Social cognition categories impact early auditory processing: asymmetrical mismatch negativities to socially-marked biological sounds

[RUNNING HEAD: Social cognition impacts early auditory processing]

Petrosino, Roberto[1*], Almeida, Diogo[2], Calabrese, Andrea[1] & Sprouse, Jon[1]

[1] *Department of Linguistics, University of Connecticut*
[2] *Psychology Program, Division of Science, New York University Abu Dhabi*

*Corresponding author: roberto.petrosino@uconn.edu

Abstract

This study explores to what extent social cognition impacts early auditory processing. We measured the event related potential known as the Mismatch Negativity (MMN) response to three non-linguistic biological sounds (*flatulence*, *coughs* and *sniffs*) that differ in terms of social markedness: *flatulence* is socially marked, while *coughs* and *sniffs* are not. We found that the MMN to the pairing *flatulence*/*cough* is larger in amplitude when *flatulence* is the oddball than when *cough* is the oddball – an asymmetrical MMN. We found no evidence of an asymmetrical MMN for the pairing *cough/sniff*. Crucially, this pattern tracks the social-markedness properties of these stimuli, but does not track their physical properties: spectral analyses suggest that *cough* and *sniff* are the most distinct acoustically (with *flatulence* in between). The MMN response has long been used for research in language and music; these results suggest that it may also be used for research in social cognition.

1. Introduction

In auditory cognition, there is ample evidence that higher-order mental faculties such as language and music training have profound effects on how sounds are processed in the brain (e.g., Winkler et al. 1999; Schön et al., 2004; Tervaniemi et al., 2009). However, how social cognition impacts auditory processing outside of these domains is still a relatively understudied topic. We report here an experiment that capitalizes on a specific event-related potential (ERP), the mismatch negativity (MMN), and that shows evidence that socially relevant structures impinge on the processing of biological sounds in the brain. Namely, we find that acoustically complex (non-linguistic) biological sounds trigger asymmetrical MMN responses in a way that tracks the social categorization of those sounds as socially-marked/unacceptable (such as *flatulence*) and socially-unmarked/acceptable (such as *coughs* and *sniffs*), but does not track the physical properties of the sounds (in which *coughs* and *sniffs* are most distinct, with *flatulence* in between).

The MMN is a negative-going event-related brain potential that arises 150-250 ms after the onset of an infrequent sound (the *deviant*) within a stream of repeated sounds (the *standard*; for a review see Näätänen, 2001). The MMN is calculated by subtracting the ERP response to the standard from the ERP response to the deviant. The amplitude of the MMN has been shown to be modulated by the relative degree of dissimilarity in the standard-deviant pairs on a number of physical properties of acoustic stimuli, such as frequency (Näätänen et al., 1978), intensity (Jacobsen et al., 2003), and duration (Jaramillo et al., 2000). This automatic difference-detection property has led many researchers to posit that the MMN reflects a relative error signal at the level of the memory representation that is formed when the stimuli are presented to participants (see Näätänen, 2001). Crucially, this functional interpretation of the MMN has led to a rich body of research that has probed how sounds are structured beyond their physical properties by investigating more abstract organizational information, such as those properties that are relevant for speech processing (Näätänen et al., 1997; Phillips et al., 2000, Kazanina et al. 2007).

Recently, work in the speech processing literature has focused on *asymmetrical* MMNs (aMMNs): a larger amplitude MMN when the two stimuli are in one standard-deviant relationship, and a smaller amplitude MMN when the same two stimuli are in the opposite standard-deviant relationship. The leading idea behind aMMNs is that the difference in amplitude[1] between the two MMNs is unlikely to be driven by acoustic properties of the stimuli, as identical stimuli are used in both MMNs; instead, the difference is more likely to be driven by an abstract feature of the stimuli, or by a more complex relationship between the acoustic properties of the stimuli and the MMN response. A number of aMMNs have been observed to pairs of speech sounds within the speech processing literature (a.o., Eulitz & Lahiri, 2004; Scharinger et al., 2012, Hestvik & Durvasula, 2016, Politzer-Ahles et al, 2016). Eulitz & Lahiri (2004) suggest that aMMNs to pairs of speech sounds could be driven by differences in the abstract *linguistic* representations of the two sounds. Their proposal builds on the idea that speech sounds can be described at two levels of representation, one more closely tied to the acoustic/articulatory properties of the sound (*phonetics*), and the other based on more abstract organizational structure (*phonology*), and that at both levels a number of abstract distinctive features are used to characterize speech sounds. They propose that aMMNs arise when one sound in each pair is unspecified for one of the abstract features, while the other sound is fully specified for that feature. (We refer readers to the papers

