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Structural meter perception is pre-attentive

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ABSTRACT

A prominent question in timing research is whether meter perception is possible without attention to meter. So far, research has probed attention effects on meter perception with a surface-based approach that may create confounds between meter and rhythm, and not with a structural approach requiring abstraction from surface patterns. The available pattern of findings suggests that different meter dimensions (meter as beat hierarchy vs. meter as regular cycle length) may yield different attention effects: meter as cycle-length regularity may require attention (it is attentive but not pre-attentive), while meter as beat-hierarchy may be pre-attentive. However, it is unknown whether this dissociation prevails under structural meter processing. We examined attention effects on the EEG correlates of structural meter-processing, considering the two dimensions of meter perception: hierarchy and cycle-length. While the results for hierarchy violations were inconclusive, cycle-length violations induced pre-attentive, but not attentive, responses. These pre-attentive responses corresponded to late ERPs (300–600 ms), consistent with deep, structural meter-processing. Our findings highlight the importance of pre-attentive processing in meter perception, and they raise the hypothesis of dissociation between surface- and structure-based meter processing.

1. Introduction

The perception of musical meter entails the response to regular-length beat cycles in music wherein the first beat of each cycle (downbeat, or strong beat) feels more prominent than the others (up-beats, or weak beats) due to complex combinations of acoustic and structural cues (Hannon et al., 2004; Fitch, 2013, 2016). The prominence of strong beats correlates with peaks in listeners' expectations, as predictions tend to focus on these points (see London, 2002). Recurrent strong beats also correlate with spontaneous body movements: a frequent embodied response to meter perception is to start a recurrent movement on the strong beat. For instance, a march induces the perception of duple meter (1–2, 1–2 …), and this is embodied in the alternation of left-right (1–2) steps. A waltz is structured on triple meter (1-2-3, 1-2-3 …), and this guides dancers to move across the floor on the first of every three beats (Fitch, 2016). Quadruple meters are also frequent, and even more complex meters like five-beat or seven-beat cycles can be found in non-Western (Yates et al., 2017) or in contemporary Western music. Irrespective of cycle length, meter tends to be regular, in the sense that the listeners' default expectation is that the cycle length remains constant across a music piece (London, 2002). Therefore, meter perception engages at least two dimensions: (1) responding to the *beat hierarchy* (different expectations for strong vs. weak beats, e.g., Abecasis et al., 2009; Bolger et al., 2013; Fitzroy and Sanders, 2015; Fujioka et al., 2015; Kung et al., 2011; Perna et al., 2018), and (2) responding to the *regularity of the beat-cycle length,* namely by perceiving varying cycle-lengths as irregularities (e.g., Geiser et al., 2010; Geiser et al., 2010; Vuust et al., 2005; Vuust et al., 2009; Zhao et al., 2017).

A prominent question in meter research concerns the effects of attention on meter perception (Grahn, 2012; Honing et al., 2014): does it occur regardless of attention paid to meter? From a formal viewpoint, there are at least three possible answers: meter perception occurs (1) both with (attentive perception) and without attention (pre-attentive); (2) with attention, but not unattentively; (3) without attention, but not attended to. One way of approaching this question is to analyze the EEG correlates of meter perception (distinguishing regular or *standard* meter from irregular or *deviant* meter) under two different conditions: explicit meter-judgement tasks (attentive perception) and tasks that focus the listeners' attention in something other than rhythm (e.g., pitch; pre-attentive meter perception). Among available EEG studies using this paradigm, there are at least two unresolved issues: first, results concerning attention effects remain mixed so far; second, meter has been approached from a surface-based, instead of a structure-based

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viewpoint.

