Context and perceptual asymmetry effects on the mismatch negativity (MMNm) to speech sounds: an MEG study

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Abstract

The mismatch negativity (MMN) of the auditory ERP/ERF has been shown to be sensitive to both phonetic and phonological contrasts. However, potential asymmetry effects and effects of the immediate phonetic contexts on this neural sensitivity are understudied phenomena.

Using magnetoencephalography (MEG), we attempted to address this lacuna by investigating native Danish listeners' MMNm to the phonological contrast between the consonants /t/ and /d/ in two different phonetic contexts in Danish: one word-initial, preserving the contrast's phonemic status, and another word-final, neutralizing it.

We found no support for effects of the immediate phonetic context on the MMNm. However, we observed an asymmetry effect for the phonological contrast: Hearing [t] among [d]s elicited a significantly stronger MMNm than hearing [d] among [t]s. This asymmetry effect was mirrored in a behavioral oddball-detection task showing reduced sensitivity for hearing [d] among [t]s. We discuss both psychoacoustic aspects and phonological underspecification as potential explanations.

Keywords: mismatch negativity (MMN); MEG; perceptual asymmetry; underspecification; phoneme; allophone; phonetic context

Introduction

A cornerstone in human speech perception is the ability to discriminate between phonemic sound contrasts and to categorize allophonic sound contrasts as belonging to the same category, the former signaling a contrast in linguistic form (e.g. different words), the latter signaling variations of the same form (e.g. different variations of the same word). Infants adapt their categorical perception of speech sounds to the phoneme inventory of their native language during the first year of life (Kuhl, Williams, Lacerda, Stevens, & Lindblom, 1992), however, one's categorical perception of speech sounds is to some extent malleable well into adulthood when e.g. acquiring a foreign language (A. H. Nielsen, Horn, Sørensen, McGregor, & Wallentin, 2015).

This heightened sensitivity to certain sound contrasts over others that characterizes categorical speech perception has been correlated with a well-studied component of the auditory event-related potential (ERP/ERF), namely the mismatch negativity (MMN) and its magnetic counterpart (MMNm) (for reviews see Kujala, Tervaniemi, & Schröger, 2007; Näätänen, Paavilainen, Rinne, & Alho, 2007; Shtyrov & Pulvermüller, 2007). Native phonemic contrasts have been shown to elicit larger or earlier MMN responses than comparable non-native or non-phonemic ones (Chládková, Escudero, & Lipski, 2013; Dehaene-Lambertz, 1997; Dehaene-Lambertz, Dupoux, & Gout, 2000; Kazanina, Phillips, & Idsardi, 2006; Kirmse et al., 2007; Miglietta, Grimaldi, & Calabrese, 2013; Näätänen et al., 1997; Noordenbos, Segers, Serniclaes, & Verhoeven, 2013; Phillips et al., 2000; Sharma & Dorman, 2000; Winkler, Kujala, et al., 1999a; Winkler, Lehtokoski, et al., 1999b; Ylinen, Shestakova, Huotilainen, Alku, & Näätänen, 2006). The most widely adopted explanation for this increased MMN to familiar phonemic contrasts is that there exist

long-term memory traces for sounds specific to one's native language, mainly in the left superior temporal lobe (Alho et al., 1998; Dehaene-Lambertz, 2000; Koyama et al., 2000; Näätänen et al., 1997; Rinne et al., 1999; Shestakova et al., 2002; Shtyrov et al., 1998; Shtyrov, Kujala, Lyytinen, Ilmoniemi, & Näätänen, 2000), proposed to function in parallel with the short-term memory traces driving the more purely acoustic MMN (Näätänen, Gaillard, & Mäntysalo, 1978).

However, some phonemic contrasts may be neutralized in certain phonetic contexts of a given language, such as word-finally in e.g. German (Iverson, 2008; Vaux & Samuels, 2006) and Danish (Basbøll, 2005). How do such phonological processes influence the effect of the proposed long-term memory traces for speech sounds on the MMN? If these memory traces are sensitive to the phonemic contrasts of one's native language, are they also sensitive to neutralizations of such contrasts in certain phonetic contexts?

Within a different strand of research, but still related to allophonic and phonemic representations, Lahiri & Reetz (2002; 2010) have put forth a theoretical framework for a Featurally Underspecified Lexicon (FUL), building on the notion that the underspecification of certain phonological features leads to more efficient lexical processing. This is exemplified by the place of articulation feature [coronal], which they propose to be underspecified in e.g. English compared to [labial] or [velar]. Hence, /n/ assimilates to [m] when followed by a [+labial] sound, whereas /m/ does not assimilate or only rarely assimilates to [n] when followed by a [+coronal] sound; compare “*lea[m] bacon*” (instead of “*lea[n] bacon*”) with “*la[m]e duck*” (and not “*la[n]e duck*”) (examples are from Lahiri & Reetz, 2002; Scharinger, Bendixen, Trujillo-Barreto, & Obleser, 2012a). Using the MMN to probe predictions from the

FUL framework, several studies have found asymmetries in the MMN to English, German and Dutch stimuli in support of certain underspecified phonological features (Cornell, Lahiri, & Eulitz, 2011; 2013; Cummings, Madden, & Hefta, 2017; Diesch & Luce, 1997; Eulitz & Lahiri, 2004; Hestvik & Durvasula, 2016; Scharinger et al., 2012a; Scharinger, Lahiri, & Eulitz, 2010; Schluter, Politzer-Ahles, & Almeida, 2016; Walter & Hacquard, 2004). However, Scharinger et al. (2011) reported non-supportive findings, Tavabi et al. (2009) only found partially supportive effects, and Bonte et al. (2005) found evidence of a phonotactic effect rather than of underspecification.

In this context, Danish phonology offers an interesting case for investigating potential underspecification effects and phonetic context effects on the MMNm response to native speech sounds. In Danish, plosives differ phonemically in place of articulation [labial, coronal, velar] and in degree of aspiration [+/-spread glottis] (Basbøll, 2005). Hence, the alveolar plosives /t/ and /d/ contrast between aspirated [+spread] and voiceless, unaspirated [-spread]¹, respectively. However, aspiration of the plosives is weakened, and thus voice-onset-time (VOT) is reduced to ~0-10 ms in several phonetic contexts in Danish (mainly word- and syllable-finally) whereby the contrasts between the aspirated /p t k/ and the voiceless, unaspirated /b d g/ are neutralized (Basbøll, 2005). To those unfamiliar with Danish phonology, referring to /b d g/ as voiceless and unaspirated may seem somewhat counterintuitive, but this is customary for the Danish plosive contrasts and corresponds with the phonetic reality (Basbøll, 2005; Grønnum, 2005).

¹ Aspiration for the alveolar plosive is realized as affrication in Danish, hence the phonetic realizations of the /t d/ contrast are more precisely denoted as affricated [t^s] vs. voiceless, unaffricated [ɖ] (all other phonetic transcriptions in this paper are broad transcriptions, and we will thus refer to the contrast simply as between [t] and [d]).