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[1] Although asymmetries in MMN latency have also been reported in the literature, this paper will focus on asymmetries in MMN amplitude.

cited above for the specific mechanisms proposed.) Crucially, this theory of aMMNs is relatively domain-specific – it relies on a representational framework that is specific to speech sounds. In this project we ask whether aMMNs are indeed language specific as potentially implied by the existing aMMN literature, or whether MMN amplitude is also sensitive to abstract features outside of language – in this case, in the domain of social cognition.

The space of non-speech sounds that could be tested within an aMMN paradigm is quite large. In order to make our test as similar as possible to the speech domain, we chose to focus on non-linguistic biological sounds that differ along the abstract dimension of social *markedness*, that is, the abstract notion that certain sounds are socially-acceptable, while others are socially-unacceptable. In our study, we focus on *flatulence*, which is assumed to be socially marked, and *coughs* and *sniffs*, which are both assumed not to be socially marked. We chose these sounds for three reasons. First, they are relatively acoustically complex biological sounds, involving complex frequency spectra and complex amplitude dynamics, similar to the way that speech sounds are acoustically complex. Second, social markedness is likely an abstract representation that must be learned, as it can vary across cultures, similar to the way that the abstract representation of speech sounds must be learned, as it can vary across languages. Finally, markedness is a theoretical primitive in most theories of the linguistic representation of speech sounds (Calabrese, 2005; Chomsky & Halle, 1968; Jakobson & Halle, 1956; Kiparsky, 1982; Prince & Smolensky, 1993/2004), though it is relatively understudied in the domain of speech perception. Social markedness, though external to language, may therefore be abstractly similar to these notions of linguistic markedness. We therefore believe these stimuli provide a relatively minimal contrast with linguistic aMMNs, differing primarily in domain of cognition.

We included three aMMN subdesigns in our experiment: a linguistic comparison of [s] versus [z], a social markedness comparison of [flatulence] versus [coughs], and a no markedness comparison of [coughs] versus [sniffs]. The linguistic comparison of [s]/[z] was included to ensure that our participants demonstrated linguistic aMMNs to sounds that have been shown to yield an aMMN (Schluter et al., 2017), and that are relatively similar to our non-linguistic sounds in spectral properties. The comparison of [flatulence] and [coughs] is our critical test of social markedness: [flatulence] is assumed to be highly marked, and [coughs] are not. The final comparison of [coughs] and [sniffs] allows us to test the impact of uncontrolled differences in frequency and acoustic properties on the MMN response in the absence of a manipulation of social markedness (see *Materials* and *Discussion* sections).

2. Method

Participants

Twenty-four self-reported native speakers of American English, all undergraduate students at the University of Connecticut, were recruited to participate in the study for course credit. No participants reported history of hearing loss or neurological disorders. Edinburgh Handedness Surveys confirmed that all participants were all strongly right-handed (>80%; Oldfield 1971).

We know of no theory of the effect size of asymmetrical MMNs within language, and no studies looking for aMMNs outside of language, so we could not predict a likely effect size a priori. We chose our sample size based on an evaluation of the previous aMMN literature, which included 13 experiments from 9 papers with a range of 12 to 24 participants (mean=17, median=16, sd=5.08). We chose the highest value in this range (24).

Materials

We created 10 tokens of each condition. The tokens for the linguistic conditions [s] and [z] were taken directly from Schluter et al. (2017). The *flatulence* and *cough* tokens were downloaded from the internet. We attempted to find tokens that were subjectively deemed to be similar by the authors. *Sniffs* were produced by 3 colleagues (all female, and native speakers of English, though there is no reason to believe that native language matters for sniff production). All tokens were cropped to be 250ms long by removing a small portion in the middle of each token using PRAAT (Boersma and Weenink 2011). We did not ramp the stimuli, but rather cropped the stimuli at zero-crossing at both ends to avoid perception of clipping artifacts. Linguistic sounds were not normalized to avoid degradation of stimulus quality. Non-linguistic sounds were normalized to 70 dB (SPL). The stimuli are available upon request.