Concerning mixed findings, a considerable number of EEG studies addressing only pre-attentive conditions showed that meter perception occurs in such circumstances (Geiser et al., 2010; Ladinig et al., 2009; Vuust et al., 2005, 2009; Zhao et al., 2017). However, direct comparisons between attentive and pre-attentive conditions indicated effects of attention on meter perception, in that it seems to occur attentively but not pre-attentively (Geiser et al., 2009). Therefore, while attentive meter processing seems to be real, evidence concerning pre-attentive processing is mixed, and the answer to the question of attention effects on meter perception seems to be either (1) or (2). One reason for mixed findings regarding pre-attentive processing may be that different EEG meter studies have emphasized different dimensions of meter perception – hierarchy vs. cycle-length (Grahn, 2012). An example of a hierarchy-violation paradigm is that of Ladinig et al. (2009), in which sound omissions were presented at strong beats (unexpected omission, see Fitch and Rosenfeld, 2007; Palmer and Krumhansl, 1990) vs. weak beats (less unexpected omission). In contrast, cycle-length-violation paradigms (e.g., Geiser et al., 2009) are based on irregularities in beat-cycle-length. The possibility of pre-attentive meter perception has been put forward in studies using hierarchy violations (e.g., Ladinig et al., 2009), but it was refuted in studies employing cycle-length deviations (Geiser et al., 2009). Therefore, there might be a dissociation in attention requirements between hierarchy-related processing (that could be pre-attentive) and cycle-length-related meter processing (pre-attentive not possible). Since no study has yet probed the two dimensions simultaneously, this putative dissociation remains undocumented.

The second unresolved issue - scarcity of *structure-based approaches* to meter - relates to the fact that meter studies have elicited little or no *abstraction* from listeners so far. Meter perception always implies some degree of abstraction (Fitch, 2013), in that any given cycle of strong-weak alternating beats (meter) must be inferred from the concrete pattern of varying durations, or inter-onset intervals that substantiate rhythm. Rhythms form the *surface* (in Fig. 1, sequences represented by Xs) from which listeners extract the underlying metric *structure* (in Fig. 1, large and short vertical bars in the upper part). If the rhythmic surface remains constant in the meter-standard condition (rhythmic pattern unchanged across bars, as in standards from Fig. 1A, S1) but varies in the deviant condition (deviants in Fig. 1A, S2-3), listeners do not need to perform deep meter-like abstraction to distinguish between standards and deviants. This type of manipulation was done by Vuust et al. (2005, see also Vuust et al., 2009), who analyzed pre-attentive MEG responses to deviations of a recurrent rhythmic pattern (three repetitions of the same pattern, one per 4/4 bar) and saw increased Event-Related-Field responses for deviants when contrasted with standards. Standards consisted of repetitions of a single rhythmic pattern across bars, and deviations were made up by deleting the last eighth-note of the second bar (second bar becomes 7/8 instead of 4/4). Geiser and colleagues (Geiser et al., 2009) used a similar approach, presenting subjects with a continuous triple-meter (3/4) rhythm that was switched occasionally (1/3 of bars) into meter deviants with shorter (5/8) or longer bars (7/8), either by deleting or adding an eighth-note. Examples in Fig. 1A (S1-3) illustrate this type of manipulation. In a slightly different approach, Zhao et al. (2017) stimulated participants with isochronous tones having regularly vs. irregularly-spaced accents (strong beats, S4). Again, we cannot be certain that deep meter-like abstraction occurred, since participants may simply have counted the inter-accent isochronous events.

In sum, it is yet unknown how attention impacts meter perception when there is proper structural processing, i.e., abstraction from surface-varying music structures. Surface-based approaches to meter suggest that the two dimensions of meter perception – beat hierarchy and cycle-length regularity – dissociate in attention effects, but we do not know whether this holds true for structure-based approaches to meter. In the present EEG study, we tested the hypothesis of dissociation between beat hierarchy and cycle-length regularity concerning attention effects on *structural* meter processing.

In order to grant a structure-based approach to meter, we made it impossible for listeners to rely on surface (rhythm) changes when perceiving meter deviants. To this end, we created 3-bar rhythmic phrases in which the second bar either kept the meter from the first bar (standard) or introduced a different meter (deviant). In both cases, the second bar always differed from the first one in terms of rhythm (see Fig. 1B). Our approach contrasts with previous ones (e.g., Geiser et al., 2009; Vuust et al., 2005; Zhao et al., 2017) - where meter standards consisted of rhythmic repetitions of the previous bar, and meter deviants consisted of rhythmic deviants (Fig. 1A). It prevents confounds between rhythm and meter processing, thus targeting structural processing proper. In order to test for the dissociation between beat-hierarchy and cycle-length regularity, we presented meter deviations of these two types to a single group of participants and probed the two dimensions simultaneously.