This means that [ta] and [da] form different words in Danish (meaning “take” and “then”, respectively) whereas [at] and [ad] are different realizations of the same word /at/ (meaning “that” in Danish). Both [at] and [ad] occur in casual Danish speech where [ad] is the, by far, most common realization, and [at] mainly appears in emphatic or hesitant contexts (e.g. before longer pauses, see Discussion for more details on their relative frequencies) (Basbøll, 2005).

To the best of our knowledge, the potential underspecification of [spread glottis] has not been investigated within the FUL framework. But we may hypothesize that [spread] could be underspecified (at least in Danish), since, as already stated, the neutralization pattern holds for all plosive contrasts in Danish, and thus, hearing [b], [d] and [g] syllable-finally in Danish does not mismatch with a possible /p/, /t/ and /k/, respectively, in the lexical representation (so-called *no-mismatch* in FUL), whereas hearing [p], [t] and [k] syllable-finally does mismatch with a possible /b/, /d/ and /g/ (so-called *mismatch* in FUL). FUL generally predicts that a given feature is underspecified regardless of phonetic context because the matching process happens at the lexical representational level (Lahiri & Reetz, 2010). We therefore hypothesized that hearing [t] as a deviant against [d] as a standard would elicit a stronger MMNm than hearing [d] as a deviant against [t] as a standard. This would be so because the predicted underspecified [spread] feature of the standard in the latter leads to a less specific and less precise representation of the standards against which the [d] as deviant only causes a minor mismatch, if any.

For the potential effect of the phonetic context on the MMNm to the phonological contrasts between /t/ and /d/, we hypothesized that if the long-term memory traces are sensitive to the neutralization of such contrasts as dictated by the phonetic context,

then we would see a stronger MMNm to the phonological contrast between /t/ and /d/ when presented word-initially in [ta] and [da] than when presented word-finally in [at] and [ad].

Finally, in order to further substantiate our neurobiological investigations, we conducted a second experiment testing a different (slightly overlapping) group of native Danish listeners on their behavioral discrimination sensitivity to the two stops in the two phonetic contexts, using a behavioral oddball design similar to that used by Scharinger et al. (2012a).

Methods

Experiment 1 (MEG): MMNm responses

Participants

Eighteen volunteers (nine women) participated in the study. One participant's data was discarded due to technical problems with the signals from the head-position-indicators (HPIs). The mean age of the remaining 17 participants (nine women) was 26.4 years (SD=4.8). All were native Danish listeners (all reporting substantial experience with 2-3 foreign languages, English being their primary second language, except for one participant whose primary L2 was Vietnamese). All reported having normal hearing, and none reported any history of neurological or psychiatric illness. Gender differences were not deemed important (Wallentin, 2009; Wallentin, Michaelsen, Rynne, & Nielsen, 2014).

The investigation was approved by the local ethics committee (De Videnskabsetiske Komitéer for Region Midtjylland) and thus in accordance with the Declaration of Helsinki. Written consent was obtained from each participant.

Stimuli

Auditory stimuli were centered around the Danish [t]-[d] contrast (aspirated versus unvoiced), which is phonemic syllable-initially, but allophonic syllable-finally (Basbøll, 2005). The target stimuli were four Danish syllables: [ta] (running speech realization of ‘take’), [da] (meaning ‘then’), and [at] and [ad] (both are realizations of the complementizer ‘that’ or the infinitive marker ‘to’). Relevant syllables were recorded by a male native Danish speaker (the first author), and the stimuli were then created by cross-splicing the sounds so that the same vowel [a] was used for all syllables, and the same [t] and [d] were each used for the two relevant syllables ([ta] and [at], and [da] and [ad], respectively, figure 1B), a process similar to that used by Shtyrov et al. (2002; 2005).

The vowel [a] used in all four stimuli was 95 ms long; [t] used in both [ta] and [at] was 74 ms long; and [d] used in both [da] and [ad] was 24 ms long (figure 1B). The total durations of the sounds were thus 169 ms for [ta] and [at], and 119 ms for [da] and [ad]. Since vowel duration is phonemic in Danish (Basbøll, 2005; Grønnum, 2005), the vowels in [da] and [ad] were not prolonged in order to match the total durations of [ta] and [at]. The initial and final 5 ms of each sound were used for fade-in and fade-out. The stimuli were finally validated by two native Danish listeners, naïve to the design of the experiment.

Analysis of the sounds prior to editing was done using Praat (Boersma & Weenink, 2013). All recording and editing was done using Audacity (<http://audacity.sourceforge.net/>).

Figure 1. (A) The experimental design was a 2 x 2 factorial design with Context ([a-] vs. [-a]) and Phoneme ([t] vs. [d]) as factors. **(B)** Spectrograms and amplitudes of the four target stimuli: [ta], [da], [at], and [ad]. The same [a]-vowel (95 ms duration) was used in all four stimuli. See the text for more details on the recording and design of the stimuli. **(C)** Examples of the multi-feature MMN paradigm for each of the four conditions. Standard sounds as every second sound, and deviant sounds as every other alternate sound. The deviants were presented in pseudo-random order so that the routine of four deviants was always repeated with a different order. The four target deviants (here D₁) are highlighted by the vertical box. The diagonal and truncated squares illustrate that the MMNm was calculated by subtracting the ERFs to the standards and deviants of the same sound (so-called identity difference waves). The colors refer to the colors of the ERF-plots in the subsequent figures.

Procedure

Participants were seated in a magnetically shielded and sound-attenuated room. They received the auditory stimuli via in-ear headphones (Etymotic ER•30), at a comfortable hearing level of approximately 70 dB. The presentation of the stimuli was controlled and executed by Presentation software (Neurobehavioral Systems,

Inc., Albany, CA, USA). The participants watched a set of silent short films while instructed not to attend to the auditory stimuli playing in the headphones.

This experiment consisted of four conditions, allowing for a direct comparison of the individual stimuli: two phonemic word-initial conditions with [ta] and [da] as both deviant and standard in reversed roles; and two allophonic word-final conditions with [at] and [ad] as both deviant and standard in reversed roles. The four conditions were all linguistic multi-feature paradigms, similar to that used by Pakarinen et al. (2007). Each condition also included three “filler” deviants: one differing in vowel: [te], [de], [et] and [ed]; one in syllable-structure: [at], [ad], [ta] and [da]; and one in intensity: [ta]+6 dB, [da]+6 dB, [at]+6 dB, and [ad]+6 dB. These were included in an attempt to develop a linguistic multi-feature paradigm in Danish that could also contain short multi-word semantic/syntactic/prosodic units. However, discussion of this matter is not within the scope of this paper and will be reported elsewhere.

The inclusion of all four conditions in the experimental design allowed for a direct comparison of each of the four target stimuli, [ta], [da], [at] and [ad], as both deviant and standard, thus controlling for exogenous effects of the stimuli (Kujala et al., 2007). And furthermore, it allowed for a 2 x 2 factorial design in which the potential effects of both context (syllable-initial vs. syllable-final) and direction of contrast ([d] among [t] vs. [t] among [d]) could be tested (figure 1A,C).