The thirty tokens were also analyzed in their spectro-acoustic properties. The analysis had two purposes. First, we wanted to make sure that the tokens chosen occupied different positions in the acoustic space. Second, we wanted to look for potential acoustic similarity relationships between sound types, so as to make specific acoustics-dependent predictions on the MMN modulation. For each token, we converted the waveforms into matrices of 12 Mel-frequency cepstral coefficients (MFCCs) and 12 delta coefficients based on 15ms windows spaced into 5ms intervals (as is standard in the speech processing literature; Mielke, 2012). These measurements were then compared using the multivariate dynamic time warping algorithm because the sounds are not time-aligned (Holmes & Holmes, 2001). These calculations generated two matrices, one representing time-frequency information (MFCCs) and one representing second order spectral change over time (delta coefficients). Each of the two distance matrices were entered into a hierarchical agglomerative clustering (HAC) analysis, in which Ward's minimum variance linkage method was adopted (a common method that minimizes total within-cluster variance). The resulting hierarchy, represented as the dendrogram in Figure 1, confirms that the three sound types are well distinct to one another. Moreover, the clustering orders are different in the MFCCs and delta coefficients. For MFCCs, [flatulence] and [cough] are clustered together first, followed by [sniff]. Under the assumption that acoustic dissimilarity drives aMMNs, this predicts that [cough]/[sniff] should lead to the largest aMMN. For delta coefficients, [flatulence] and [sniff] are clustered together first, followed by [cough]. This predicts that we should expect similar ERP responses for both the [flatulence]/[cough] and [sniff]/[cough] subdesigns. Similar patterns were found when the HAC analysis was run with the other three linkage methods (single-linkage, complete-linkage and average-linkage).

