1 **Foreign language learning and the mismatch negativity**
2 **(MMN): a longitudinal ERP study**

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Abstract

An early component of the auditory event-related potential (ERP), the mismatch negativity (MMN), has been shown to be sensitive to native phonemic language sound contrasts. The potential changes to this neural sensitivity from foreign language learning have only been marginally studied. The existing research seems to suggest that the MMN can adapt to foreign language sound contrasts with very target-specific training, but whether the effects are long-lasting or generalize to proper foreign language learning is yet to be investigated in a viable longitudinal study design. We therefore recorded the electroencephalography (EEG) from two groups of language officer cadets (learning either Arabic or Dari) while they listened to language sound contrasts from both languages. We recorded their EEG four times over the course of 19 months of intensive foreign language training (immediately before they started, after three weeks, after six months, and after 19 months).

We did not find any language-specific effects of learning on the cadets' MMNs to the language sound contrasts. We did, however, elicit statistically reliable MMNs to both language contrasts for both groups at most of the four times of measurement. Furthermore, we found that the Arabic learners' MMNs to the Arabic stimuli diminished over time, and that the Dari learners' P3a responses to the Arabic stimuli diminished over time. Correlating the participants' MMNs with their behavioral perception of the language stimuli did not reveal any strong links between behavior and neurophysiology. However, those Dari learners whose MMNs to the Dari stimuli increased the most within the first three weeks, also received the highest grades on a listening task after 17 weeks.

Keywords:

Mismatch negativity (MMN); event-related potential (ERP); longitudinal; foreign language learning; speech perception

1. Introduction

The brain changes during learning (Bennett, Diamond, Krech, & Rosenzweig, 1964; Fields, 2013; Lövdén, Wenger, Mårtensson, Lindenberger, & Bäckman, 2013; Thomas & Baker, 2013). Learning to understand and speak a foreign language requires learning of multiple new things, including learning to perceive (and produce) new subtle sound differences. In the present study we investigated the potential functional brain changes in language sound processing as an effect of foreign language learning. We did so in a longitudinal study across 19 months of intensive language training, measuring electroencephalography (EEG) on two groups of language officer cadets learning either Arabic or Dari (Afghan Farsi). We employed the well-studied mismatch negativity (MMN) paradigm with linguistic stimuli targeting changes in the brain's pre-attentive perception of foreign language sounds as learning progressed.

The MMN is a well-studied component of the auditory event-related potential (ERP) (Kujala, Tervaniemi, & Schröger, 2007; Näätänen, Gaillard, & Mäntysalo, 1978; Näätänen, Paavilainen, Rinne, & Alho, 2007). Native phonemic contrasts have been shown to elicit larger MMNs than comparable non-native or non-phonemic ones (Dehaene-Lambertz, 1997; Dehaene-Lambertz, Dupoux, & Gout, 2000; Kazanina, Phillips, & Idsardi, 2006; Näätänen et al., 1997; Phillips et al., 2000; Sharma & Dorman, 2000). This sensitivity is suggested to be an effect of the categorical nature of speech perception whereby memory traces for native language sounds boost the MMN to the oddball sound beyond what the mere acoustic difference between the sounds would elicit (Näätänen, 2001; Näätänen et al., 1997; 2007; Shtyrov & Pulvermüller, 2007). Hence, as foreign language learners obtain more categorical perception for the foreign language sounds of their target language, the formation of specific memory traces for these now less foreign language sounds may be well under way, leading to

increases in their MMNs to these language sounds. This makes the MMN an obvious candidate for studying learning-driven brain changes in relation to speech perception.

A few existing studies have already targeted the effects of auditory discrimination training on the MMN to language sounds (Kraus et al., 1995; Kujala et al., 2007; Menning, Imaizumi, Zwitterlood, & Pantev, 2002; Näätänen et al., 1978; 2007; Tremblay & Kraus, 2002; Tremblay, Kraus, & McGee, 1998; Tremblay, Kraus, Carrell, & McGee, 1997; Tremblay, Kraus, McGee, Ponton, & Otis, 2001; Zhang et al., 2009). However, the training regimes used in these studies have all been of relatively short duration and have very specifically targeted auditory discrimination training of particular language sound contrasts and not language learning as a more integrated process (Dehaene-Lambertz, 1997; Dehaene-Lambertz et al., 2000; Kazanina et al., 2006; Kraus et al., 1995; Menning et al., 2002; Näätänen et al., 1997; Phillips et al., 2000; Sharma & Dorman, 2000; Tremblay et al., 1997; 1998; 2001; Tremblay & Kraus, 2002; Ylinen et al., 2010; Zhang et al., 2009). Also, the potentially long-lasting effects of these short-term training regimes have not been investigated except for Kraus et al. (1995) showing lasting effects both neurally and behaviorally one month after training.

One cross-sectional study has investigated the effects of foreign language immersion by comparing Hungarians who had moved to Finland and learned Finnish with native Finns and with Hungarians naïve to Finnish on their MMNs to Finnish vowel contrasts (Winkler, Kujala, et al., 1999a). Their results suggest that foreign language learners may obtain native-like MMNs to target language sound contrasts after in-depth foreign language acquisition. However, if relying solely on classroom-based learning, the few existing studies suggest that even up to five years of university studies of a foreign language is not enough to obtain native-like MMNs to foreign sound contrasts (Grimaldi et al., 2014; Hisagi et al., 2016; Peltola et al., 2003). The duration of the linguistic immersion

of the Hungarians having learned Finnish in Winkler et al. (1999a) ranged from 2 to 13 years. Behavioral cross-sectional studies on the effects of linguistic immersion on perceptual adaptation are not conclusive (Moyer, 1999), but results do suggest an effect of immersion when comparing groups with lengths of residence (LORs) of ~0.5-2 years to comparable groups with LORs of ~6-8 years (Flege, Bohn, & Jang, 1997; Flege & Liu, 2001). Whether these effects are additional effects to initial adaptation or they reflect the learners' main perceptual adaptation cannot be discerned from those findings.

A few studies have shown increased MMNs to phonemic French vowel contrasts in Finnish 3- to 6-year-old children after only two-four months of enrollment in French school or daycare (Cheour, Shestakova, Alku, Ceponiene, & Näätänen, 2002; Shestakova, Huotilainen, Ceponiene, & Cheour, 2003) or after three years in a French language immersion program (Peltola, Kuntola, Tamminen, Hämäläinen, & Aaltonen, 2005). However, this was not the case for 8-year-old Swiss and Finnish children learning English in school, neither of which showed adaptations to their MMNs to the foreign English sound contrasts (Jost et al., 2015; Peltola, Tuomainen, Koskinen, & Aaltonen, 2007). These results thus suggest relatively rapid neural adaptation in children at the ages of 3-6 years in an authentic language environment, but not necessarily for slightly older children (around 8 years) in more classroom-based learning settings. It is, however, difficult to directly relate these findings to the time course of neural adaptation in adult second language learners due to the high degree of maturation and ongoing adaptation of children's brains.

Hence, the potential effects of foreign language learning, not specific auditory discrimination training, on the MMN to foreign language sound contrasts have not yet been studied in a viable longitudinal design (except for by Hisagi et al., 2016 to some extent). In this perspective, not much is known about the time course of the potential neural adaptation to the new sound categories during adult foreign language learning except that it seems to be possible for linguistic

immersion of at least two years' duration (Winkler, Kujala, et al., 1999a), but not for prolonged university studies (Grimaldi et al., 2014; Hisagi et al., 2016; Peltola et al., 2003). To add to this, Tremblay et al. (1998) showed that neural adaptation may occur already before effects in behavior are detectable.

We therefore set out to conduct an almost 2-year-long longitudinal study on the potential functional changes in the brains of highly motivated adult foreign language learners enrolled in an immersive and intensive foreign language learning program. More specifically, we investigated the adaptation of two groups of language officer cadets to the sounds of the foreign language they were learning during 20 months of intensive language training. The target languages for the two groups of participants were Arabic ($n = 8$) and Dari (Afghan Farsi) ($n = 12$), respectively. We identified a phonemic sound contrast in each language that was not phonemic in the other, or in Danish (the cadets' mother tongue). This allowed us to use the two groups as each other's control group. We tested the two groups at four time points during their 20-months-long language training, using electroencephalography (EEG) with a linguistic mismatch negativity (MMN) paradigm in which sequences of the same language sound (standard) is infrequently and unpredictably interrupted by one or more slightly different language sounds (deviants). In a parallel study with the same two groups of cadets as participants, we also tested for changes in their ability to behaviorally identify and discriminate the sounds of the two target languages (Nielsen, Horn, Sørensen, McGregor, & Wallentin, 2015).

We hypothesized that the two groups of language officer cadets would show an increase in their MMNs to the language sound contrast of their target language as learning progressed, but not to the sound contrast of their non-target language.