In a multi-feature MMN paradigm the standard stimulus (here: [ta], [da], [at], or [ad]) is presented as every second sound, and the four deviants (here consisting of consonant, vowel, syllable structure and intensity variations) are then presented in pseudo-random order as every other alternate sound (figure 1C). The pseudo-randomization ensured that all four deviants were presented before the routine was

repeated with a different order (similar to Näätänen, Pakarinen, Rinne, & Takegata, 2004; Pakarinen et al., 2009). Each deviant was presented a total of 120 times. The inter-stimulus-interval (ISI) was jittered between 180 ms and 480 ms (mean 330 ms). Each condition consisted of two blocks of approx. 4 min duration (i.e., 480 stimuli per block, totaling 960). The order of the 4 x 2 blocks was counter-balanced across participants, and identical blocks were never presented back to back. Participants were given a small break between each of the 8 blocks, leading to a total duration of the experiment of approx. 40 min.

Recording and preprocessing of MEG data

All MEG data were collected at the MEG Unit, MINDLab Core Experimental Facility, Aarhus University, using an Elekta Neuromag TRIUX MEG system with 204 planar gradiometers and 102 magnetometers. The data were sampled at 1000 Hz (0.1-330 Hz). Each participant's head position in the MEG system was continuously recorded using five head coils. Bipolar recordings of vertical and horizontal eye movements were obtained using surface electrodes placed above and below the left eye and at the outer canthi of both eyes, respectively.

Data were pre-processed using the temporal extension of the signal source separation (tSSS) technique (Taulu & Simola, 2006; Taulu, Kajola, & Simola, 2004) using Elekta's MaxFilter software (Version 2.2.15). This included removing head-externally generated electromagnetic sources, and compensating for head movements using continuously recorded head position indicators (cHPI). Next, data were band-pass filtered at 0.8-40 Hz using MNE-Python (Gramfort et al., 2013; 2014), and eye-blinks were removed using independent component analysis (ica) and the *find_bads_eog* detection algorithm in MNE-Python where detection of eye blinks is based on a

combination of Pearson's correlations between vertical/horizontal EOG and the independent components of the data. The topographies of the identified eye blink components and the averaged epochs of these components around identified peaks in the EOG were subsequently visually inspected for any inconsistencies in the eye blink component detection, and we did not find any such.

All subsequent preprocessing steps were conducted using SPM8 (Wellcome Department of Cognitive Neurology, London, UK; see Litvak et al. (2011)). Data were epoched around deviance onset instead of stimulus onset in order to compare brain responses time-locked to the onsets of the target sounds [d] and [t] (see figure 3). Stimulus onset and deviance onsets differed for the two allophonic conditions ([ad] and [at]) relative to the two phonemic conditions ([da] and [ta]), thus epoching was shifted 95 ms (equal to the duration of [a]) later for the former two conditions. Time after deviance onset included in the epoching was 400 ms.

Baseline-correction was conducted using the pre-*stimulus* interval of 100 ms, and not the pre-*deviance* interval of 100 ms, which would otherwise have included the responses to the initial [a]-sound in the allophonic condition (see figure 3). Further artifact rejection was conducted using first thresholding and then robust averaging (Litvak et al., 2011; Wager, Keller, Lacey, & Jonides, 2005). Thresholding was done using peak-to-peak thresholds of 8 pT for magnetometers; 200 pT/m for planar gradiometers; and 300 μ V for EOG. The 300 μ V threshold for the EOG channels is a common level for the Neuromag TRIUX MEG system and does not compare well to levels used with EEG/EOG data recorded using an EEG-only amplifier. Because robust averaging may induce high frequency artifacts in the data, the epochs were after averaging again low-pass filtered at 40 Hz and baseline-corrected (again with

reference to the pre-stimulus interval of -100 ms to stimulus onset). Mean number trials passed through to averaging after applying the above-mentioned thresholds was for the four standard stimuli 433 trials (SD=1.9 across the four standards, and SD=52.3 across participants) out of 480 standard trials per condition; and for the four times four deviant stimuli, 108 trials (SD=0.8 across the 16 deviants, and SD=12.9 across participants) out of 120 deviant trials were passed through to averaging; for both standards and deviants equivalent to ~90% of the total number of trials.

We computed the relevant difference waves by subtracting each participant's ERF to the standard version of any given stimulus (e.g. [ta]) from their ERF to the deviant version of that very same stimulus (e.g. [ta]), thus contrasting participants' neural responses to acoustically identical stimuli. The four difference waves for each participant were then finally cropped so that only the epoched time windows from deviance onset to 400 ms after deviance onset (thus leaving out the baseline) were passed on to the subsequent statistical analyses.

Statistical analyses

For statistical analyses of the MEG data, we focused on the magnetometer data. In order to identify significant differences within and between the four conditions, we analyzed the difference waves from the four conditions at the sensor-level across temporal and spatial dimensions. All statistical analyses were conducted using SPM12b (v5642). The resulting *F*-maps from the statistical tests were for each test visually compared to the full channel overlays of the group-averaged ERFs to the relevant standard and deviant sound. This was done in order to ensure that the effects identified by the statistical tests corresponded to the typical topographical characterizations of the MMNm in magnetometers, viz. a bipolar anterior-posterior

field pattern over either hemisphere consistent with an inferred underlying dipole locus in or in close vicinity of the auditory cortex in the superior temporal gyrus (Alho et al., 1996; Hari et al., 1984; Phillips et al., 2000; Shtyrov et al., 2012; Tiitinen, May, Reinikainen, & Näätänen, 1994).

This entailed first modeling each of the four contrasts individually using two-tailed one-sample t-tests in the GLM framework of SPM in order to test whether the four conditions elicited detectable MMNms. Next, in order to test for main effects of context and perceptual asymmetry, we modeled each of the four averaged conditions in a flexible factorial design with the two factors of interest Context (2 levels: phonemic and allophonic), and Phoneme (2 levels: [t], [d]). Furthermore, a Subject (17 levels) factor was included in order to model the subject-specific variance inherent to within-subjects designs.

To this end, we first re-arranged the data into a suitable format. We created three-dimensional volumes for each of the four ERF difference waves (these volumes included all channels and the full time span of the ERF post deviance onset, i.e., from 0 to 400 ms). We did this by first projecting each participant's preprocessed and averaged data onto a 2D image (64 x 64 pixels) of the sensor-array for each sample in the epoch (i.e., time occupying the third dimension). This resulted in a 3D-volume (space [left-right] x space [front-back] x time) for each participant for each difference wave for each condition (two phonemic and two allophonic). For an informative illustration of this process of re-arranging the data, see the lower panel of Fig. 3 in Shtyrov et al. (Shtyrov et al., 2012:2609). Finally, all four of these 3D-volumes were smoothed with a kernel of 20 mm x 20 mm x 20 ms FWHM (full-width-half-max).

In each voxel of each participant's four 3D-volumes we modeled the response

difference by our contrast of interest using either one-sample t-tests (MMNms in the individual conditions) or our flexible factorial design. This resulted in sensor space-by-time statistical parametric maps (SPMs) of the relevant contrasts (Kilner & Friston, 2010; Litvak et al., 2011).