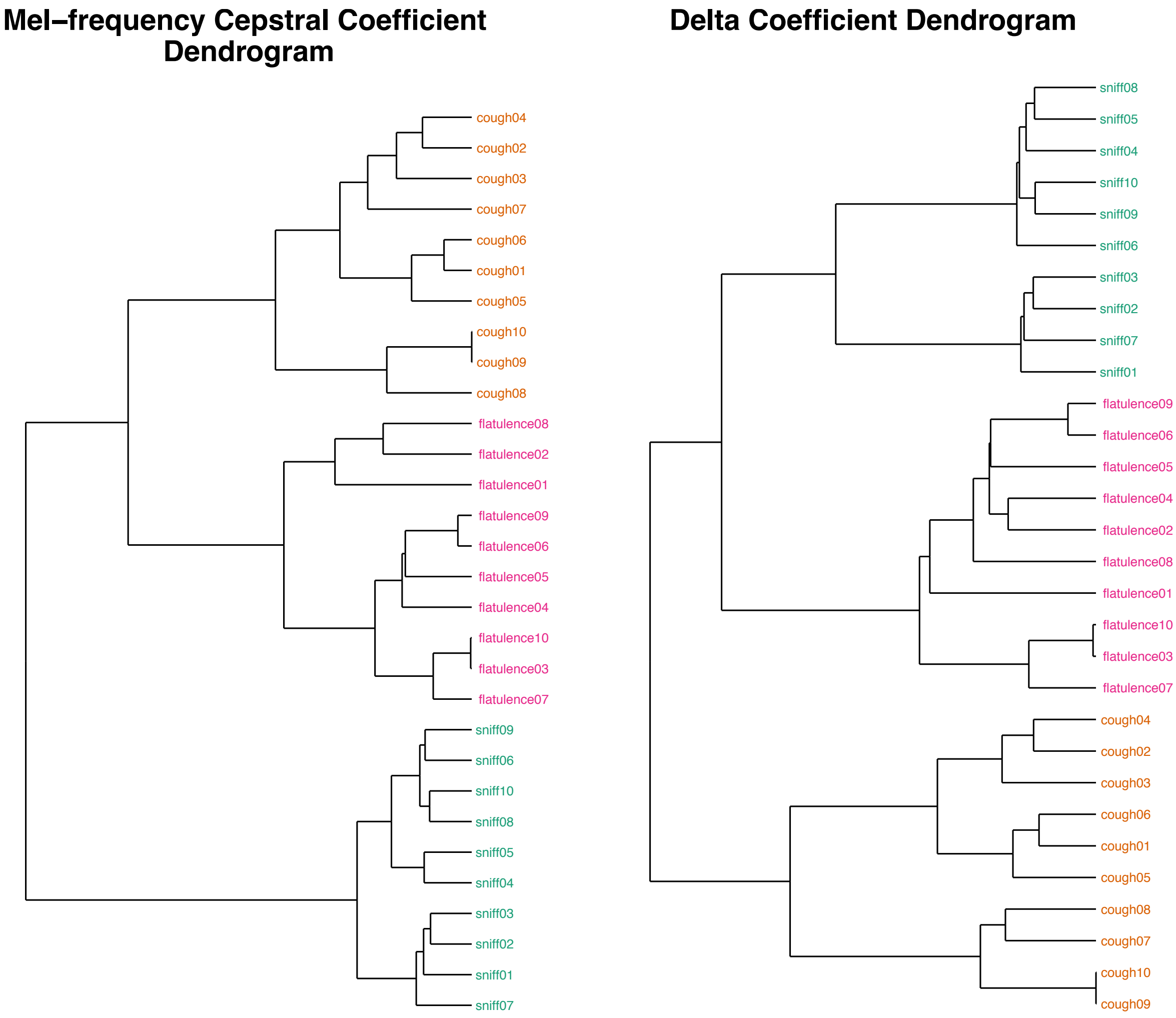

Figure 1. MFCC and Delta coefficient dendrograms of the tokens used in the experiment.

Design

The experiment consisted of 6 blocks, each with a different MMN paradigm (standard/deviant): s/z, z/s, cough/flatulence, flatulence/cough, cough/sniff, sniff/cough. Within each block, each pair of sounds was presented in a many-to-one oddball paradigm, in such a way that, in each block, the standard occurred 700 times and the deviant occurred 100 times, for a total of 800 stimuli per block. The number of trials per condition was chosen by consulting the previous aMMN literature. Out of the thirteen aMMN experiments in the literature, a plurality of five used 700 standards and 100 deviants; the number of trials in the other 8 experiments were very similar.

During each trial, the script randomly selected one of the 10 distinct tokens for each stimulus. Using multiple tokens of each stimulus helps to ensure activation of neuronal populations linked to the abstract representation, rather than to a specific phonetic realization (Phillips et al., 2000; Hestvik & Durvasula, 2016, Politzer-Ahles et al., 2016). Each block was required to begin with 9 standard stimuli; the minimum number of standards between two deviants (inter-deviant interval; IDI) was set at 4. This ensures that the standard-elicited and deviant-elicited responses are robust. The inter-stimulus interval (ISI) varied pseudo-randomly between 500-1000 ms. The order of blocks was counterbalanced across subjects. Each block lasted about 12 min; overall, the experiment took about 1.5 hours (including participant preparation, clean-up, and debriefing). There was a 5-min break between blocks.

Procedure

Stimuli were presented using the software packaged Presentation® (Neurobehavioral Systems) and ER-3A insert earphones (Etymotic Inc.), calibrated to a volume of 70 dB, using disposable eartips to dampen most environmental noise. Subjects watched a self-chosen movie or show with audio off and subtitles turned on. Allowing participants to watch a TV show or movie during an auditory experiment has been shown to help reduce eye movement and to help maintain alertness during the experiment (Tervaniemi et al., 1999). Following the traditional MMN experimental protocol, subjects were instructed not to attend to the sounds, but rather to attend to the movie.

EEG recording

EEG was recorded continuously from 30 AgCl active electrodes using an ActiChamp amplifier (BrainProducts GmbH), and an ActiCap electrode cap. The electrodes were midline: Fz, Cz, Pz, Oz: lateral: FP1/2, F3/4, FT9/10, FC1/2, FC5/6, C3/4, T7/8, TP9/10 (M1/2), CP1/2, CP5/6, P3/4, P7/8. Online recordings were dc-coupled (with no filters) and referenced against the tip of the nose. This tip-of-the-nose reference is used to distinguish MMNs from the relatively similar N2b by looking for a polarity reversal at the mastoid electrodes (the MMN shows inverse polarity at the mastoids, while the N2b does not). Impedances were kept below 20 kΩ. Recordings were sampled at a rate of 1000 Hz.