2. Methods

The participants in the present study took part in two experiments at each time of measurement: an electroencephalographic (EEG) experiment (the present study) and a behavioral experiment (Nielsen et al., 2015). The first measurement (T0) was immediately before they started their intensive language training (and right after four months of intensive physical military training). The second measurement (T1) was after exactly three weeks of teaching; the third measurement (T2) was after six months of language training (24 weeks); and the fourth and final measurement (T3) was after 19 months (81 weeks) at the end of their education (see Figure 1B). At this point they had reached a very high degree of proficiency in their target language allowing them to function as military interpreters, linguistic consultants and cultural experts on missions with the Danish Armed Forces. They were able to hold fluent conversations in their target language already after six months (T2). The order of the two experiments was the same for all participants at all three measurements: EEG first and behavioral testing secondly.

The investigation was approved by the local ethics committee (The Central Denmark Region Committees on Health Research Ethics), and written consent was obtained from each participant.

2.1. Participants

Participants consisted of two groups of volunteer cadets from the Institute for Languages at the Royal Danish Defence College. One group was studying Dari (Afghan Farsi) and consisted of 12 participants (seven women, five men, $n=12$). The other group was studying Arabic (both Modern Standard Arabic (MSA) and Egyptian Arabic) and consisted of nine participants of which one dropped out of the education and hence also the study (three women, five men, $n=8$). Gender was not deemed important (Wallentin, 2009; 2020). The two groups

served as control groups for each other since the stimuli were constructed in such a way that the Dari stimulus contrast was not phonemic in Arabic, and the Arabic stimulus contrast was not phonemic in Dari (see 2.2 Stimuli and Figure 1A).

The participants had been pre-screened by the Royal Danish Defence College on the basis of their school achievements, study skills, intelligence and emotional stability among a large group of applicants (~200) prior to enrollment into the two-year program. All participants were native Danish speakers, and all reported having near-normal to normal hearing. None reported any history of neurological or psychiatric illness.

A few of the participants reported some minor knowledge of either Arabic (n=5) or Dari (n=2) prior to enrollment. In our analyses of the behavioral experiment (Nielsen et al., 2015), we did not find any reliable differences between the participants' with some prior knowledge of their target language and those who did not have any prior knowledge of their target language. The two groups did not differ significantly in age, years of education or number of languages spoken (see Nielsen et al., 2015, for more details).

During the first measurement (T0), one of the Arabic learners' EEG was interrupted by a sudden technical error in the equipment, and we were not able to redo the experiment due to the limited time we had available for data collection with the participants. This interruption happened ~10 min before the 70 min paradigm was over, which meant that she still completed two out of three deviant blocks (for each language) and both deviant-as-standards blocks. We therefore chose to keep her remaining data from the first recording session as well as keep her in the experiment for the following three recording sessions (see 2.5 EEG preprocessing for more details).

2.2. Stimuli

The stimuli consisted of two phonetic contrasts, one that is phonemic in Dari and one that is phonemic in Arabic (see Figure 1A). The Dari contrast consisted of the fricative voicing contrast between /f/ and /ɣ/ (Entezar, 2010:24-25). [ɣ] does exist as a realization of the phoneme /dʒ/ in some of the Levantine and Maghribi dialects of Arabic (Watson, 2007:15-16), but the group of Arabic learners in the present study were learning MSA and Egyptian Arabic, in which the corresponding phoneme is realized as [dʒ] and [g], respectively (Watson, 2007:15-16, 20-21), hence the contrast's lack of phonemic status for the Arabic learners was still upheld. The Arabic contrast consisted of the emphatic contrast between /h/ and /ħ/, which is mainly realized by constriction of the lower pharynx in combination with retracted tongue root (RTR) for [ħ] (Bin-Muqbil, 2006:45-50; Laufer & Baer, 1988; Watson, 2007:44-46). This constriction most often results in a prolonged and strengthened frication for the emphatic [ħ] compared to the non-emphatic [h] (Obrecht, 1968:26-27). The pharyngeal constriction of /ħ/ is also characterized by a spreading to the neighboring vowels, however only minimally for the Arabic vowel /a/ which we used in this study (Bin-Muqbil, 2006:153-169, 174-186, 199-200; Watson, 2007:270-273).

Relevant Dari syllables ([ja:] and [ɣa:]) were recorded from a male native Dari speaker using an SM58 Vocal Microphone (Shure Inc., Niles, IL, USA) in a sound-attenuated room. Relevant Arabic syllables ([hæ] and [ħæ]) were taken with permission from the CD-ROM accompanying the teaching material *al-Kitaab fii ta'allum al-'Arabiyya* (Brustad, Al-Batal, & Tūnisī, 1995) and was originally recorded by a male native Arabic speaker. The stimuli were then constructed by cross-splicing the recorded syllables so that the same vowel [a] with a duration of 109 ms was used for both Dari stimulus categories. This gave rise to [ja] and [ɣa], both with a total duration of 299 ms, hence the duration of the frication was 190 ms (both voiceless and voiced). The same procedure was

applied to the vowel in the Arabic stimuli so that the same vowel [æ] with a duration of 90 ms was used for both Arabic stimulus categories. The [h] was manipulated to resemble [hæ] by inserting 70 ms of frication from the [h]-recording into the [h] from 35 ms and onwards, giving rise to [hæ] with a total duration of 178 ms and [hæ]+70ms with a total duration of 248 ms (roughly equivalent to [hæ]). The durations of [h] and [h]+70ms were thus 88 ms and 158 ms, respectively, with the earliest noticeable difference at 35 ms. Since the participants were native Danish speakers and vowel length is phonemic in Danish (Basbøll, 2005:79-82; Grønnum, 2005:100-101), the duration of [æ] was not adjusted to compensate for the durational difference between [h] and [h].

Figure 1. (A) Main experimental design, (B) timeline of the longitudinal experiment, and (C) overview of the Arabic/Dari MMN paradigm. (A) The experimental design was a 2 x 2 (x 2) factorial design with Language (Arabic [hæ]-[hæ] vs. Dari [ʃa]-[ʃa]) and Group (Arabic vs. Dari learners) as main factors, and Stimulus type (deviant vs. standard) as subsequent factor. Colored corners indicate color codes in the subsequent figures: solid blue = Arabic learners and Arabic deviant; dashed blue = Arabic learners and Dari deviant; solid green = Dari learners and Dari deviant; dashed blue = Dari learners and Arabic deviant; solid grey = standards. (B) The longitudinal experiment spanned a total of 81 weeks (~19 months). This was roughly equivalent to the full duration of the language officer cadets' intensive language teaching (~20 months). (C) The Arabic and Dari MMN paradigms each included three deviants (two of which were sounds in between the two phonetic categories, D₁ and D₂). We have focused on the largest deviant (D₃, i.e. [hæ] and [ʃa]). Summed average frequency was ~16.7% and individual average frequency was 5.6%. The grey boxes highlight the largest deviants presented in isolation (deviants-as-standards).

Two 11-step continua were created for the Dari and the Arabic of stimuli categories (see Nielsen et al., 2015, for further details on this process). From the two stimulus continua two steps were selected together with the endpoints for use with the EEG recordings. For the Dari voicing contrast the four selected sounds thus were [ʃa], [ʃ/ʒa]-step4, [ʃ/ʒa]-step7, and [ʒa]. And for the Arabic emphatic contrast the four selected sounds thus were [hæ], [hæ]+28ms, [hæ]+49ms and [hæ]+70ms (roughly equivalent to [ħæ]).

All sounds were finally normalized, and the initial and final 5 ms of each sound were used for fade-in and fade-out. 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/>).

The Dari stimuli were validated by three native Dari speakers, and the Arabic stimuli were validated by one native Arabic speaker (see Nielsen et al., 2015 for more details on the native speakers' perception of the stimuli).

2.3. Procedure

The EEG recordings were carried out at the Institute for Languages at the Royal Danish Defence College, in rooms that had been cleared to accommodate the needs of the experiment. The four different rooms employed for the experiment all turned out to inflict minimal line noise in the recorded EEG signals, and they displayed relatively good sound attenuation, thus keeping environmental factors relatively constant across the three measurements. Participants were tested two at a time, either sitting back-to-back with approximately 1-1.5 m between them or sitting side-by-side with a divider between them. In both cases they were unable to see each other and each other's screens. The pairing of participants was registered, but not controlled for.

Participants' electroencephalograms (EEG) were recorded while they watched a silenced film during presentation of the auditory stimuli. All participants

watched a nature documentary during the first measurement. At the subsequent measurements (T1, T2, and T3) they watched one of three animated films, the order of which was controlled for across measurements (one participant watched the same film at T2 and T3 due a technical error). Participants were instructed to ignore the auditory stimuli and just focus on the film.

The auditory stimuli were presented to them in an oddball paradigm (MMN paradigm) in which sequences of identical stimuli (standard sounds) were infrequently interrupted by different stimuli (deviant sounds). [ja] and [hæ] served as standard sounds in the Dari and Arabic MMN paradigms, respectively. And correspondingly, the Dari deviant sounds consisted of the group of [ʃ/za]-step4, [ʃ/za]-step7 and [za]; and the Arabic deviant sounds consisted of the group of [hæ]+28ms, [hæ]+49ms and [hæ]+70ms (roughly equivalent to [hæ], and referred to as [hæ] henceforth). There were thus three levels of deviants in both the Dari and the Arabic condition (see Figure 1C). The probability of any deviant occurring was 0.167, and the probability of any specific of the three deviants occurring was thus 0.056. Each condition consisted of three blocks of 540 stimuli each (three times 30 deviants and 450 standards), presented with a jittered stimulus-onset-asynchrony (SOA, i.e. onset-to-onset) with an average of 900 ms, ranging from 800 to 1000 ms. The blocks of both conditions were mixed so that a block of Arabic stimuli would always follow a block of Dari stimuli and vice versa.