We measured attention effects with the EEG paradigm that has been used so far (e.g., Geiser et al., 2009): a single group of participants underwent both an attended-meter condition (*attended*, hereafter) – where explicit meter-judgements on standard vs. deviant meter patterns were required – and an unattended-meter condition (*unattended*) – where they were asked to perform a pitch-deviant detection task on the same stimuli. In the attended condition, we gathered both behavioral and EEG meter-processing-related data. We were thus able to analyze the correlations between these two data types in order to make sure that the observed ERPs reflect meter perception. This has not been done in previous studies, and it represents an additional improvement of previous experimental designs.

Regarding predictions, the surface-based literature pointed, as we saw, to a dissociation in attention effects between the 2 m dimensions - beat-hierarchy vs. cycle-length regularity: in the latter case, meter processing should occur with attention, but not unattentively (attention effects, answer 2, see above); for the hierarchy-related dimension, meter processing should occur pre-attentively, and the most parsimonious complementary guess would be that it would also occur with attention (no attention effects, answer 1). However, since we adopted a structural-based approach to meter, deviations to these predictions were possible: specifically, we admitted the possibility that – given the increased complexity of structural compared to surface-based meter processing – structural meter processing loads the explicit processing system and shows up *without, but not with* attention (Masters, 1992; Reber et al., 1980). This would speak in favor of attention effects on meter perception with a different direction, matching the alternative answer - answer 3 - to our research question.

Concerning the expected ERP components responding to meter perception, most EEG studies carried out so far have highlighted early components such as the Mismatch Negativity (150–200 ms) and the P3a (~300 ms) for pre-attentive meter processing, or on the N2b (150–200 ms) for attentive processing (see Honing et al., 2014). Given that we used structural-processing-inducing stimuli, and structural processing in music perception reflects into later ERPs (Koelsch, 2011), we predicted that meter deviants would impact late ERPs rather than early ones.

2. Materials and methods

2.1. Participants

Eighteen participants (6 men; age, *Mean* + *SD*: 23.6 + 6.7; schooling: 15.4 + 1.6) volunteered to take part in the experiment. They were all right-handed and had normal hearing. None was taking medication or struggling with psychiatric or neurological disease. Five participants had musical training beyond elementary school (one with four years of training, three with five, one with six). All signed informed consent, according to the declaration of Helsinki.