EEG Analysis

EEG filtering and analysis were performed using EEGLAB (Dolorme & Makeig, 2004) and ERPLAB (Lopez-Calderon & Luck, 2014), two free Matlab (Mathworks, 2016) toolboxes. The continuous EEG signal was band-pass filtered at 0.1 and 30 Hz (the high-pass cutoff at 0.1 Hz has been shown to not introduce artifacts; see Tanner, Morgan-Short and Luck, 2015). After checking for the polarity reversal indicative of an MMN, the signal was re-referenced offline against the linked mastoids for plotting and statistical analysis. We used the identity MMN (iMMN) method to calculate MMNs (Pulvermüller & Shtyrov, 2006). The iMMN method calculates the difference between the deviant response and the standard response to the same physical stimulus *across different blocks* (e.g., [s] as standard in block 1 and [s] as deviant in block 2). The advantage of the iMMN calculation is that it subtracts out the neurophysiological response to the physical differences of the two stimuli. Event-related potentials were computed separately for each participant, and for each block, with a 100 ms pre-trial baseline before the onset of each stimulus, and a 600ms post-stimulus epoch after the onset of each stimulus. Trials containing artifacts were removed using a combination of automatic and manual artifact detection. The first nine standards of each block and the first standard after each deviant were discarded. One participant was removed from analysis because of the high proportion of trials with artifacts (>25%), leaving twenty-three participants for the analysis.

3. Results

Figure 2 displays the grand-averaged iMMNs for electrode Cz, arranged by aMMN subdesign: linguistic (s/z), social (flatulence/cough), and social (cough/sniff), along with bootstrapped 95% confidence intervals. Asymmetrical MMNs appear as an amplitude difference between the iMMNs of the two conditions in the 100ms to 300ms post-stimulus window. Figure 3 isolates asymmetrical MMNs by calculating the difference between the iMMNs for each stimulus from Figure 2, along with bootstrapped 95% confidence intervals. Figure 4 displays the mean difference in iMMN amplitude between the two conditions in the 125-225ms time window for all channels in a topographic arrangement. For statistical analysis, we ran a repeated measure, two-tailed cluster-bases *t-sum* permutation test (Bullmore et al., 1999) using the Mass Univariate Toolbox (Groppe et al. 2011). Cluster-based permutation tests provide weak control of the familywise error rate for the extreme multiple comparison problem created by EEG data (control over the error rate of the clusters), while still maintaining decent statistical power. The entire epoch (0-599 ms) and all channels were included in the test (i.e., 18,000 total comparisons). Clusters were formed based on an uncorrected *p*-value threshold of .05, with neighboring channels defined as any within an approximate arc-length distance of 5.24 cm (assuming an idealized spherical head with 56 cm circumference, as implemented in the Mass Univariate Toolbox).