For the tests of MMNms in the individual conditions, we fitted a GLM to the data in each voxel of the 3D volumes of each participant's four difference waves separately. And for the flexible factorial design, we fitted a general linear model (GLM) that included all condition and subject effects to the data in each voxel of each participant's four difference-wave-volumes. In the resulting SPMs, clusters of suprathreshold voxels (at $p_{\text{UNC}} < 0.001$, uncorrected) were family-wise-error corrected at $p_{\text{FWE}} < 0.05$ for spatial extent using random field theory (Kilner & Friston, 2010; Worsley & Friston, 1995). The actual extent threshold for the FWE-correction at cluster-level was queried using the CorrClusTh script, provided by Thomas Nichols (<http://www-personal.umich.edu/~nichols/JG5/CorrClusTh.m>).

The more classical approach of selecting an a priori spatial and/or temporal region of interest for analysis runs the risk of inflating the probability of false-positives (type II errors) (Kilner, 2013). Mass univariate statistics (such as GLM analyses), on the other hand, allow for more unbiased statistical analyses of the contrasts of interest across both spatial and temporal dimensions when combined with the appropriate corrections for multiple comparisons, e.g. using random field theory (Crowley, Wu, McCreary, Miller, & Mayes, 2012; Kilner, 2013; Kriegeskorte, Simmons, Bellgowan, & Baker, 2009; Lage-Castellanos, Martínez-Montes, Hernández-Cabrera, & Galán, 2010).

Experiment 2 (behavioral): Oddball detection

Participants

Eight participants (three women) volunteered to take part in the study. Two of these (two women) had also participated in Experiment 1. All reported Danish as their native language, and all reported having normal hearing.

Stimuli

The stimuli were exactly the same syllables as used in Experiment 1.

Procedure

Participants were seated in a quiet office temporarily employed for testing purposes. They received the auditory stimuli via in-ear headphones at a hearing level of approximately 70 dB and were asked to focus on a fixation cross at the center of the screen during the experimental conditions. The stimuli were presented using Presentation software (Neurobehavioral Systems, Inc., Albany, CA, USA) on a Windows partition of a MacBook Pro 15" laptop.

The experiment consisted of four multi-feature oddball conditions, exactly as in Experiment 1: one condition with [ta] as the standard, [da] as the target deviant, and [te], [at] and [ta]+6 dB as filler deviants; one with [da] as the standard, [ta] as the target deviant, and the relevant filler deviants; one with [at] as the standard, [ad] as the target deviant, and the relevant filler deviants; and one with [ad] as the standard, [at] as the target deviant, and the relevant filler deviants. The multi-feature oddball paradigms were the same as those used in Experiment 1, except that the number of presentations of each deviant was 20 for each condition, and the ISI was varied between 600 and 900 ms in order to allow participants more time to respond.

Participants were instructed to make speedy responses using the space bar whenever they detected a target deviant.

The order of the four conditions was randomized across participants. Each condition was preceded by an exposure to the target deviant and a practice session. The exposure consisted of three repetitions of the target deviant with an ISI of 750 ms. Participants were instructed that the sound playing in their ears during the exposure would be their target sound in that condition. We referred to the syllables as ‘sounds’ in order not to confound the experiment by the use of the concept of a ‘word’. (The reader is reminded that [ta] and [da] represent two different words in Danish, whereas [at] and [ad] are different phonetic realizations of the same word.) The practice session consisted of one or two practice runs of the experiment with three target deviant presentations (in a total of 24 trials). If participants achieved two or more hits (out of three possible) and less than five false alarms, they were given the option of proceeding to the real experiment or trying one more practice session. One participant received the instructions an extra time after twice failing to meet the criteria during the first condition.

Statistical analyses

For the statistical analyses, we considered responses between 210-1110 ms. This interval was based on the distribution of responses by identifying the longest gap between response times in the 0-300 ms time window, which was between 207 and 285 ms (see Supplementary materials, figure S1). Responses given during the first 210 ms of the following sound, which were thus treated as belonging to the preceding trial, accounted for 4.3% of the total amount of responses, and these were mainly (~89%) given to trials with an ISI below the mean ISI of 750 ms. This

correction was particularly important in order not to bias the results in favor of the [t]-oddballs (since these sounds were longer than the [d]-oddballs, and would thus have given participants, on average, 50 ms longer response times).

We used participants' discrimination sensitivity as indexed by their d-prime (d') values as our dependent measure. We calculated participants' d' values by subtracting their standardized (z-value) false alarm rate from the z-value of their hit rate (Macmillan & Creelman, 2005). False alarm rates were based on all non-target stimuli, i.e., both standards and filler deviants of the multi-feature MMN paradigm. Because z-values approach infinity for response rates of 0% and 100% these were corrected by $+1/(2*N)$ and $-1/(2*N)$, respectively (Macmillan & Creelman, 2005), where N is the number of observations that the given rate was calculated on, hence 140 for the false alarm rate (80 standards + 60 filler deviants) and 20 for the hit rate (20 target deviants) for each condition.

In order to test for both main and interaction effects of our factorial design, we conducted a repeated measures ANOVA with Context and Phoneme as within-subjects factors (using the `repanova.m` function in MATLAB, <http://www.mrc-cbu.cam.ac.uk/people/rik.henson/personal/analysis/>).

Results

Experiment 1 (MEG): MMNm responses

The participants' grand-averaged ERFs to both the standard and deviant versions of the four target deviants ([da], [ta], [ad], and [at]) are presented as full channel overviews in the supplementary material (figure S2). In figure 2, grand-averaged ERFs for the standards and deviants of all four conditions are presented together.

These ERFs are averages of eight left-posterior sensors (top row) and eight right-posterior sensors (middle row). The selection of sensors was based on the largest M100-fields (defined as averages of 75-125 ms after sound onset) to both standards and target deviants in all four conditions (see Kazanina et al., 2006 for a similar selection criterion). For each condition, the topographies of the difference waves are shown for averaged intervals of 100-170 ms, 170-240 ms, 240-310 ms, and 310-380 ms (bottom row) in order to further substantiate the differences observed in the standard and deviant ERFs with typical MMNm topographies wherever relevant. The statistical analyses of the MMNm in each of the four condition are presented in figure 3A-D (for full reporting, thresholds are set to $p_{\text{UNC}} < 0.001$) together with the results of the factorial analysis in figure 3E (see the supplementary material, tables S1 and S2, for further details on the SPM statistics, as well as figure S3 for statistical maps with $p_{\text{FWE}} < 0.05$ thresholds).