We also presented the deviants outside of the oddball context in short sequences of 180 repetitions each in order to contrast the participants' neural responses to physically identical stimuli. Such control for potential exogenous effects of comparing physically different stimuli is particularly important when comparing neural responses to complex sounds such as speech sounds (see e.g. Kujala (2007)). These standards were presented in two blocks, which consisted either of the first and third Dari deviants ([ʃ/za]-step4 and [za]) with

the second Arabic deviant ([hæ]+49ms) in between, or of the first and third Arabic deviants ([hæ]+28ms and [hæ]) with the second Dari deviant ([ʃʒa]-step7) in between. Both blocks thus contained 540 stimuli that were presented with the same jittered SOA as in the oddball blocks. The two blocks with deviants presented as standards were always presented as block number three and four, and the block starting with 180 Dari deviants would always follow an Arabic oddball block and vice versa (see Figure 1C).

There were thus two different block sequences with a total of 8 blocks: three Dari oddball blocks, three Arabic oddball blocks and two deviants-as-standards blocks. The two sequences were counterbalanced across the two groups of participants. Each block of 540 stimuli lasted approximately 8 min and was separated from the next by a 30 sec pause. The full MMN paradigm thus lasted approximately 70 min. The first five stimuli of any oddball block were all standards, and there would always be a minimum of four standards between two successive deviants. The stimuli were presented in pseudorandom order so that the subsequent deviant would always differ from the previous one. Participants were given the same randomized sequence of stimuli (and ISI) across measurements in order to keep the signal-to-noise level as stable as possible.

The auditory stimuli were delivered binaurally via Etymotic ER•2 insert earphones at a hearing level of approximately 80 dB. The presentation of the stimuli was controlled and executed by Presentation software (Neurobehavioral Systems, Inc., Albany, CA, USA).

2.4. EEG recording

The EEG (Ag/AgCl electrodes, BrainAmp DC amplifier, sampling rate 1000 Hz) was recorded continuously from 28 scalp sites according to the international 10-20 system using ActiCap systems (Brain Products GmbH, Gilching,

Germany): Fp1, Fp2, F7, F3, Fz, F4, F8, FC5, FC1, FC2, FC6, T7, C3, Cz, C4, T8, CP5, CP1, CP2, CP6, P7, P3, Pz, P4, P8, O1, Oz, and O2. The reference electrode was placed at FCz, and the ground electrode was placed either at AFz or POz. Two additional electrodes were manually placed at the left and right mastoids (in relative proximity of TP9 and TP10). Electro-ocular activity was recorded at the left eye with one supraorbital electrode (VEOG) and one electrode placed at the outer canthus (HEOG). Impedances were kept below 20 k Ω .

2.5. EEG preprocessing

The continuous EEG data was preprocessed and analyzed using a combination of EEGLAB (Delorme & Makeig, 2004) and SPM8 (Wellcome Department of Imaging Neuroscience, www.fil.ion.ucl.ac.uk/spm). Both are open source toolboxes implemented in MATLAB (Mathworks Inc., Natick, USA).

The data were first down-sampled to 250 Hz, band-pass filtered at 1-40 Hz and re-referenced to the common average reference, all using EEGLAB. For correction of eye artifacts, we used ICA in the EEGLAB environment. We provisionally epoched the data with a peri-stimulus window of -100 to 500 ms so as to disregard the short breaks between conditions where the participants were free to move around, which caused heavy EMG- and EOG-related artifacts. We applied the *runica* ICA algorithm to the concatenated epochs in order to identify and reject independent components with the typical topographical characteristics of eye artifacts. For the identification of relevant components we used the EyeCatch algorithm (Bigdely-Shamlo, Kreutz-Delgado, Kothe, & Makeig, 2013). We visually inspected the components identified by EyeCatch and disregarded irrelevant components on the grounds of their topographies and power spectra, which amounted to ~10% of them. We

390 projected out the remaining components from the non-epoched datasets and
391 used SPM8 for the rest of the preprocessing of the data.

392 In SPM8, we epoched the data with a peri-stimulus window of -100 to 500 ms.
393 We discounted the first 10 presentations of each set of 180 deviants-as-
394 standards in order to exclude deviant-like effects from the transition between
395 the different blocks of deviants-as-standards. And we baseline-corrected the
396 epochs by subtracting the average of the pre-stimulus window of -100 to 0 ms
397 from the entire epoch.

398 We conducted further artifact rejection by using first peak-to-peak thresholding
399 and then robust averaging (see Litvak et al., 2011; Wager, Keller, Lacey, &
400 Jonides, 2005, for more details). The peak-to-peak threshold was set at 200
401 μV , thus discarding epochs where the difference between in EEG activity
402 between two adjacent peaks or troughs exceeded 200 μV . The robust
403 averaging technique gives smaller weights to extreme values when computing
404 the average of the individual epochs, e.g. values just within the peak-to-peak
405 threshold used for the first step of the artifact rejection.

406 The mean numbers of deviant trials passed through to averaging after the
407 above-mentioned thresholds had been applied were 78 for the group of Dari
408 learners (SD=9.8 for the 12 participants, SD=1.3 for the four times of
409 measurement, and SD=0.1 for the two languages), and 83 for the group of
410 Arabic learners (SD=5.3 for participants, SD=1.9 for time, and SD=0.2 for
411 language). These numbers were equivalent to ~87% of the total of 90 for each
412 of the deviant trials for the Dari learners, and ~92% for the Arabic learners. The
413 corresponding numbers of deviant-as-standards passed through preprocessing
414 before averaging were 151 for the Dari learners (SD=14.1 for participants,
415 SD=2.1 for time, and SD=1.7 for language), and 160 for the Arabic learners
416 (SD=10.1 for participants, SD=2.0 for time, and SD=0.1 for language). These
417 numbers were equivalent to ~89% of the total of 170 for each of the deviant-
418 as-standards trials for the Dari learners, and ~94% for the Arabic learners. A

two-sample t-test revealed that there were no significant differences between the Dari and Arabic learners' numbers of trials for the deviants ($t(18)=1.2$, $p=0.24$) and for the deviants-as-standards ($t(18)=1.4$, $p=0.16$) passed on to averaging.

For the participant whose EEG was interrupted at ~10 min before the experiment was over at T0, the number of trials that passed through preprocessing was 59 for the Arabic stimuli and 70 for the Dari stimuli. These numbers were in the very low range for the group of Arabic learners, however, they were both within 2*SD of the Dari learners' average. Taken together with relatively low participant numbers, we saw it reasonable to keep this participant's data in the experiment.

The robust averaging resulted in averaged epochs for the relevant standards and deviants at each time of measurement. In order to reduce the dimensionality of the array of ERPs to be compared, we focused on the largest deviant in each condition (i.e. [hæ] and [ʒa]). This gave rise to 16 event-related potentials (ERP) per participant (2 types x 2 conditions x 4 times). All ERPs were then again low-pass filtered at 40 Hz and baseline-corrected with the pre-stimulus window of -100 to 0 ms because the robust averaging technique may occasionally introduce high-frequency artifacts.

We computed the relevant difference waves by subtracting each participant's ERP to the [hæ] deviant-as-standard (i.e. from outside the oddball context) from his or her ERP to the [hæ] deviant, and likewise for his or her ERP to the [ʒa] deviant-as-standard and the [ʒa] deviant. This procedure resulted in a total of eight (2 conditions x 4 times) difference waves per participant (and per electrode): one for each set of language stimuli at each of the four times of measurement.

2.6. Statistical analyses

We conducted the statistical analyses in a two-step process. We first used the RAGU software (Koenig, Kottlow, Stein, & Melie-García, 2011) to establish which conditions elicited reliable MMNs, and next we used IBM SPSS Statistics version 20 for Mac OS X to compute a mixed design analysis of variance (ANOVA). Finally, we conducted a set of correlation analyses using MATLAB (R2010a).

2.6.1. Topographic consistency tests (TCTs) and identification of MMNs

In order to statistically confirm the presence of MMNs in the different conditions, we identified the time points with maximal difference between global field power (GFP) of the deviant and standard ERPs across all participants and all times of measurement, but separately for the two languages. We compared this temporal information with a set of topographic consistency tests (TCTs, Koenig et al., 2011; Koenig & Melie-García, 2010) and the relevant topographies to establish in which conditions and at what times each group elicited a reliable MMN in each language condition.