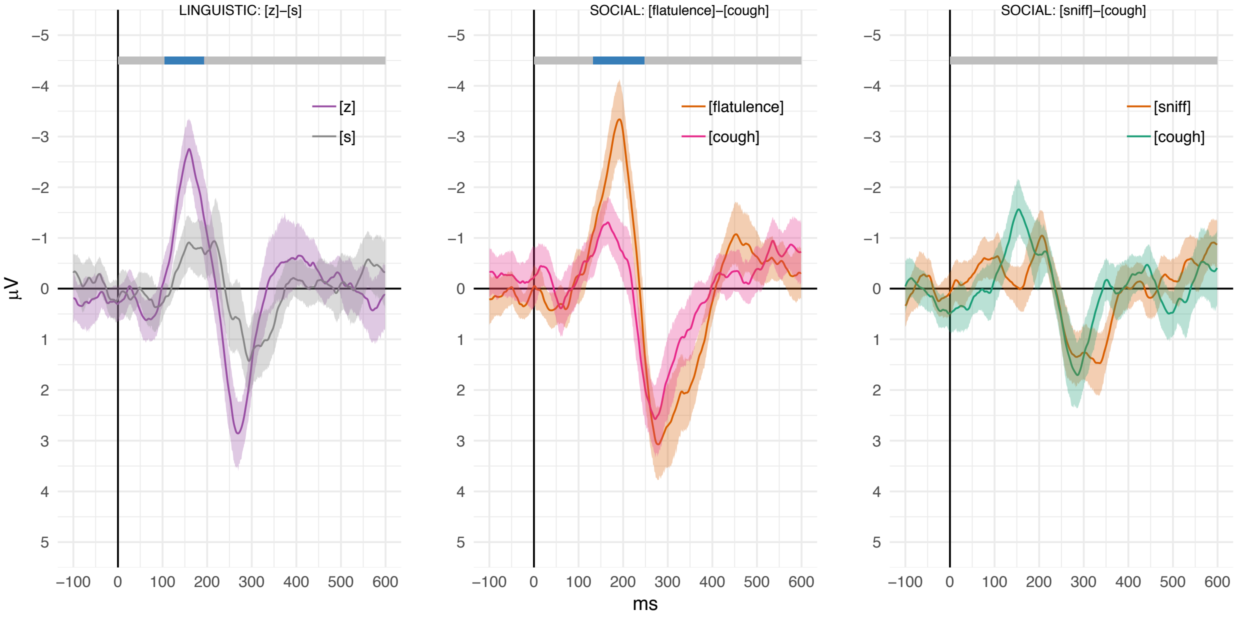

Figure 2. Grand-averaged ERP waveforms of the six conditions tested, along with bootstrapped 95% confidence intervals, arranged by subdesign for channel Cz. The colored bars above waveforms indicate statistical significance by cluster-based permutation test: grey for n.s., blue for significant in the negative direction, red (not present) for significant in the positive direction.

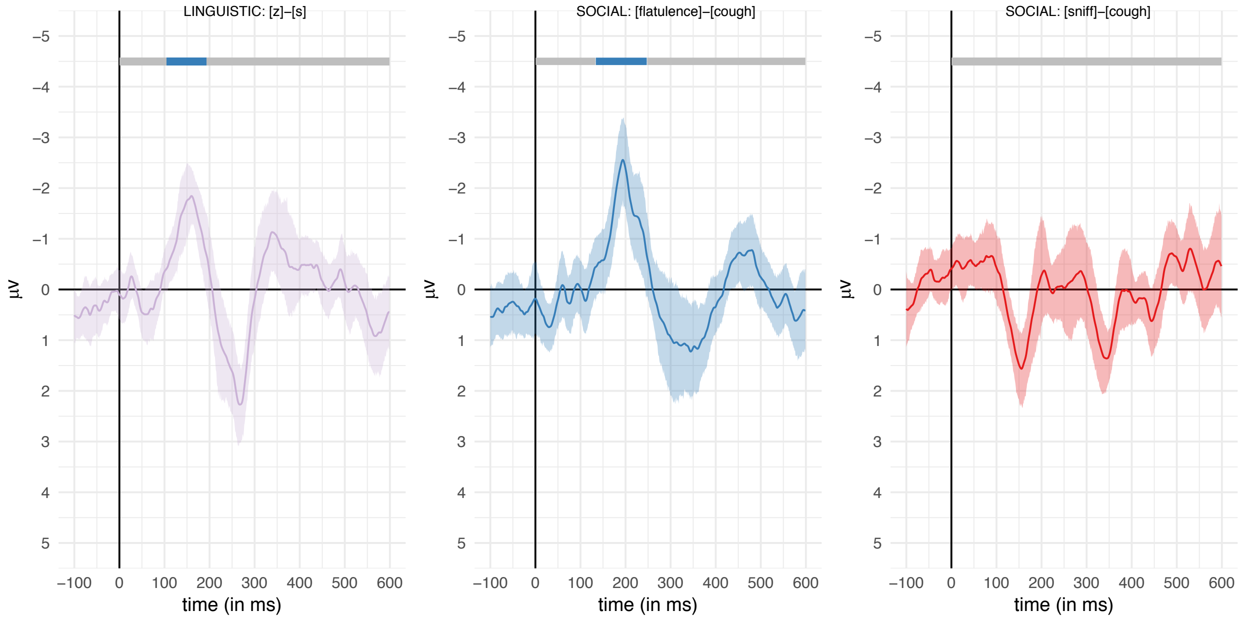

Figure 3. Grand-averaged ERP difference waveforms isolating the asymmetrical MMNs, along with bootstrapped 95% confidence intervals, arranged by subdesign for channel Cz. The colored bars above waveforms indicate statistical significance by cluster-based permutation test: grey for n.s., blue for significant in the negative direction, red (not present) for significant in the positive direction.