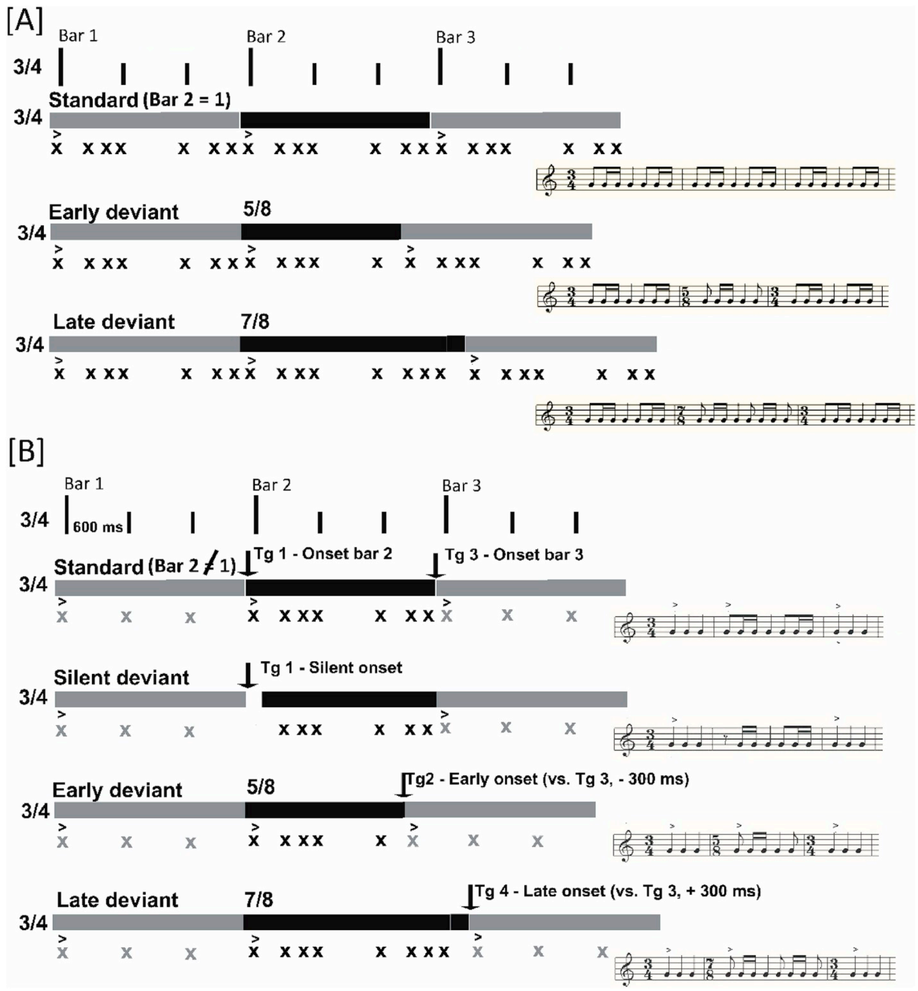

Fig. 1. (A) Structure of stimulus materials (meter standard vs. meter deviants) used in previous studies (e.g., Geiser et al., 2009), where the critical bar (here, bar 2) repeats bar 1 in the standard condition and allows surface-based discrimination between standards and deviants. Xs represent sound onsets. (B) Stimuli used in the current study, where bar 2 always differed from bar 1, thus eliciting structural meter processing. In the current EEG study, trigger 1 (Tg 1) contrasted silent deviants with the onset of bar 2 at standards; both Trigger 2 at early deviants and Trigger 4 at late deviants contrasted with Trigger 3 at standards (onset of bar 3).

2.2. Stimuli

We created 87 3-bar, triple meter (3/4) rhythmic phrases (Fig. 1B, S5), all with a beat length of 600 ms. The first and last (third) bars were filled with quarter-notes, setting the meter, and the first event/note in each bar had an intensity accent in order to highlight metric structure (Windsor, 1993). The second bar had various rhythms (one per sequence, see example sequence at Fig. 1 and Appendix 1), built with combinations of eighth-, quarter-and sixteenth-notes. Rhythmic values were defined at a MIDI sequencer (www.propellerheads.se/en/reason) with no human performance involved, and they were played with constant, flat pitch set to G3.

The 87 Standard versions were modified in order to generate 87 m deviants (Appendix 1). These were of three types (Fig. 1B): *silent deviant* (n = 29, S6), with the onset of the second bar filled with silence; *early deviant* (n = 29, S7), with second bar shortened by 300 ms (half beat, 5/8 time signature) and third bar accent coming earlier-than-expected; *late deviant* (n = 29, S8), with second bar lengthened by 300 ms (half beat, 7/8 signature) and third bar accent coming later than expected. Standards and silent deviants lasted for 5600 ms; the length of early deviants was 5300 ms, and that of late deviants 5900 ms. Silent deviants represented hierarchy-related violations, and early and late deviants represented cycle-length violations.

Approximately half of the 87 standard versions (n = 45) contained silent onsets *at weak beats* (second or third beat) of the second bar (see Appendix 1). These 45 standard versions with silent onsets were distributed by the three deviant conditions in the meter-deviant generation procedure (16 for silent deviants, 14 for early deviants, 15 for late deviants). Therefore, deviant versions contained the same proportion of silent onsets at weak beats as standard versions, and the three deviant types (silent, early, late deviants) were matched for this. This way we could ensure that discrimination between standards (silent onsets at second/third beat) and silent deviants (silent onsets at first beat) was not due to the mere perception of silences, and that it was a specific response to silences at the strong beat.