To this end, we computed the GFP in each sample of each participant's standard and deviant ERPs at each time of measurement and each language. The GFP is analogous to the standard deviation across all channels and provides an unbiased measure of the strength of the signal at each time sample (Koenig & Melie-García, 2010; Lehmann & Skrandies, 1980; Murray, Brunet, & Michel, 2008; Tzovara, Murray, Michel, & De Lucia, 2012). At the single subject level and for each standard-deviant contrast, we subtracted the GFP of the standard ERP from the GFP of the deviant ERP. For each language we then calculated the grand average across all four times of measurements and all participants' GFPs of the standard and deviant ERPs, as well as the differences between the two. This grand average gave an overall measure of when the

474 difference between the signal strengths in the ERPs was the largest. We
475 analyzed the participants' responses to the Arabic and Dari stimuli separately
476 because the acoustic nature of the two sets of stimuli was qualitatively different
477 (see 2.2 Stimuli and Nielsen et al. (2015)), and we therefore expected the ERPs
478 to the corresponding sounds to be comparable only at a more abstract level
479 (e.g. after identifying the temporal locations of the MMNs).

480 For each language, we located the two highest peaks of the average of the
481 differences between the GFPs of the standard and deviant ERPs. We did so
482 using the *findpeaks* function in MATLAB. We used two peaks (and not just one)
483 because we suspected that the ERPs might contain a P3a response besides
484 the potential MMN (Calcutt et al., 2014; Escera, Alho, Schröger, & Winkler,
485 2000; Näätänen, 1992; Näätänen & Gaillard, 1983). Around these peaks we
486 defined a 48 ms time window (the sampling rate of the data was 250 Hz, and
487 therefore 48 ms was the closest product of 4 to a 50 ms window). For a
488 motivation of the choice of window length, see 2.6.2 Mixed design ANOVA. For
489 these windows we plotted the relevant topographies of the group averaged
490 difference wave ERPs. This allowed us to confirm or disconfirm the MMN-
491 typicality of the identified peaks by looking for patterns of the strongest signal
492 at fronto-central electrodes and polarity reversal at the mastoids. If neither of
493 the two topographies were identified as MMN-typical, we re-inspected the
494 GFPs to see if a potential MMN might be masked by the larger signal strength
495 in a potential P3a response (since the GFP is a calculation of power it contains
496 no information on the polarity of the signals, and if the MMN and the P3a are
497 temporally very close, the difference in GFP may not detect the two responses
498 with separate peaks).

499 Next, we computed topographic consistency tests (TCTs) on the difference
500 wave ERPs for each group, language and time of measurement (hence a total
501 of $2 \times 4 = 8$ TCTs for each group). We used the RAGU software (Koenig et al.,
502 2011) to compute the TCTs. This computation is based on empirically

estimating a null-distribution of GFPs of the group-averaged topographies, i.e. the distribution where there are no consistent patterns in the topographies. It capitalizes on the fact that the GFP of the grand average is not identical to the average of the participants' individual GFPs. Therefore, if each participant's channel array is randomly shuffled and the grand average is calculated anew, then the GFP of the new grand average will be an element of the null-distribution (see Fig. 1 in Koenig & Melie-García, 2010:235, for an illustration of this principle). We computed 5000 randomizations for the TCT of each of the difference waves (as is recommended by Koenig et al. (2011) and Manly (2007)). We thresholded the p-values at $p < 0.001$ and the duration of consecutive p-values at 0.05 (corresponding to an average of 8 ms) in order to minimize the risk of false positives given the multitude of tests over many samples and conditions.

Finally, we compared the time windows identified by the grand-averaged GFPs with the time periods of the TCTs that exceeded both p-value and duration thresholds. If we found overlap between the two, we considered this to be a statistically reliable MMN. And where there was no overlap, we considered this condition to not have elicited a statistically reliable MMN.

A common way to statistically confirm the presence of MMNs in the previous MMN literature is by means of one-tailed one-sample t-tests on the windowed means of the difference waves (see e.g. Pakarinen et al., 2009; Ylinen, Huottilainen, & Näätänen, 2005; Ylinen, Shestakova, Huottilainen, Alku, & Näätänen, 2006). We opted for the above-mentioned procedure using TCTs in order to obtain a reference-independent measure of the MMN since different references have been shown to shift effects in both time and space (Murray et al., 2008; Tzovara et al., 2012). Also, TCT is a useful tool if the signal strength is not optimal (Tzovara et al., 2012), and due to the somewhat limited number of deviants in our experimental design (78 and 83 for the Dari and Arabic learners, respectively) we suspected that our signal strength might not be

optimal. However, in order to ensure that we did not overlook any MMN effects that would have been detected with the more classical MMN analyses, we subsequently also conducted one-tailed one-sample t-tests for each windowed mean.

2.6.2. Mixed design ANOVA

Next, to assess any effects of learning on the participants' MMNs we used the temporal information from the grand-averaged GFPs and the TCTs to compute windowed means across four fronto-central electrodes (Fz, FC1, FC2, and Cz, see Figure 2 and Figure 3) for each participant. We then submitted these windowed means to a mixed design ANOVA in SPSS where we included Group as our between-subjects factor and Language and Time as our within-subject factors (see e.g. Ylinen et al., 2006, for a similar procedure). Based on our hypotheses of language-specific learning effects, we specifically looked for a Group x Language x Time interaction effect, but seeing as such three-way interactions can be difficult to both detect and interpret, we a priori planned for four one-way repeated measures ANOVAs with Time as within-subject factor (similar to what we did in Nielsen et al., 2015).

The choice of window length was based on the literature where e.g. Pakarinen et al. (2009) and Noordenbos et al. (2013) both relied on a 50 ms window, and both also investigated MMNs to speech sounds. However, there is not a strong consensus in the MMN literature on the size of the window used for windowed means: Ylinen et al. (2006) used a 20 ms window, and Näätänen et al. (1997) used a 150 ms window, both also investigating speech sounds. We settled on a 50 ms window as this was the window size showing the strongest convergence in the linguistic MMN literature (besides the already-mentioned, see e.g. Brandmeyer, Desain, & McQueen, 2012; Miglietta, Grimaldi, &

Calabrese, 2013). We adapted this window to 48 ms to match our down-sampled sample rate of 250 Hz.

The choice of electrodes was motivated by a compromise of what we could discern from the literature. There are several reports of choosing only Fz (e.g. Noordenbos et al., 2013; Pakarinen et al., 2009; Peltola et al., 2003; Scharinger, Bendixen, Trujillo-Barreto, & Obleser, 2012; Winkler, Kujala, et al., 1999a). However, such a narrow scope increases the risk of missing effects that would be just slightly off from the canonical electrode site. Others report averages of up to nine fronto-central electrodes (e.g. Brandmeyer et al., 2012; Chládková, Escudero, & Lipski, 2013). Such an approach, on the other hand, runs the risk of averaging out MMN effects that would peak around just two-three fronto-central electrodes. We therefore opted for the compromise between the too narrow and too broad scopes and averaged across the four most central fronto-central electrodes, i.e. Fz, FC1, FC2, and Cz (see Figure 2 and Figure 3; and see e.g. Miglietta et al. (2013) for a similar selection of Fz, FCz, and Cz).

2.6.3. Factorial analysis of global dissimilarity maps

By using the grand average GFP to identify the relevant time periods for the windowed means, we tried to eliminate experimenter bias in that respect. However, windowed mean analyses are prone to experimenter bias, nonetheless (e.g. channel selection and size of time window in this case). Therefore, in order to minimize the risk that we would miss an effect in the data due to the narrow temporal and spatial scope of the windowed mean analyses, we also conducted factorial analyses of the global map dissimilarities (DISS) and the GFPs of the difference waves using their implementations in the RAGU software (Koenig et al., 2011).

2.6.4. Correlations with behavior and grades

Finally, we correlated participants' windowed means with their behavioral data (Nielsen et al., 2015), as well as with their grades from two exams after 17 and 40 weeks.

We focused our scope of the correlation analyses of the behavioral and neurophysiological measurements on those data obtained at the same time of measurement and on differences over the same time spans (all in comparison to baseline at T0). In Nielsen et al. (2015) we observed a modest learning effect on the Dari learners' steepness of their identification (ID) functions for the Dari stimuli, but not for their d-prime values. We therefore used only the participants' slope values as behavioral data in our correlation analyses (and thus not their d-prime scores). These choices of narrowing our focus were motivated by keeping the number of correlation analyses at a sensible level.

With this focused scope, we conducted 12 correlation analyses on differences in the participants' ERP values and changes in slope values (2 groups x 2 languages x 3 time contrasts [T1-T0, T2-T0, T3-T0]). We conducted 16 correlation analyses on participants' ERP values and slope values at the four times of measurement (2 groups x 2 languages x 4 times).

Lastly, we investigated the correlation analyses between participants' grades and their ERP means. We focused on the participants' changes in ERP values over time rather than the ERP values at each time of measurement. We did so because our original hypothesis was to investigate the potential changes in neurophysiological responses as an effect of intensive foreign language learning. We used the same three time contrasts as mentioned above (i.e. against T0) to correlate with participants' speaking grades and listening grades at both exams (after 17 and 40 weeks). The grades on the Danish grading scale are not evenly distributed (see Nielsen et al., 2015, for more details on the Danish grading scale), and we therefore conducted Spearman's rank correlations on the comparisons of the participants' grades and their windowed

mean ERPs. When comparing the participants' ERP means to their behavioral results, we consistently compared one set of ERP means (or differences) with their corresponding values in the behavioral results. For the comparison with their grades, we compared each groups' ERP means to four different grades measures (i.e. both their speaking and listening grades after both 17 and 40 weeks), and we therefore used a Bonferroni-corrected alpha of 0.0125.