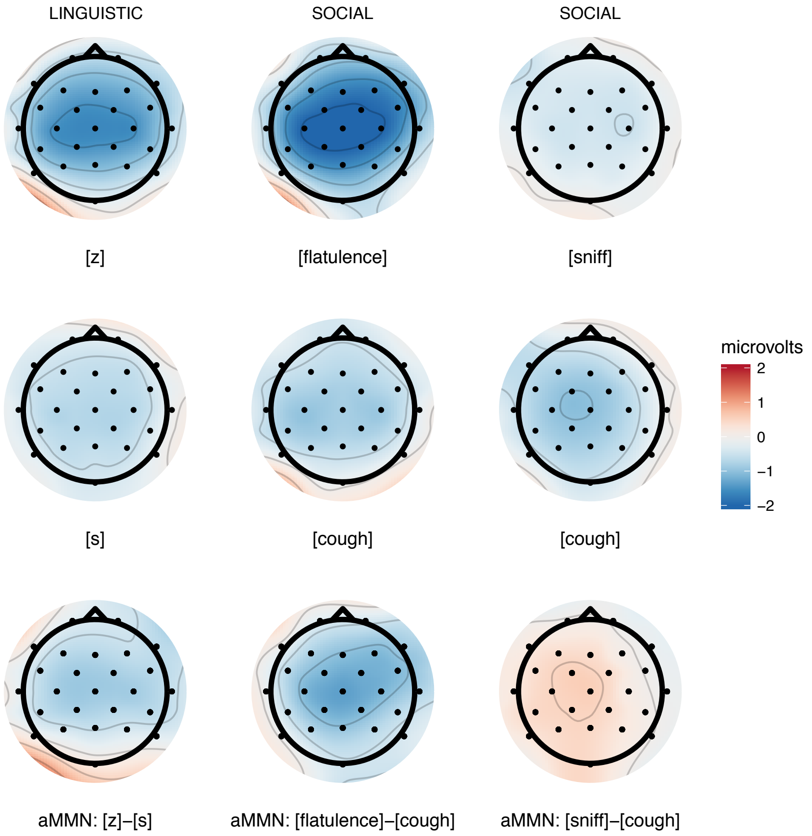

Figure 4. Topographic plots of the MMN mean amplitude in the 125-225ms time window across the three subdesigns.

As Figures 2 and 3 demonstrate, we observed a significantly larger MMN for [z] as deviant than [s] as deviant, replicating the finding of an aMMN for [s]/[z] by Schluter et al. (2017). We also found a significantly larger iMMN for [flatulence] as deviant than [coughs] as deviant, suggesting that there is an aMMN for [flatulence]/[coughs]. Finally, we found no significant difference in the size of the iMMN for [cough] as deviant relative to [sniff] as deviant at any channel, suggesting no aMMN for [cough]/[sniff]. We also found no significant difference between [cough] in the flatulence-block and [cough] in the sniff-block; this suggests that the difference in the [flatulence] and [sniff] aMMN analyses was not driven by the [cough] stimuli behaving differently in the two blocks.

In the interest of replicability, we also ran a second experiment that fully replicates the social aMMN effect of [flatulence] vs [cough] using the same sample size, and the same number of deviant and standard trials. The replication compared the social aMMN response to a vowel quality aMMN (as in Scharinger et al. 2010) rather than consonant aMMN to see if the linguistic context of the experiment influenced the social aMMN. The linguistic context had no effect on the social aMMN, so, for space reasons, we do not report the full details here. Both data sets will be posted online for reproducibility (http://sprouse.uconn.edu).

4. Discussion

Our goal in this experiment was to investigate whether aMMNs arise outside the domain of speech processing, and in particular within social cognition. To that end, we tested three aMMN paradigms: an [s]/[z] comparison to replicate an established linguistic aMMN, a [flatulence]/[cough] comparison to test for an effect of social markedness under the assumption that [flatulence] is more socially marked than [coughs], and a [cough]/[sniff] comparison to test for a lack of an aMMN when there is no difference in social markedness (but potentially other uncontrolled differences). The results show: (i) an aMMN to the [s]/[z] comparison, with a larger MMN to [z] than to [s]; (ii) an aMMN to the [flatulence]/[cough] comparison, with a larger MMN to [flatulence]; and (iii) no difference in the MMN amplitudes in the [cough]/[sniff] comparison. Taken at face value, these results suggest that our participant sample does indeed show linguistic aMMNs, and that there is an aMMN when social markedness is manipulated, but no aMMN when social markedness is equal between the two stimuli. One possible conclusion is that MMNs are sensitive to abstract representations in at least one domain outside of language – social cognition. However, for this conclusion to go through, we must exclude the possibility that other, uncontrolled properties of the [flatulence]/[cough] conditions (or even the [s]/[z] conditions) were driving the aMMNs, such as the frequency of occurrence of the stimuli, or the acoustic properties of the stimuli. We cannot rule these possibilities out completely, because the range of properties that could potentially drive aMMNs is large, and these experiments were not designed to explicitly test these other potential hypotheses. Nonetheless, these hypotheses would face significant challenges given the results that we found, in particular the contrast between [flatulence]/[cough] on the one hand, and [cough]/[sniff] on the other.