Figure 2. Grand-averaged ERFs to the standard and deviant sounds of all four conditions (**A:** [da]; **B:** [ta]; **C:** [ad]; **D:** [at]). Averages of eight peak sensors at the left posterior site (**top row**) and eight peak sensors at the right posterior site (**middle row**). These sensors were selected on the basis of the largest M100-fields (averaged

from 75-125 ms after sound onset) across standards and target deviants in all four conditions. The amplitudes of the relevant stimulus for each condition illustrate the epoching of the ERFs around deviance onset. **Bottom row:** For each condition, topographies of the relevant difference waves are shown as averages of four intervals: 100-170 ms after deviance onset, 170-240 ms, 240-310 ms, and 310-380 ms, where only the last interval is outside the typical temporal range for an MMN (i.e., 100-300 ms after deviance onset). A solid purple box around the time interval indicates an MMNm topography overlapping with the statistical analyses (see figure 3); a truncated purple box indicates an MMNm topography that passed the uncorrected, but not the FWE-corrected, statistical threshold; a dotted purple box indicates a weak MMNm topography that did not pass any statistical thresholds.

[d] (phonemic condition)

The phonemic condition with [da] as the target deviant (presented against [ta] as the standards) elicited MMNm-like bipolar field pattern differences in the 170-240 ms range (figure 2A). This was somewhat later than for [ta] and [at] as target deviants (see “[t] (phonemic condition)” and “[t] (allophonic condition)” below), where the MMNm appeared in the 100-170 ms range. A cluster over the left posterior (LP) lateral sensors with a temporal extent of 179-216 ms almost passed the $p_{\text{FWE}} < 0.05$ threshold for extent (LP: $k=6050$, $p_{\text{FWE}}=0.057$, where k is the number of voxels in the cluster and p_{FWE} refers to the cluster-statistics, see figure 3A and table S1).

Furthermore, a late effect was elicited in the SPM analyses around 290-365 ms, which revealed significant clusters over left posterior (LP) and right posterior (RP) lateral sensors (LP: $k=34610$, $p_{\text{FWE}} < 0.001$; and RP: $k=15745$, $p_{\text{FWE}}=0.003$, figure 3A and table S1). This effect overlapped with a strong field pattern complex in the 310-380 ms range. However, this latency was outside the typical MMN-range (100-300 ms), and yet the scalp topography (of which both left and right posterior fields overlapped with the SPMs) was somewhat similar to the MMNm in the [ta] and [at] conditions in

the 100-170 ms range (figure 2B,D), as well as the MMNm-like effect that nearly passed the $p_{\text{FWE}} < 0.05$ threshold for extent in this very same condition in the 170-240 ms range ($k=6050$, $p_{\text{FWE}}=0.057$, figure 3A and table S1 (in grey)). The butterfly-plot of the difference wave in all the channels in figure 3A, upper right quadrant, confirms two distinct peaks: one in the 170-240 ms range, and another one peaking in the 310-380 ms range.

[t] (phonemic condition)

The phonemic condition with [ta] as the target deviant (presented against [da] as the standard) elicited significant clusters over left anterior (LA), left posterior (LP), and right posterior (RP) lateral sensors with a temporal extent of 97-164 ms (LA: $k=7973$, $p_{\text{FWE}}=0.037$; LP: $k=26793$, $p_{\text{FWE}} < 0.001$; and RP: $k=7581$, $p_{\text{FWE}}=0.041$; figure 3B and table S1), all overlapping with the clear MMNm-like bipolar field pattern differences over both hemispheres in the 100-170 ms range after deviance onset (figure 2B).

[d] (allophonic condition)

The allophonic condition with [ad] as the target deviant (presented against [at] as the standard) did not elicit any clusters that survived the $p_{\text{FWE}} < 0.05$ threshold for extent (figure 3C). At the $p_{\text{UNC}} < 0.001$ threshold for height, there were traces of effects over right anterior and right posterior lateral sensors, and the butterfly-plot of the difference wave in all the channels (figure 3C, upper right quadrant) shows vague indications of a peak in the 100-170 ms range together with only a very weak MMNm-like topography in the 100-170 ms range (figure 2C), and as already stated, none of these weak indications were mirrored in statistically significant effects from other conditions.

[t] (allophonic condition)

The allophonic condition with [at] as the target deviant (presented against [ad] as the standard) revealed significant clusters over left posterior (LP) and right posterior (RP) lateral sensors with a temporal extent of 106-167 ms (LP: $k=18781$, $p_{FWE}=0.002$; and RP: $k=19796$, $p_{FWE}=0.001$; figure 3D and table S1), both of which overlapped with the two posterior field patterns of the clear MMNm-like bipolar field pattern differences over both hemispheres in the 100-170 ms range after deviance onset (figure 2D).

Figure 3. Statistical parametric maps (SPMs) of the difference waves from each of the four conditions (A: [da]; B: [ta]; C: [ad]; D: [at]), as well as the only main effect from the flexible factorial analysis showing significant effects (E: main effect of Phoneme). See the text for more details on the computation of the SPMs and the designs of the contrasts for the individual conditions and the flexible factorial analysis. The SPMs are thresholded at $p_{UNC} < 0.001$ (for height) for full reporting. See Supplementary material (Figure S6) for the same SPMs thresholded at $p_{FWE} < 0.05$ (for extent). Warmer colors mean higher F-values. For each four quadrants, the **lower left**

quadrant shows the max F-values of the SPM for the 2D sensor space projected onto a 64 x 64 pixel array, irrespective of time (0-400 ms). The **upper left quadrant** shows the max F-values of the SPM for the left-right axis of the 2D sensor array with time (0-400 ms) on the y-axis, hence the front-back axis is collapsed. The **lower right quadrant** shows the max F-values of the SPM for the front-back axis of the 2D sensor array with time (0-400 ms) on the x-axis, hence the left-right axis is collapsed. The **upper right quadrant** shows the difference wave ERFs for all magnetometers with the ERF from the peak sensor of the most MMNm-typical effect plotted on top in the condition-relevant color. See caption for figure 2 for details on the criteria for the purple boxes.

Factorial design with Context and Phoneme

The main effect of Context did not reveal any clusters surviving the FWE-correction at $p_{\text{FWE}} < 0.05$, nor any noteworthy effects at $p_{\text{UNC}} < 0.001$. Hence, we could not find support for the Context hypothesis that the [da] and [ta] contrasts should elicit systematically stronger MMNm responses compared to the [ad] and [at] contrasts (table S2).

The main effect of Phoneme, on the other hand, revealed two clusters of consistent differences in the participants' neural responses to the [ta] and [at] contrasts compared to the [da] and [ad] contrasts. These clusters were located over the left anterior (LA) and left posterior (LP) lateral sensors (LA: $k=18410$, $p_{\text{FWE}}=0.004$; and LP: $k=25918$, $p_{\text{FWE}}=0.001$; figure 3E and table S2), and they overlapped with the left posterior and anterior field patterns in both [ta] and [at] contrasts (figure 2B,D).

There was no significant Context*Phoneme interaction effect.

Experiment 2 (behavioral): Oddball detection

Results of participants' discrimination sensitivities from the four conditions are

presented in figure 4.

Figure 4. d-prime (d') values from the behavioral follow-up experiment (behavioral MMN oddball task) with eight native Danish listeners. A repeated measures ANOVA with both Context and Phoneme as factors revealed only a significant main effect of Phoneme and (no interaction effects). This indicates that the participants were generally better at discriminating [t] as a deviant from [d] as a standard than at discriminating [d] as a deviant from [t] as a standard. Due to the repeated measures design, errorbars show the standard errors of the mean with across-participant differences removed (see Cousineau, 2005; Morey, 2008 for more details).