Figure 2. Full channel overlay (30 electrodes) for the Arabic stimuli at T0 showing the two groups' grand average ERPs to [hæ] as both deviant and deviant-as-standard. Arabic learners' ERPs are depicted in solid blue. Dari learners' ERPs are depicted in dashed green. Key electrodes are marked indicated by their international 10-20-labels. Fz, FC1, FC2, and Cz over the vertex were the four electrodes used for the windowed mean ANOVAs, and the average ERP across these four electrodes are enlarged in the center of the figure. TP9 and TP10 indicate left and right mastoids, respectively. Nose is facing upwards. ERPs have been low-pass-filtered at 15 Hz for illustrative purposes.

3. Results

The two groups' ERPs to the standard and deviant sounds at T0 are shown in full channel overviews in Figure 2 and Figure 3 (and at T3 in supplementary figure S2). Butterfly plots of standard, deviant, and difference wave ERPs for all channels are shown across all four times of measurement and each group and each set of stimuli in Figure 6 and Figure 7.

Figure 3. Full channel overlay (30 electrodes) for the Dari stimuli at T0 showing the two groups' grand average ERPs to [3a] as both deviant and deviant-as-standard. Arabic learners' ERPs are depicted in dashed blue, Dari learners' in solid green. Averages across Fz, FC1, FC2, and Cz are enlarged in the center of the figure. Nose is facing upwards. ERPs have been low-pass-filtered at 15 Hz for illustrative purposes.

3.1. TCTs and individual MMNs

The results of the grand-averaged GFPs are illustrated in Figure 4. In the grand averages of the differences between the GFP analyses of participants' responses to the standard and the deviant Arabic [ħæ] contrast, the two highest peaks were located at 296 ms and 448 ms after stimulus onset (corresponding to 261 ms and 413 ms after deviance onset). We identified the difference wave

topography for the time window from 237-285 ms after deviance onset as a potential P3a response with a strong fronto-central positivity. The window from 389-437 ms was also not MMN-typical regarding both latency and topography. After re-investigating the grand-averaged GFPs, we noticed that the large P3a peak in the averaged differences was potentially masking an MMN. We located the onset of this potential MMN at 200 ms after stimulus onset (165 ms after deviance onset) as this was the onset of the temporally distributed P3a-peak. The relevant difference wave topography from 165-213 ms after deviance onset showed MMN-typical fronto-central negativity with polarity reversal at the mastoids. Since the P3a response was so salient in the grand-averaged GFP analyses we passed both time windows (i.e. 165-213 ms and 237-285 ms after deviance onset) on to the comparison with the topographic consistency tests (TCTs).

In the GFP analyses of the participants' standard and deviant ERPs to the Dari [ʒa] contrast, the two highest peaks of the grand-averaged differences were located at 128 ms and 264 ms after stimulus (and deviance onset). The relevant difference wave topography from 104-152 ms showed an MMN-typical fronto-central negativity with polarity reversal at the mastoids. The difference wave topography for the time window from 240-288 ms was not MMN-typical regarding either latency or topography. It showed a weak positivity over right frontal electrodes and a weak negativity at the occipital electrodes. This response pattern was not clearly indicative of a P3a response, and we therefore passed on only the 104-152 ms window for full comparison with the TCTs. We opted to also tentatively include the 240-288 ms window for comparison with the TCTs in order to attest that the observed difference in the GFP analyses was not indicative of a P3a response in any of the conditions.

Figure 4. Grand averages of each participant's global field power (GFP) across both groups and all four times of measurement. Black lines indicate deviants, grey lines indicate standards, and dashed red lines indicate the grand average of differences of the GFP of each participant's ERPs to the standard and deviant sounds. Black crosses indicate the two highest peaks on the averaged differences. Topographies are shown for the windowed mean of 48 ms around each peak of the grand average difference wave ERP. The topography for the windowed mean of 200-248 ms for the Arabic stimuli is also shown. This window did not show a separate peak because it was masked by the immediately subsequent response of opposite polarity. The label "adjusted" refers to the latency of the time windows for the Arabic stimuli when the onset of deviance (35 ms) is taken into consideration.

The results of the TCTs and the relevant difference wave topographies are illustrated in Figure 5. For the Arabic stimulus contrast, the TCTs revealed overlaps with the potential MMN time window from 165-213 ms after deviance onset at T0 and T1 for the group of Arabic learners, and at all four times of measurement for the group of Dari learners. The relevant topographies all showed negativities over frontal and/or central electrode sites with polarity reversal at one or both mastoids. We took this as support for statistically reliable MMNs to the Arabic stimuli at the first two out of four times of measurement for the Arabic learners and at all four times of measurement for the Dari learners. We noted, however, that the topographies at the different times of measurement were not homogenous within the groups. This further motivated

our choice of a subsequent factorial analysis of the global map dissimilarities of the two groups' ERPs to both sets of stimuli (DISS, see e.g. Koenig et al., 2011; Murray et al., 2008), i.e. in addition to the mixed design ANOVA (see 3.3 Factorial analyses of DISS and GFP).

For the Dari stimulus contrast, the TCTs revealed overlaps with the potential MMN time window from 104-152 ms at T1 and T3 for the group of Arabic learners and at all four times of measurement for the group of Dari learners. The relevant topographies also here showed negativities at fronto-central electrode sites and polarity reversal at the mastoids. We took this as support for statistically reliable MMNs to the Dari stimuli at the second (T1) and fourth (T3) measurement for the Arabic learners and at all four times of measurement for the Dari learners. We note that the time windows for the MMNs to the Arabic and the Dari stimuli are noticeably different, and the windowed means thus allowed us to compare the MMNs to the two sets of stimuli only on the basis of their mean amplitudes (see 3.3 Factorial analyses of DISS and GFP for a statistical confirmation of this latency difference).

The potential P3a time window from 237-285 ms after deviance onset for the Arabic stimuli revealed overlaps with the TCTs at all four measurements for both groups of learners. And all the relevant difference wave topographies showed a consistent pattern of fronto-central positivity. The potentially corresponding time window from 240-288 ms for the Dari stimuli revealed a few overlaps with the TCTs; however, the relevant difference wave topographies did not reveal any P3a-typical response patterns. We therefore decided to analyze the P3a response for only the Arabic stimuli separately in an additional mixed design ANOVA with Group as between-subjects factor and Time as within-subject factor in order to see if this might reveal any learning effects (as has been seen for e.g. orchestra conductors (Nager, Kohlmetz, Altenmüller, Rodríguez-Fornells, & Münte, 2003)).

The one-tailed one-sample t-tests for each of the windowed means revealed MMNs significantly more negative than zero for the Arabic learners at T0 and T1 to the Arabic stimuli and at T1 and T3 to the Dari stimuli ($p < 0.05$), just as the TCTs did. For the Dari learners the t-tests revealed significant MMNs to the Arabic stimuli at T0, T2, and T3, and at T0, T1, and T3 to the Dari stimuli ($p < 0.05$). Hence, slightly different from the TCTs where all four times of measurement revealed statistically reliable MMNs to both sets of stimuli. However, the Dari learners' MMNs to the Arabic stimuli at T1 and to the Dari stimuli at T2 both trended towards significance in the t-tests ($p = 0.052$ and $p = 0.061$, respectively). Finally, one-tailed one-sample t-tests on the P3a windowed means for both groups to the Arabic stimuli revealed P3a responses significantly larger than zero at all four times of measurement, again in accordance with the TCTs.

Figure 5. Topographic consistency tests (TCT) of the difference waves for each group, each language, and each time of measurement. Grey bars indicate the p-value in that particular time sample. These p-values are calculated on the basis of 5000 permutations of each participant's electrode array before calculating new grand averages and calculating the global field power of those new grand averages. Green blocks indicate time periods within which the duration of consecutive p-values < 0.001 were longer than expected by chance (defined by an alpha level of 0.05). Green patches thus indicate periods of time in the difference wave ERPs where the topographies showed consistencies. Red boxes indicate an overlap between the MMN time windows that we identified in the grand-averaged GFP analyses (see

Figure 4) and the TCTs. We took such overlaps as an indication of a statistically reliable MMN in those conditions. Black boxes indicate overlaps between the P3a time windows and the TCTs, which we took as an indication of a statistically reliable P3a response in those conditions. The relevant topographies are shown for the relevant time windows for each time, language and group.

