equiprobable stimulus presentation paradigm. If the experimenter's goal is to use between-stimulus differences in ERP responses for the purpose of examining brain discrimination of auditory inputs, either stimulus paradigm appears adequate for the task.

It is noteworthy, however, that May and Tiitinen (2010) suggest that the oddball design may not always be needed as similar results could be achieved with conventional N1 paradigms (which typically use equiprobable stimulus presentation). Assertions that MMN, but not N1, conclusively indicates sound discrimination (e.g., Näätänen et al., 2004, 2007) have been challenged by a number of studies (see Bishop, 2007 and May & Tiitinen, 2010, for reviews) that demonstrate that participants, who were unable to discriminate sounds behaviorally, evidenced MMN responses (Shafer, Morr, Datta, Kurtzberg, & Schwartz, 2005); while those who were able to discriminate stimuli, showed no MMN responses (Sharma et al., 2006; Wunderlich & Cone-Wesson, 2001). We are unaware of similar studies evidencing behavioral discrimination of the auditory stimuli in the absence of sound-related differences in N1 amplitudes.

From the developmental perspective, the MMN response may be a desirable measure given its reputation as being present even in premature infants (Cheour-Luhtanen et al., 1996; Fellman et al., 2004). However, given the difficulties of interpreting the absence of MMN response, it may be difficult to apply to longitudinal studies. Prior research noted that up to 50% of newborns and 25–30% of healthy infants exhibited no MMN (Cheour et al., 1998; Leppanen et al., 1997). Räikkönen, Birkás, Horváth, Gervai, and Winkler (2003) observed no clear MMN in a 3-stimulus oddball paradigm with healthy 6-year-olds and while responses to standard tones showed the most stability (77% shared variance) over a 3 months period, responses to deviants shared only 17–31% of variance across the test–retest. Additionally, in 7–11-year-old children, MMN has been shown to have limited within-session reliability or short-term stability over a 2-week period (Uwer & von Suchodoletz, 2000). MMN to speech deviants was present in both sessions only in 43% of children; the rest of the sample did not demonstrate MMN in at least one of the sessions. There were no group differences in age, nonverbal IQ, or behavioral discrimination measures between the participants for whom an MMN was present in one session and those for whom an MMN was present in both sessions. Within a recording session, MMN responses to duration deviants showed significant split-half reliability (r = .78–.79, 210–310 msec), but only one of the two speech deviants elicited a reliable MMN and only in the second of the two sessions (/ga/: r = .63) in the temporal window later than the typical MMN.

On the other hand, N1/P2 responses appear to be more robust. Although their amplitude and latency vary with age and cortical maturity level (e.g., Ponton, Eggermont, Khosla, Kwong, & Don, 2002), evidence of sound discrimination has been consistently observed for these responses or their developmental analogues in participants across the age spectrum. Furthermore, in 7–11-year-olds, split-half reliability of N1 response to all speech sounds was high (standard: r = .94, /ga/ deviant: r = .57, /ba/ deviant: r = .74). The N1 response was also stable between sessions (standard: r = .83, /ga/ deviant: r = .74, /ba/ deviant: r = .76; Uwer & von Suchodoletz, 2000).

While our findings and interpretations are consistent with previously published reports, the present study has several limitations. In the interest of ensuring maximal comparability of the analyzed data, we applied the same referencing and data reduction procedures to both data sets from the oddball and equiprobable paradigms. The need to use the same reference forced us to use a montage different from that used in some oddball studies. For example, many of the oddball studies utilized a nose rather than an average reference as was common for montages with fewer electrodes (Näätänen et al., 2007). However, the use of the average reference is not unusual for modern data sets acquired with high-density electrode arrays (Bruder et al., 2011a, 2011b; Kujala et al., 2007). A related issue is the inclusion of only selected electrodes in the analyses. While we followed the standard practice (utilized even by those who use high-density arrays, e.g., Bruder et al., 2011a, 2011b; He & Trainor, 2009) of identifying electrodes of interest based on most frequently reported scalp locations associated with ERP effects for each of the two paradigms, future studies could take advantage of the increased spatial resolution offered by multi-channel arrays by considering all electrode data in topographic analyses (e.g., Murray, Brunet, & Michel, 2008). Finally, if one wishes to generalize to other samples from these current results, effects with unadjusted *p*-values over .05 should be interpreted with caution. Readers viewing the current results as a demonstration of within-sample sound discrimination can interpret effects with unadjusted p-values as informative. The intended purpose of the current study was not to identify latency and electrode locations evidencing sound discrimination per se but to investigate whether each stimulus presentation paradigm could be used to detect stimulus differences in brain activity when potentially important aspects of the data collection procedures were equated.

In summary, our findings suggest that the equiprobable paradigm may offer an alternative to the oddball design in documenting brain's ability to discriminate speech sounds when a shorter recording session is of prime importance. Both the oddball and equiprobable paradigms have rich history of successful use. However, when the likelihood of data acquisition success is dependent on limiting the number of trials as is often the case when working with young infants, toddlers, or with persons with disabilities, a shorter recording session using the equiprobable paradigm may be a feasible choice.

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