Main effects and interactions

There was no main effect of Context on participants' discrimination sensitivity as indexed by their d' values ($F(1,7)=0.23$, $p=0.64$, $\eta^2=0.01$). There was, however, a main effect of Phoneme on participants' discrimination sensitivity ($F(1,7)=19.73$, $p=0.003$, $\eta^2=0.29$), with participants' d' values, on average, being 0.48 ($SD=0.31$)

larger for the [t]-targets than for the [d]-targets. Participants' were thus significantly more sensitive in their discrimination of the [t]-targets than of the [d]-targets. There was no significant Context*Phoneme interaction effect ($F(1,7)=0.01$, $p=0.93$, $\eta^2=0.00$).

The direction and significance of these results did not change if we discarded the responses from 0-210 instead of counting them as belonging to the preceding trial; this only made the main effect of Phoneme stronger.

Discussion

Main findings

In the present study we set out to investigate the potential effects of phonetic context and of asymmetries in speech perception on the human brain's passive auditory processing of language sounds. We hypothesized that a phonetic context (word-final) neutralizing the phonological contrast between /t/ and /d/ in Danish would lead to a diminished MMNm compared to a non-neutralizing context (word-initial). We did not find any support for this hypothesis in that there was no consistent effect of hearing the contrast between /t/ and /d/ either preceded or followed by the vowel /a/, respectively.

We furthermore hypothesized that [spread] may be underspecified as phonological feature of plosives in Danish, and if so, we would see an asymmetry in the MMNm to /t/ and /d/ in native Danish listeners. This hypothesis was, indeed, supported by our results which show that hearing [t] as a deviant with [d] as a standard elicited a consistently stronger MMNm than the opposite conditions (i.e., [d] as a deviant with [t] as a standard). And this pattern of asymmetric neuronal sensitivity was confirmed

by a behavioral study with a group of native Danish listeners (n=8) who showed significantly higher d-prime (d') values to [t] as target oddball over [d] as target oddball.

Perceptual asymmetry and the MMN

A few other linguistic MMN studies have used stimuli similar to ours when investigating phonological effects in other languages than Danish; some directly address asymmetry and underspecification hypotheses and others only report them as bi-products of their design. Phillips et al. (2000) probed phoneme categories of native English listeners with a many-to-one design for the standards and showed a reliable MMNm to /da/ when contrasted with /ta/, but not to /ta/ when contrasted with /da/. Hence, they report indirect support for what could seem like an asymmetry in the opposite direction of what we find in Danish, however, this asymmetry effect was not explicitly tested by the authors. This was addressed by Hestvik and Durvasula (2016) who recently replicated Phillips et al.'s (2000) asymmetry findings with similar stimuli by testing the asymmetry directly, and they extended this finding by showing that the asymmetry effect disappeared when the paradigm was modified to probe phonetic memory traces of /d/ and /t/ rather than phonemic ones. Finally, Kazanina et al. (2006) used a similar experimental design to Phillips et al. (2000) when investigating /d/ and /t/ in native Russian and native Korean listeners. The contrast is only phonemic in Russian (since Korean stops contrast between plain, tense and aspirated), and only the native Russian listeners showed an MMNm to the contrast. Unfortunately, the authors collapsed the /ta/-as-deviant and /da/-as-deviant conditions without commenting on the presence or absence of any asymmetries.

In the more general MMN literature, there is no clear evidence suggesting inherent

asymmetries in the MMN as an effect of the direction of a given contrast, rather the opposite, namely that the MMN is sensitive to the size of the change, but not the direction (Jaramillo, Paavilainen, & Näätänen, 2000; Kaukoranta, Sams, Hari, Hämäläinen, & Näätänen, 1989; Näätänen, 1992; Näätänen et al., 2007; Rinne, Särkkä, Degerman, Schröger, & Alho, 2006; Ritter et al., 1992). And as such, only a few studies have reported smaller MMN amplitudes to tone deviants of shorter duration than comparable tone deviants of longer duration (Catts et al., 1995; Jaramillo, Alku, & Paavilainen, 1999; Näätänen, Paavilainen, & Reinikainen, 1989). Finally, Ylinen et al. (2006), reported larger MMN amplitudes to a prolonged vowel deviant than to a shortened vowel deviant, but only when the stimuli were presented within a word, not in isolation. However, both tonal and vowel stimuli are acoustically radically different from the [t]-[d] contrast of the present study, which is perhaps most similar to the white noise burst contrasts used by Jaramillo et al. (2000) where no clear asymmetry effects were observed.

There is, however, one study that has reported very clear asymmetry effects on the MMN to more low-level auditory processing. With inspiration from Cusack & Carlyon's (2003) seminal work on auditory pop-out effects, Bishop et al. (2005) showed a stronger MMN to frequency-modulated deviant tones among unmodulated standard tones than to unmodulated deviant tones among frequency-modulated standard tones (see also Timm, Weise, Grimm, & Schröger, 2011 for somewhat similar results). These findings speak to the potential involvement of low-level feature detectors in perceptual asymmetry, and we therefore acknowledge that our observed asymmetry effect could, indeed, have been caused by differences in more low-level psychoacoustic processing with more broad-spectrum noise and longer duration of [t] than of [d], rather than differences in the participants' phonological or lexical

representations of the speech sounds. Further studies using closely matched non-linguistic stimuli acoustically similar to those used in this study would be needed in order to properly tease apart psychoacoustic and psycholinguistic explanations of our observed effects.

However, since the majority of the MMN literature on non-linguistic stimuli gives inconclusive evidence for perceptual asymmetries inherent to the more general MMN, we therefore propose that the explanations put forth by the proponents of the FUL (Lahiri & Reetz, 2002; 2010) fit our findings and the asymmetries in the linguistic MMN literature the best. In this relation, a number of studies have found support for [coronal] as an underspecified place of articulation feature in German for both plosives and vowels (Cornell et al., 2011; Eulitz & Lahiri, 2004; Scharinger et al., 2010; 2012a), and in English for plosives and fricatives (Cummings et al., 2017; Schluter et al., 2016), and, as already mentioned, for [voice] as an underspecified laryngeal feature in English (Hestvik & Durvasula, 2016; Phillips et al., 2000). To these findings, our present study adds an investigation of the laryngeal feature [spread] for a plosive contrast in Danish, showing an opposite pattern to that for English which seems to be in line with differences in markedness and thus specification of the [spread] feature in Danish and English. We have thus found tentative support for an asymmetric perception of aspirated and unvoiced plosives in native Danish listeners, and we take this as preliminary and relatively tentative support for [spread] as an underspecified phonological feature in Danish.