3.2. Mixed design ANOVA

The results of the mixed design ANOVA using the windowed mean MMNs are illustrated in Figure 8A. This mixed design ANOVA with Group as between-subjects factor and Language and Time as within-subject factors revealed no main effects of Group ($F(1,18)=1.47$, *ns*), Language ($F(1,18)=0.46$, *ns*) or Time ($F(3,54)=1.25$, *ns*). There was a significant Language x Time interaction effect ($F(3,54)=3.76$, $p<0.05$). This indicates that across both groups their windowed mean MMNs over time grew larger or smaller to a different degree for the Arabic stimuli compared to the Dari stimuli. To explore this interaction effect, we conducted contrasts that compared the six different time contrasts (i.e. T0-T1, T0-T2, T0-T3, T1-T2, T1-T3, and T2-T3) for the MMNs to the Arabic stimuli with corresponding time contrast for the MMNs to the Dari stimuli. These revealed three significant interactions: across both groups, (1) the participants' MMNs to the Dari stimuli grew larger (i.e. more negative) from T0 to T3 than their MMNs to the Arabic stimuli, which, in fact, diminished from T0 to T3 ($F(1,18)=7.26$, $p<0.05$); (2) their MMNs to the Dari stimuli grew larger from T1 to T3 than their MMNs to the Arabic stimuli, which, in fact, diminished from T1 to T3 ($F(1,18)=5.53$, $p<0.05$); and (3) their MMNs to the Dari stimuli grew larger from T2 to T3 than their MMNs to the Arabic stimuli, which, in fact, diminished from T2 to T3 ($F(1,18)=4.77$, $p<0.05$). This indicated that, across both groups, the participants' MMNs to the Dari stimuli grew larger towards the fourth and final measurement (T3) than their MMNs to the Arabic stimuli (which, in fact, diminished towards the last measurement). There were no other significant interaction effects, and we specifically note that our hypothesized Group x Language x Time interaction effect was not significant ($F(3,54)=1.90$, *ns*).

We also conducted four a priori planned one-way repeated measures ANOVAs with Time as the within-subject factor and each group's MMNs to each of the sets of language stimuli as our dependent measure. These revealed one effect, which was a main effect of Time for the Arabic learners on the Arabic stimuli ($F(3,21)=4.02$, $p<0.05$, see Figure 8A, upper panel). Contrasts revealed that their MMNs to [ħæ] were significantly smaller (i.e. less negative) at T3 than at T0 ($F(1,7)=5.66$, $p<0.05$), hence a diminished MMN over time.

Figure 6. Butterfly plots of the ERPs of all channels at each time of measurement for each group separately to the Arabic stimuli. Grey lines indicate each of the 30 channels used for the EEG recordings. Red lines indicate Fz (typical peak locus for MMN). Black lines indicate the global field power (GFP) of each group's grand averages (only shown for the ERPs to the standard and deviant sounds). Yellow lines indicate the left mastoid (TP9). The MMN is characterized by opposite polarities of the signal at Fz (and surrounding channels) and at the mastoids. The MMN and P3a responses identified in the TCTs (Figure 5) are indicated over the difference waves with black brackets. ERPs have been low-pass-filtered at 15 Hz for illustrative purposes.

The mixed design ANOVA with Group as between-subjects factor and Time as within-subjects using the windowed mean P3a responses as the dependent measure did not reveal any significant effects. As we did with the windowed mean MMNs, we also conducted two one-way repeated measures ANOVAs for the P3a responses to the Arabic stimuli with Time as the within-subject factor.

These showed a main effect of Time for the group of Dari learners ($F(3,33)=4.07$, $p<0.05$, see Figure 8A, upper panel), and no main effect of Time for the group of Arabic learners. Contrasts revealed that the Dari learners' P3a responses to the Arabic stimuli were significantly smaller (i.e. less positive) at T3 than at T0 ($F(1,11)=6.27$, $p<0.05$) and T2 ($F(1,11)=8.39$, $p<0.05$). Hence, the Arabic learners' diminished MMNs over time to the Arabic stimuli were not mirrored in any effects in their P3a responses. And likewise, the Dari learners' diminished P3a responses over time to the Arabic stimuli were not mirrored in any effects in their MMNs.

Figure 7. Butterfly plots of the ERPs of all channels at each time of measurement for each group separately to the Dari stimuli. Grey lines indicate each of the 30 channels used for the EEG recordings. Red lines indicate Fz (typical peak locus for MMN). Black lines indicate the global field power (GFP) of each group's grand averages (only shown for the ERPs to the standard and deviant sounds). Yellow lines indicate the left mastoid (TP9). The MMN is characterized by opposite polarities of the signal at Fz (and surrounding channels) and at the mastoids. The MMN and P3a responses identified in the TCTs (Figure 5) are indicated over the difference waves with black brackets. ERPs have been low-pass-filtered at 15 Hz for illustrative purposes.

3.3. Factorial analyses of DISS and GFP

For the factorial analyses of both DISS and GFP, we included Group as the between-subjects factor and Language and Time as the within-subject factors. The results did not reveal any new effects compared to the mixed design ANOVA on the windowed means (see supplementary Figure S1). There was a main effect of Language in the DISS analysis, which showed effects at exactly the three time windows we identified in the grand-averaged GFP analyses, i.e. around 104-152 ms (MMN to Dari stimuli), around 200-248 ms (after stimulus onset, MMN to Arabic stimuli), and around 296-344 ms (after stimulus onset, P3a to Arabic stimuli). Since these temporal windows were different for the two sets of stimuli, it was to be expected that they would show up as a main effect of Language when the full epochs of the difference wave ERPs were compared. The point of the windowed mean analyses is partly to ignore this latency difference and compare the MMNs solely on the basis of their mean amplitudes. We therefore considered this main effect of Language as a confirmation of what we had already found in our analyses of the grand-averaged GFP analyses and the TCTs. The GFP analysis also showed a main effect of Language, but only around the 296-344 ms window (after stimulus onset). Since a few studies have shown learning effects on the standard and deviant responses separately (Pantev et al., 1998; Pantev, Roberts, Schulz, Engelien, & Ross, 2001; Reinke, He, Wang, & Alain, 2003; Tremblay et al., 2001; Tremblay & Kraus, 2002), we furthermore conducted factorial analyses of DISS and GFP of the deviant and standard ERPs separately (the explicit results are not reported or illustrated, only the following summary). Because the RAGU implementation of the factorial analysis of DISS and GFP cannot include more than two within-subject factors, we ran the analyses separately for the two languages, hence Group was still included as between-subjects factor, and Stimulus type (deviant or standard) and Time were included as within-subject factors. These analyses both revealed widespread main effects of Stimulus

type for both languages, but no other effects, and crucially thus no effects of Time.

3.4. Correlations with behavioral data and grades

The results of the correlation analyses are illustrated in Figure 8B-C. The Arabic learners' MMNs were positively correlated with the slopes of their ID functions (Nielsen et al., 2015) to the Dari stimuli at T3 ($r(6)=0.89$, $p<0.01$, Figure 8B). Hence, those Arabic learners with the largest MMNs (i.e. the most negative MMNs) showed the shallowest ID slopes (i.e. the least categorical perception of the contrast). This was the only significant correlation between the participants' windowed mean MMNs and their behavioral responses to the two sets of stimuli.

When comparing the participants' windowed mean MMNs to their grades, the Dari learners' changes in MMNs to the Dari stimuli between T0-T1 were negatively correlated with their listening grades after 17 weeks ($r_s=-0.71$, $p=0.01$, Figure 8C). Hence, those Dari learners whose MMNs to the Dari stimuli increased the most (i.e. became more negative) between T0-T1, received the highest listening grades after 17 weeks. This effect was further corroborated by two similar correlations, which did not pass the Bonferroni-corrected alpha level, but did pass an uncorrected alpha level of 0.05. The Dari learners' changes in MMNs to the Dari stimuli between T0-T2 were negatively correlated with their listening grades after 17 weeks ($r_s=-0.61$, $p<0.05$), and their changes between T0-T3 were negatively correlated with their listening grades after 40 weeks ($r_s=-0.60$, $p<0.05$).

Figure 8. (A) group averages of the windowed means for each language at all four times, (B) correlations between participants' windowed mean ERPs and the slopes of their ID functions, and (C) correlations between changes in participants' windowed mean ERPs and their grades. (A) All windowed means were calculated as an average over the four fronto-central electrodes (Fz, FC1, FC2, and Cz). The windowed mean MMNs to the Arabic stimuli ([hæ]) was calculated from 165-213 ms after deviance onset, and to the Dari stimuli ([ʒa]) from 104-152 ms after stimulus (and deviance) onset. The windowed mean P3a responses to the Arabic stimuli were calculated from 237-285 ms after deviance onset. Solid blue lines indicate Arabic learners' MMN and P3a responses to the Arabic stimuli. Dashed blue line indicates Arabic learners' MMNs to the Dari stimuli. Dashed green lines indicate Dari learners' MMN and P3a responses to the Arabic stimuli. And solid green line indicates Dari learners' MMNs to the Dari stimuli. Errorbars show the standard error of the mean. (B) For the Dari stimuli, Arabic learners' windowed mean MMNs correlated positively with the slopes of their ID functions, both at T3. (C) Changes in Dari learners' windowed mean MMNs to the Dari stimuli between T0 and T1 (i.e. after the first three weeks) correlated negatively with their grades on a listening task after 17 weeks. For illustration purposes, changes in the windowed mean ERP that were nearly identical have been slightly adjusted. Correlations between changes in ERPs and the grades were conducted using Spearman's rank correlations and therefore no regression lines are visualized.