The first challenge is that the aMMN paradigm is explicitly designed to control for simple effects by using the same stimuli in the two conditions, just in different functional relationships (deviant or standard). If the MMN amplitude is driven by the simple difference in a given property between two stimuli, then we would expect the amplitude to be the same regardless of the functional relationship. In other words, aMMNs are an interaction effect, as can be seen in the calculation of the effect: aMMN = ([flatulence] as deviant - [flatulence] as standard) - ([cough] as deviant - [cough] as standard). Crucially, explanations of aMMNs in the literature rely on an interaction between the representational properties of the stimuli, and memory mechanisms that encode those properties in either short-term or long-term memory. Though we don't explore it here, our results would suggest that a similar interaction could exist between social-cognition representations and memory mechanisms. A theory that seeks to explain these results with either frequency or acoustic properties must posit a similar interaction.

The second challenge is that the explanation must divide [flatulence] from [coughs] on the one hand, and group [coughs] and [sniffs] together on the other. Frequency seems an unlikely candidate. All three biological sounds have a non-zero daily frequency (Levitt et al. (1996) reports that humans pass gas 10±5 times per day; we could find no studies counting the frequencies of coughs or sniffs). Thus, the MMN system must either be sensitive to relatively subtle differences in non-zero frequencies, or it must use some other mechanism to differentiate the sound types. One possibility could be to condition the frequency counts based on self-generated sounds versus externally-generated sounds (given the existence of feedback in a biological system), such that the only frequency that matters for MMNs is the externally-generated frequency. In that case, there would be a strong correlation between social-markedness and external-generation frequency that may not be dissociable. Future work could look for (i) evidence of a self/external-generation frequency distinction in other domains like speech or music processing, or (ii) stimuli that differ in social-markedness but not external-generation frequency.

The space of possible explanations of aMMNs based on acoustic properties is unmanageably large. Since there are no concrete proposals for this in the literature, we ran an acoustic similarity analysis on the tokens used in the experiment along two relatively common dimensions used in the analysis of acoustic similarity (see *Materials* section). Those results suggest that [cough] and [sniff] are most distinct acoustically, with [flatulence] in between. The standard claim in the literature is that MMN amplitude is dependent upon acoustic dissimilarity, so this would predict that the largest MMN difference should occur in the [cough]/[sniff] pair. In theory, one could entertain the novel assumption that acoustic similarity somehow drives asymmetric MMNs; however, we know of no such proposal in the literature. Therefore, we cautiously conclude that an acoustic explanation of our aMMN pattern is unlikely without a theory that either postulates mechanisms based on acoustic similarity, or uses acoustic properties that are more complex than these two common acoustic properties.

5. Conclusions

This study explored to what extent aMMNs are specific to linguistic categories, and to what extent aMMNs may be elicited by social cognition categories such as social markedness. We contrasted non-linguistic biological sounds such as *flatulence*, *coughs* and *sniffs*, that are spectrally complex but for which categorizations in terms of physical similarity and social markedness mismatch. The aMMN results we observed patterned with the social acceptability categories, and not with acoustic similarity (see also Schluter et al. (2016) in the domain of language). These results suggest not only that aMMNs are not specific to language, but that social cognition categories impinge on early stages of auditory processing in the brain. These results add to the growing body of evidence that it is possible to uncover organizing principles of auditory cognition that reflect abstract higher order information from different cognitive domains, such as language, music, and now social cognition. This interpretation could potentially lead to future studies searching for aMMNs to representational differences in domains other than language, to future studies leveraging aMMNs within social cognition, and to future studies investigating the source of aMMNs.

Authors contributions. All authors developed the study concept and designed the study. R. Petrosino prepared the materials and collected the data. R. Petrosino, D. Almeida and J. Sprouse performed the data analysis. All authors contributed to the interpretation of the results. All authors wrote the manuscript and approved the final version for submission.

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