Furthermore, since [spread] as a distinctive phonological feature also applies to the contrasts between /b-p/ and /g-k/ in Danish (which also both show neutralization word-finally), we would predict on the basis of our findings that we should see

similarly stronger MMNm to [p] than to [b] and to [k] than to [g]. And given the amount of research into the specification of phonological representations in dyslexia (Bogliotti, Serniclaes, Messaoud-Galusi, & Sprenger-Charolles, 2008; Elbro, 1996; Noordenbos, Segers, Serniclaes, Mitterer, & Verhoeven, 2012; Serniclaes, Heghe, Mousty, Carré, & Sprenger-Charolles, 2004), with both underspecification and overspecification put forth as potential explanations of the phonological deficit (Noordenbos, 2013; Noordenbos & Serniclaes, 2015), future studies expanding on the present findings in terms of more stimuli and employing a many-to-one paradigm (as used by Hestvik & Durvasula, 2016; Phillips et al., 2000) may allow us to better probe and understand the neurophysiology of this debilitating aspect of dyslexia.

No support for a context effect

Regarding the lack of support for an effect of phonetic context on the MMNm in the present study, one should always be careful to interpret such null results without further substantiation of said null effect, and we will therefore stress that this should not be interpreted as support for no effect of phonetic context on the MMNm. The context of the auditory scene has previously been shown by Sussman (2007; 2013) and Sussman et al. (2005; 1998; 2002) to affect MMN amplitudes to pure tones. But given that these were non-linguistic effects, they may not be directly comparable to our study.

The effect of English as a second language could potentially influence our results, given that the [t]-[d] contrast is not neutralized syllable-finally in English (Giegerich, 1992). All subjects reported having English as their second language (except one with Vietnamese as L2, but English as L3) including at least 10 years of teaching, and self-rated proficiency scores between 7-10 on a 1-10 scale. There are, however, important

differences between the English phonological contrast and the Danish allophonic contrast. The English contrast is partly realized syllable-finally in the vowel/consonant duration ratio (Port & Dalby, 1982). It has shorter aspiration durations and longer closure time than in Danish (Hutters, 1985), and is affected by other factors not directly realized in the voiced-aspirated segment itself (Lisker, 1977; 1986). And hence, the realizations of the two contrasts are so different that the lack of syllable-final neutralization for this contrast in English seems unlikely to have affected the phonemic status of the contrasts in our participants' L1.

Potential effects of duration and frequency

The relatively late effect in the [da]-condition around 300-400 ms seems best explained as a duration MMNm. The durations of [da]/[ad] and [ta]/[at] were 119 ms and 169 ms, respectively. It is therefore plausible that the difference in overall duration of the sounds might have elicited a subsequent MMNm of its own, timelocked to the later deviance onset (at 119 ms). The temporal extent of the late MMNm in the [da]-condition was 290-365 ms relative to sound onset, which would be equivalent to 171-246 ms relative to the duration deviance onset, namely the sound offset of [da], which is within the typical temporal range of the MMN. However, we would expect such a duration MMNm to be present in the other three conditions as well (since the standard and target deviant were always of different durations). In fact, the topographies of the difference waves in figure 2 show MMNm-like topographical patterns in all four conditions in the late window (310-380 ms), even though only the [da]-condition showed up in the statistical analyses. Unfortunately, this experiment was not designed to tease apart potential asymmetries in the MMNm to different durations of linguistic stimuli in Danish and differently tailored experimental designs

would be needed in order to fully explore this observation.

Finally, Shtyrov et al. (2011) have shown that high-frequency words elicit a larger MMN-like response than do comparable low-frequency words. Differences in frequencies between our stimuli are, however, unlikely to have driven the effects we see in the present study. *at* (i.e., [ad] and [at]) is the third most frequent word in the largest Danish written korpus, KorpusDK (www.ordnet.dk/korpusDK, including 56 million words), with ~1,527,000 occurrences. The most common written equivalents of [da] (*da*) and [ta] (*tage*, *tag*, and *ta'*) have ~134,000 and ~33,000 occurrences, respectively. [ta] is thus the most infrequent word of the three words we used as stimuli (i.e., *at*, *da*, and *ta'*), and we saw the strongest MMNm to the mono-morphemic word forms with [t] (i.e., [ta] and [at]), and if anything, a stronger MMNm to [da] than [ad].

Limitations

Given the intended multipurpose design of the paradigm, the present study faces a couple of limitations. First, in order to unequivocally probe phonological representations with MMN paradigms, which is important for the claims we make with respect to e.g. FUL, one should optimally employ a relevant version of the many-to-one paradigm introduced by Phillips et al. (2000) and also used by Kazanina et al. (2006) and Hestvik & Durvasula (2016). This entails using several allophones (differing systematically along a relevant dimension, e.g. VOT) within an individually-tested phonemic category as standards, as well as using a deviant that differs along the same dimension and with the same degree of acoustic difference from some of the standards as between some of the standards themselves. This paradigm has not been tested within a multifeature MMN paradigm where the use of

each deviant depends on its particular feature being kept constant in the other deviants (Näätänen et al., 2004). Whether this would be feasible in combination with deviant features such as intensity, vowel quality and syllable structure as used in this study remains an empirical question. But since the multifeature MMN paradigm used in this study had not been attested before, we opted for a version of the paradigm that mirrored the original multifeature MMN paradigm as closely as possible. Eulitz & Lahiri (2004) proposed using a multiple-token approach using e.g. three different tokens of the standard in order to “to simulate more natural speech perception conditions” (Eulitz & Lahiri, 2004) which has been used by several studies investigating underspecification (Bonte et al., 2005 four tokens; Cornell et al., 2011 six tokens; 2013 three tokens; Eulitz & Lahiri, 2004 three tokens; Scharinger et al., 2010 four tokens; 2011 ten tokens; Scharinger, Monahan, & Idsardi, 2012b ten tokens; 2016 ten tokens [same as 2012b]; Schluter et al., 2016 five tokens; Tavabi et al., 2009 four tokens). While such an approach is certainly interesting in terms of increasing the ecological validity of linguistic MMN paradigms, it is not entirely clear that the approach would ensure probing phonological representations unless the relevant acoustic dimension is controlled and manipulated along the lines of the already mentioned many-to-one paradigm introduced by Phillips et al. (2000). Otherwise, the multiple-token approach may rather be tapping into e.g. online talker-specific adaptations (Eisner & McQueen, 2006; Norris, McQueen, & Cutler, 2003). In broader terms, several previous MMN studies (e.g. Chládková et al., 2013; Dehaene-Lambertz, 1997; 2000; Näätänen et al., 1997; Winkler, Kujala, et al., 1999a; Ylinen et al., 2006) have been interpreted as probing phonological representations using single-token paradigms.