3.5. Re-referencing

In parts of the MMN literature there are reports of re-referencing to the average of the two mastoids in order to improve the signal-to-noise ratio (see e.g. Pakarinen et al., 2009; Pakarinen, Takegata, Rinne, Huottilainen, & Näätänen,

2007; Ylinen et al., 2006). We have not previously been successful in obtaining better SNR by re-referencing to the average of the mastoids. But in order to ensure that we did not miss any subtle effects of learning in the present experiment, which would only be detectable by re-referencing to the mastoids, we ran the relevant analyses using the mastoid-referenced data. These analyses thus included the one-tailed one-sample t-tests, the mixed design ANOVAs, the pre-hoc-planned one-way ANOVAs for repeated measures, as well as all the correlation analyses, all with respect to the windowed mean MMNs (not the P3a responses). The GFP analyses, per definition, do not change noticeably when re-referencing. These analyses did not reveal any substantially new results.

They showed most of the above-mentioned one-tailed one-sample t-test effects, but they failed to show a significant MMN for the Arabic learners to the Dari stimuli at T1; and for the Dari learners, they showed a significant MMN to the Arabic stimuli at T1 instead of T2 as in the previous analyses, as well as a significant MMN to the Dari stimuli at T2 where the previous analyses only showed a tendency towards significance at T2. The mixed design ANOVA failed to show the Language x Time interaction effect ($F(3,54)=1.80$, *ns*). The four one-way ANOVAs for repeated measures with Time as within-subject factor did, however, also show the main effect of Time for the Arabic learners to the Arabic stimuli ($F(3,21)=3.73$, $p<0.05$, diminishing over time). And they also showed no effects in the other three ANOVAs as in the analyses with the common-averaged data.

4. Discussion

4.1. Main findings

In this study we present results from a longitudinal EEG study stretching over 19 months of intensive language training. We initially hypothesized that the two groups of language learners would show increased MMNs to the language sound contrast of their target language as learning progressed. We did not find any results in support of this hypothesis. We were able to detect statistically reliable MMNs in all conditions for the group of Dari learners and in half of the conditions for the group of Arabic learners. We furthermore detected robust P3a responses in both groups to the Arabic stimuli at all four times of measurement. We specifically looked for the Group x Language x Time interaction effect in the mixed design ANOVA on the windowed mean MMNs, as well as for the Group x Time interaction effect in the mixed design ANOVA on the P3a responses to the Arabic stimuli. But none of these interaction effects were significant, and hence we did not find any language-specific learning-induced effects on the participants' neurophysiological responses that directly matched our initial hypothesis.

Interestingly, we did show a Language x Time interaction for the participants' MMNs. Collapsing both groups of learners, we saw that the changes in their MMNs from the first three measurements (T0, T1 and T2) to the fourth and last measurement (T3) were more negative to the Dari stimuli than they were to the Arabic stimuli. In other words, their MMNs to the Dari stimuli grew larger (more negative) towards the last measurement, whereas their MMNs to the Arabic stimuli diminished towards the last measurement. Since this interaction effect did not further interact with the Group factor, we cannot interpret these differences as specific to the learners' target languages (i.e. as language-specific effects). They reflect that the participants' MMNs to the two sets of stimuli changed differently over time regardless of their target language. Even

though the effect seems to be driven by both amplitude increases in their MMNs to the Dari stimuli and amplitude decreases in their MMNs to the Arabic stimuli, it is not evident that the different changes in the participants' MMNs should necessarily be related. It is possible that the effect came about due to two weak, but independent, tendencies towards changes in the participants' neural responses to the two sets of stimuli.

Moreover, we observed two effects of Time within each of the two groups of learners' in relation to the Arabic stimuli. The Arabic learners' MMNs to the Arabic stimuli diminished over time, most noticeably between T0 and T3 – however, this was not mirrored in their P3a responses, which did not change significantly over time. On the other hand, the Dari learners' P3a responses to the Arabic stimuli showed a diminishing over time, most noticeably from both T0 and T2 to T3, and conversely these effects were not mirrored in their MMNs to the Arabic stimuli, which did not show any significant changes over time. This seems to suggest that the changes regarding the Arabic stimuli in the more global Language x Time interaction effect for the MMNs were driven mainly by the group of Arabic learners (this is also evident in the upper panel of Figure 8A). As is visualized in the lower panel of Figure 8A, the changes regarding the Dari stimuli, however, seemed to follow a more common pattern for both groups. We take this as suggestive of two independent tendencies driving the observed Language x Time interaction effect.

We can only speculate as to what may be the cause of the observed diminished MMNs to the Arabic stimuli in the Arabic learners. Since we did not observe any behavioral learning effects for the Arabic stimuli (Nielsen et al., 2015), nor any correlations between the Arabic learners' behavioral and neural responses to the Arabic stimuli, it seems this neurophysiological effect was not very directly related to what we could observe from the Arabic learners' behavior. And without a behavioral correlate, it is difficult to meaningfully interpret an effect with opposite directionality of our pre-stated hypothesis. It is worth noticing that

for the last two measurements (T2 and T3) we did not observe statistically reliable MMNs to the Arabic stimuli in the group of Arabic learners. And the observed effect of Time on their MMNs to the Arabic stimuli was mainly driven by the contrast between T0 and T3, one of which thus did not elicit a statistically reliable MMN in the group. The lack of a statistically reliable MMN could be due to a genuinely very diminished MMN within the group, but it could also be due to large variances within the group. The relevant standard errors of the mean, which are visualized in the upper panel of Figure 8A, do not suggest drastic increases in the group's variances between T0/T1 and T2/T3, and the fact that the contrast between T0 and T3 was, in fact, significant, suggests that the lack of reliable MMNs at T3 in the group of Arabic learners reflect genuinely diminished MMNs.

It is also possible that the lack of statistically reliable MMNs at T2 and T3 for the Arabic stimuli (and at T0 and T2 for the Dari stimuli) could be due to an underpowered sample size ($n = 8$). Arguments against this include the fact that we did elicit statistically reliable MMNs in the other four conditions, but also that in two cross-sectional neurophysiological studies also investigating foreign language learning effects between groups (Peltola et al., 2003; Winkler, Kujala, et al., 1999a) sample sizes were ~ 10 for each group. Only Winkler et al. (1999a) showed effects of language learning on the MMN (after in-depth linguistic immersion), but Peltola et al. (2003) did, however, also show differences in MMNs between different groups of native language speakers (they did not show any effects of long-time educational exposure to a foreign language). Thus both studies were able to elicit reliable MMNs and differences between these for group sizes of ~ 10 . Cross-sectional studies generally require larger sample sizes compared to longitudinal studies (such as the present study) because the variances between the different groups are independent, whereas longitudinal studies rely on repeated measures, and hence group sizes of ~ 10 do not necessarily indicate underpowered studies. Furthermore, all the studies

reported earlier in this paper investigating the effects of auditory discrimination training on the MMN (Kraus et al., 1995; Menning et al., 2002; Tremblay et al., 1997; 1998; 2001; Tremblay & Kraus, 2002; Zhang et al., 2009) also used ~10 (range: 7-13) participants in their studies. And they all showed effects of auditory discrimination learning on the MMN.

Along the same lines, the number of deviant trials that we were able to include in our experimental design (i.e. 90 deviant trials) was lower than what is generally recommended for MMN experiments (see e.g. Duncan et al., 2009; Kujala et al., 2007). But again, the fact that we did indeed elicit statistically reliable MMNs to the Arabic stimuli for both at T0 and T1, as well as at T2 and T3 for the group of Dari learners, speaks against the number of deviant trials severely affecting the signal-to-noise ratio (SNR) in the present study. And as already stated above, the fact that the contrast between T0 and T3 for the Arabic learners' MMNs to the Arabic stimuli elicits a significant difference, also speaks against the lack of statistically reliable MMNs at T3 reflecting merely low SNR (due to e.g. sub-optimal amounts of deviant trials).

Longitudinal studies face the challenge of adaptation to the stimuli. Any effect of learning may thus be masked by adaptation effects going in the opposite direction. The Dari learners' diminished P3a responses to the Arabic stimuli over time could be suggestive of an adaptation effect. The learning effects should be language-specific; a putative experimental adaptation effect should not. And since we did not see any reliable P3a responses to the Dari stimuli, it is difficult to tell whether the Dari learners' diminished P3a responses could be explained by an adaptation to the experimental paradigm and stimuli (and thus ought to occur for both stimuli). On the other hand, it is difficult to argue that the Dari learners' diminished P3a to the Arabic stimuli should reflect learning effects from the intensive Dari teaching.

4.2. The Dari fricative voicing contrast [ʃ]-[ʒ]

To add to this, both [ʃ] and [ʒ] are phonemic in English (e.g. Giegerich, 1992), the second or third language of all the participants of the present study, for which they had received teaching since 4th or 5th grade in elementary school. This could lead to the interpretation of the results that the cadets (pre-selected on the basis of among other things their linguistic skills) had already developed long-term memory traces for this contrast, and that their MMNs were already 'at ceiling'. The results from the behavioral experiment (Nielsen et al., 2015) speak against a so-called ceiling effect for the group of Dari learners since they do, in fact, show behavioral effects of learning. The slopes of their identification functions are significantly steeper at T1, T2, and T3 compared to T0, reflecting more categorical perception of the stimulus continuum for the later time points (Nielsen et al., 2015, Fig. 2D). And compared to three native Dari speakers, their categorical perception was not at native speaker level. So at least behaviorally, the Dari learners did not seem to be at ceiling already at T0. This still does not entirely rule out that their MMNs were at ceiling at T0 since Tremblay et al. (1998) showed that an increase in MMN may occur before the behavioral effect appears. But even if the learning effect we observed in the Dari learners' behavioral data within the first three weeks would have happened earlier in the learning progress for the neurophysiological responses than for the behavioral responses, we should still have caught it within the first time contrast between T0 and T1. So if we take the behavioral learning effect from T0 to the subsequent measurements at face value, it suggests that there was at least some amount behavioral learning, which was not reflected in the MMNs.

4.3. The Arabic emphatic pharyngeal fricative [ħ]

From the results of the behavioral experiment, it was evident that the Arabic stimulus contrast was subtler and thus more difficult to identify and discriminate

than the Dari contrast (Nielsen et al., 2015, Fig. 2 and 3). In this context, it is relevant to observe the latencies of the time windows we identified for the participants' MMNs to the two sets of stimuli. The MMNs to the Dari stimuli were centered on a peak in the differences of the GFP analyses at 128 ms after stimulus and deviance onset, whereas the MMNs to the Arabic stimuli were centered at 189 ms after deviance onset. This tentative difference in latency supports the behavioral findings of the Dari contrast being more readily identified and discriminated than the Arabic contrast.

Furthermore, Burnham (2013:7-9) reports that the /h-ħ/ contrast is one of the most, if not the most difficult contrast for learners of Arabic to acquire (both perceptually and in production), and that even advanced learners in their fourth or fifth year of university studies struggle with it. This confirms the reports we received from the group of Arabic learners who could all recognize the [hæ-ħæ] contrast as Arabic, but also as a contrast that they still found difficult to tell apart, even after 19 months of intensive language training. To add to this, since the acoustic cues that characterize the /ħ/ also involve vowel co-articulation, especially for /i/ and /u/ (Bin-Muqbil, 2006: 145-205), it may be that the Arabic learners to a large extent had relied on such co-articulation cues in the transitions into the neighboring vowels during their training with the /h-ħ/ contrast, and thus had relied to a lesser extent on the acoustic cues within the fricative itself. This is particularly plausible when we take the very densely packed vowel inventory of Danish into account (Basbøll, 2005:44-52; Grønnum, 2005:267-274), which would have allowed the Arabic learners to rely on their L1 phonology to pick up even subtle vowel co-articulation cues. Our present experiment does not allow us to investigate these speculations further in depth because we do not have data on the participants' perception of the /h-ħ/ contrast with different vowel co-articulations. And the acoustic cues used for the discrimination and identification of this contrast have also not been

investigated in any great detail with either native or non-native speakers (Burnham, 2013:9-10).

In this light, it is noteworthy that we were able to elicit statistically reliable MMNs to the Arabic contrast in both groups at most of the times of measurement, and that the contrast also elicited a robust P3a response in both groups at all four times of measurement.

The presence of P3a responses to the Arabic stimuli, but not to the Dari stimuli, may also be related to the more subtle nature of the Arabic contrast than the Dari contrast. All three levels of the Dari deviants may have been detectable to the participants, and hence they would perceive any of the three deviants occurring with an average summed frequency of 16.7%. However, due to the more subtle nature of the Arabic contrast, the participants' auditory systems may to a much lesser extent have perceived the two smallest deviants as deviants at all, and this would have led to an overall deviant frequency in the range of 5.6% (the average frequency of the largest deviant). Such a low probability constitutes very rare events, and stimulus probability is known to enhance the P3a response (Katayama & Polich, 1996; and see Winkler, Lehtokoski, et al., 1999b, p. 3 for traces of a responses with a deviant probability of 2.5%).

4.4. Correlations with behavior and grades

Our correlation analyses showed only one correlation between the MMNs and the behavioral results, namely for the Arabic learners' MMNs to the Dari stimuli at T3. These were positively correlated with the slopes of the Arabic learners' ID function, also at T3. Hence, those Arabic with the smallest MMN (i.e. least negative windowed mean) had the steepest slopes. This relationship did not reveal much about the potential link between behavior and neurophysiological responses, since its direction is opposite of what we would expect if higher

behavioral sensitivity would entail stronger neural responses indexed by the MMN (Kujala, Kallio, Tervaniemi, & Näätänen, 2001; Novitski, Tervaniemi, Huotilainen, & Näätänen, 2004; Tiitinen, May, Reinikainen, & Näätänen, 1994). And since no other similar correlations appeared at the other times of measurement, we are inclined to interpret this correlation as a false positive (see also Shafer, Schwartz, & Kurtzberg, 2004 who did not find any correlations between behavior and MMN on a Hindi bilabial-retroflex stop contrast). For the grades, the only significant correlation was more readily interpretable and it was corroborated by two supporting correlations that did not survive our corrected threshold, but which did pass an uncorrected alpha level of 0.05. The changes in Dari learners' MMNs to the Dari stimuli between T0-T1 correlated negatively with their listening grades after 17 weeks, indicating that those Dari learners with the largest increase in MMN (i.e. more negative) within the first three weeks received the highest grades after ~4 months.

Given the lack of results in the present study, it is thus possible that the full potentials of the effects of foreign language learning on the long-term memory traces for language sounds have not yet taken place in the two groups of language officer cadets, especially when we take the attested difficulty of the Arabic contrast into account. At the time of the last measurement, the participants had undergone 19 months of intensive language training including weekly interactions with native speakers and countless hours of conversation practice, as well as many other multi-faceted language learning tasks, but they had yet to experience a full in-depth linguistic immersion. Many of the participants have since the final measurement joined the Danish Armed Forces on missions in Arabic and Dari speaking countries where they have interacted with the local people on a daily basis. Whether such in-depth linguistic immersion in highly stressful situations could lead to further behavioral and/or neural adaptation to the sound categories of their target language remains a

speculation. But comparing the lack of results for educationally experienced L2 learners (Grimaldi et al., 2014; Hisagi et al., 2016; Peltola et al., 2003) with Winkler et al.'s (1999a) results for in-depth linguistically immersed L2 learners, lends some merit to this speculation.

5. Conclusion

In summary, we could not reject our null hypothesis regarding language-specific learning effects on the MMN. Despite 19 months of intensive foreign language training in two groups of highly motivated L2 learners of Arabic and Dari, we did not find any neurophysiological changes specific to their target language. We did observe changes over time in both groups' neural responses to the Arabic sound contrast, but these changes could not be meaningfully linked to any learning effects. Moreover, in a parallel behavioral study we observed a language-specific learning effect for the Dari learners, but this was thus not mirrored in that group's neurophysiological responses. We successfully elicited statistically reliable MMNs in the Dari learners ($n = 12$) to both target and non-target language stimuli at all four measurements, and in the Arabic learners ($n = 8$) to both target and non-target language stimuli at two out of four times of measurement.

There is some evidence that the Arabic contrast was of such a subtle nature that the Arabic learners might not have adapted to this until even later in their learning progress. This could seem to fall in line with the lack of learning effects seen in Peltola et al.'s (2003) study on experienced native Finnish L2 learners of English. However, this cannot be said about the Dari stimuli (a fricative voicing contrast). We cannot entirely rule out a ceiling effect for the Dari learners' MMNs to their target language contrast, but this seems unlikely when compared to our observed behavioral learning effect (Nielsen et al., 2015).

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Supplementary materials

Sounds 1-4: [hæ], [hæ]+28ms, [hæ]+49ms, and [hæ]+70 ($\approx$ [ħæ])

Sounds 5-8: [ʃa], [ʃa]-step4, [ʃa]-step7, and [ʃa]-step11 (= [ʒa])

Figure S1. Results of 2 x 2 x 4 factorial analyses of **(A)** global map dissimilarities (DISS) and of **(B)** global field power (GFP) of the difference waves. Between-subjects factor: Group (2); within-subject factors: Language (2) and Time (4).

Figure S2. Full channel overlays (30 electrodes) for both the Arabic stimuli **(left)** and the Dari stimuli **(right)** at T3 (deviants and deviants-as-standards). See figure captions for Figure 2 and 3 for more details. Nose is facing upwards. ERPs have been low-pass-filtered at 15 Hz for illustrative purposes.

Figure S3. Full channel overlays (30 electrodes) of the two groups' grand average difference wave ERPs for both the Arabic stimuli (**left**) and the Dari stimuli (**right**) at both T0 (**top**) and T3 (**bottom**). See figure captions for Figure 2 and 3 for more details on the color codes. Nose is facing upwards. ERPs have been low-pass-filtered at 15 Hz for illustrative purposes.