Nonetheless, we cannot rule out that the observed asymmetry in this study pertains to

an asymmetry of phonetic rather than phonological categories. In this light, it is relevant to consider recent extensions of the Natural Referent Vowel (NFR) framework (Polka & Bohn, 2003; 2010) which have attempted to include consonants as well (Bundgaard-Nielsen, Baker, Kroos, Harvey, & Best, 2015; Nam, 2014; Nam & Polka, 2016), suggesting that one member of a contrast serves as a perceptual anchor (or referent) to the other during language acquisition by virtue of that member's psychoacoustic saliency. For vowels, these referents are at the extremes of the vowel inventory, and for consonants, stops have tentatively been suggested as referents for fricatives due to their steeper attack time (Nam, 2014; Nam & Polka, 2016), and alveolar stops as referents for retroflex and dental stops (Bundgaard-Nielsen et al., 2015). It may thus be that there is a psycholinguistic relevance to low-level feature detectors potentially sensitive to broad-spectrum noise in terms of increased psychoacoustic saliency for aspirated over non-aspirated sounds. The NFR framework posits that such perceptual asymmetries are strongest in infants, but still persist into adulthood. Hence, to assess its applicability for the observed asymmetry in this study, further studies assessing the degree of the potential asymmetry in infants would be needed.

Furthermore, Phillips et al.'s (2000) posited that most that behavioral data from two-alternative-forced-choice (2AFC) tasks, in fact, support the presence of phonetic rather than phonological categories. However, their point pertains only to the use of 2AFC tasks (also known as identification tasks) as behavioral evidence, not the use of oddball tasks as the one used in the present experiment. Interestingly, Scharinger et al. (2012a) used both an identification task and an oddball task (similar to the one used in the present study) and only found asymmetry effects in the oddball task. The authors explained this discrepancy by the nature of the oddball task which allowed the

participants to build up a prediction of the forthcoming sounds, and this prediction was less precise for the standard carrying the underspecified feature, leading to an asymmetry in the ability to detect the oddballs, and thus tapping into phonological representations (Scharinger et al., 2012a).

Nonetheless, future research on underspecification in Danish would preferably employ the many-to-one paradigm in order to ensure probing phonological representations.

Finally, the support reported herein for underspecification of [spread] in Danish rests on our own preliminary hypothesis about this effect. There is no independent analysis available on [spread] as an underspecified feature more globally nor on Danish phonology within the FUL framework, which are thus advances that would be advantageous to pursue.

Conclusion

In the present study, we have shown a stronger MMNm to [t] when it was presented as an oddball among [d]s compared to when [d] was presented as an oddball among [t]s, a finding that was corroborated in a behavioral oddball task. At the same time, we did not find support for our hypothesis regarding effects of the phonetic context on the MMNm to language sounds.

We thus report on an asymmetry effect where the brain reacts differently to the *same* acoustic difference depending on the direction of presentation. Given the linguistic nature of the stimuli used in these experiments, we treat this asymmetry effect on the MMNm to /t/ and /d/ as tentative support for the notion of underspecification of the

laryngeal feature [spread] (i.e., aspiration) in Danish. And given the potential role of under- and overspecification in phonological deficits, such as dyslexia, we speculate that there may be a role for paradigms similar to the current one in further exploring these aspects of phonological deficits.

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Supplementary materials

Sound 1: “da.wav” – standard and deviant sound [da], phonemic condition

Sound 2: “ta.wav” – standard and deviant sound [ta], phonemic condition

Sound 3: “ad.wav” – standard and deviant sound [ad], allophonic condition

Sound 4: “at.wav” – standard and deviant sound [at], allophonic condition

Sound 5: “mmn_dev_da.wav” – excerpt of multifeature MMN paradigm with [da] as the target deviant

Sound 6: “mmn_dev_ta.wav” – excerpt of multifeature MMN paradigm with [ta] as the target deviant

Sound 7: “mmn_dev_ad.wav” – excerpt of multifeature MMN paradigm with [ad] as the target deviant

Sound 8: “mmn_dev_at.wav” – excerpt of multifeature MMN paradigm with [at] as the target deviant

Tab. S1

Contrast	Cluster-level			Peak-level				Coordinates		
	p_{FWE}	p_{UNC}	k	p_{FWE}	p_{UNC}	F	Z	x	y	ms
Phonemic [dæ]-[dæ]	< 0.001	< 0.001	34610	0.012	< 0.001	56.410	4.710	-40	-27	365
	0.003	0.002	15745	0.060	< 0.001	39.650	4.250	49	-30	323
				0.349	< 0.001	24.500	3.620	28	-25	290
	0.057	0.035	6050	0.279	< 0.001	26.370	3.720	-30	-22	216
				0.385	< 0.001	23.660	3.580	-45	-46	183
				0.447	< 0.001	22.370	3.510	-21	-22	179
Phonemic [tæ]-[tæ]	< 0.001	< 0.001	26793	0.108	< 0.001	33.380	4.030	-15	-52	122
	0.041	0.028	7581	0.151	< 0.001	30.540	3.910	45	-27	141
	0.037	0.025	7973	0.239	< 0.001	26.770	3.740	-23	45	132
				0.475	< 0.001	21.060	3.430	-40	40	97
				0.502	< 0.001	20.570	3.400	-21	32	164
Allophonic [æd]-[æd]				n.s.						
Allophonic [æt]-[æt]	0.001	0.001	19796	0.012	< 0.001	56.330	4.710	23	-22	167
				0.025	< 0.001	47.970	4.500	34	-22	106
	0.002	0.001	18781	0.097	< 0.001	35.030	4.090	-23	-25	106
				0.378	< 0.001	23.630	3.580	-23	-19	147

Table S1. Results of the SPMs of the individual conditions, i.e., testing the difference waves against 0. The x, y, z coordinates refer to the 3D SPM volumes visualized in Fig. 3 (and S3) where x and y express the lateral plane (left-right) and the frontal plane (front-back) of the 64 x 64 pixel array of the sensors, respectively, and z express the temporal dimension (0-400 ms).

Tab. S2

Contrast	Cluster-level			Peak-level				Coordinates x y ms
	p_{FWE}	p_{UNC}	k	p_{FWE}	p_{UNC}	F	Z	
Main effect of Context					<i>n.s.</i>			
Main effect of Phoneme	0.001	0.001	25918	0.005	< 0.001	31.460	4.760	-28 -54 121
				0.044	< 0.001	23.250	4.180	-19 -22 141
	0.004	0.003	18410	0.014	< 0.001	27.420	4.490	-32 48 133
Interaction effect of Context* Phoneme					<i>n.s.</i>			

Table S2: Results of the SPMs of the flexible factorial design with Context and Phoneme as factors. The x, y, z coordinates refer to the 3D SPM volumes visualized in Fig. 3 (and S3), see the caption for Table S1 for more details.

Figure S1. Histograms of the RTs from the behavioral paradigm.

Figure S2: Full channel overview (of the magnetometers) for all four conditions (**A:** [da]; **B:** [ta]; **C:** [ad]; **D:** [at]). ERFs to the standard and the deviant. For each sensor site typically showing MMNm effects, four channels are highlighted: left anterior, left posterior, right anterior, and right posterior lateral sensor sites. Positive values reflect magnetic flux out of the scalp while negative values reflect magnetic flux into the scalp. Low-pass-filtered at 15 Hz for illustrative purposes.

Figure S3. The SPMs of the four individual conditions and the flexible factorial analysis, thresholded at $p_{FWE} < 0.05$. See caption to figure 3 for more details.