The 174 rhythms (87 Standard + 87 Deviants) were organized in two blocks: block 1, 43 standard + 17 silent deviants + 16 early deviants + 11 late deviants; block 2: 44 standard, 12 silent deviants, 13 early deviants, 18 late deviants. These two blocks (174 rhythms in total, half standard, half deviant) were presented twice – in the pitch-deviant detection and then in the explicit meter-judgement task (see procedure). In order to allow pitch-deviant detection, we inserted pitch deviants (one high-pitch quarter note, C4) in 54 trials (~31% of trials) – 28 in block 1 and 26 in block 2. Pitch deviants were balanced across standard and deviant metric-types, such that we had 26 pitch deviants for standard-meter phrases (30% of 87), 9 for silent deviants (∼30% of 29), 8 for early deviants (∼30% of 29) and 10 for late deviants (∼30% of 29). Since pitch deviants were included in both stimulus presentations (pitch-deviant detection and explicit meter-judgement), we placed them always at one of the three quarter-notes of the third bar (see Fig. 1), in order not to interfere with meter-deviant detection.

Each stimulus was marked with four different triggers (Fig. 1): Trigger 1 (Tg1), at the onset of the second bar, marking the silence onset at the strong beat in the silent deviant condition; Trigger 2, at the onset of the early deviant (third bar of early deviant), marking the early appearance of the strong beat (300 ms earlier than standard); Trigger 3, at the onset of the third bar of standards; Trigger 4, at the onset of the late deviant (third bar of late deviant), marking the late appearance of the strong beat (300 later than standard).

2.3. Procedure

All participants started with the pitch-deviant detection task, and then proceeded to the explicit meter-judgement task. In the former task, they were instructed to press the YES key if they heard a high-pitched sound, different from all the others in the phrase, and the NO key in case they did not. In the explicit meter-judgement task, participants (most of them non-experts) were given a verbal and graphic explanation of what we meant by standards ("right" rhythms, with accents every three beats) and deviants ("wrong" rhythms, comprising absent accents/silent deviant, early accents/early deviant and delayed accents/late deviant). During the explanation, it became obvious that participants were generally unfamiliar with the concept of meter. In each trial, they were asked the question "anything wrong?", and then press the YES key in case they heard "wrong" rhythms, and NO if they heard the "right" ones. In both tasks, we provided participants with auditory examples and with a practice period of three trials.

The experiment was self-paced. Each trial started with a 200 ms fixation cross, after which the auditory stimulus would follow. Once the stimulus ended, a question appeared at the monitor, and the participant pressed a key to provide his/her response. S/he then moved on to the next stimulus by pressing the space bar. Participants were advised to blink during this period.

Each of the two tasks was presented in two blocks, with 12 min each, so that participants were allowed to have breaks. Stimuli were pseudorandomized and delivered through loudspeakers. The disposition of the YES/NO keys (left vs. right CTRL keys) was counterbalanced across participants. The total duration of the experiment (scalp preparation included) ranged between 60 and 70 min.

At the end of the experiment, participants filled in a questionnaire with sociodemographic data, as well as ratings on the levels of difficulty and fatigue (scale from 1 to 5) for each of the two tasks.

2.4. Recording and preprocessing

The EEG was recorded at 512 Hz with a Biosemi ActiveTwo system (www.biosemi.com). We collected data from 64 active channels, mounted on an elastic headcap (BioCap) based on the 10/20 system. Three additional external electrodes were placed at the mastoids, for reference, and under the left eye, for detecting vertical EOG artefacts. Signal quality was controlled according to Biosemi system-specific guidelines.

EEG data were analyzed with the fieldtrip toolbox (Oostenveld et al., 2011) for Matlab (mathworks.com). Epochs from correct trials were marked 200 ms before and 1000 ms after trigger points. Ocular artefacts were visually inspected, based on referencing the external EOG electrode to Fp2 (vertical movements), and F7 to F8 (horizontal movements). After this first rejection stage, additional epochs were eliminated by inspection of trial variance. Final trials were band-pass filtered (0.01–30 Hz) and detrended. Data were referenced to the two mastoid electrodes. Subject-level averages were obtained for the different conditions, and these were later grandaveraged.

2.5. Statistical analysis

We analyzed participants' behavioral discrimination in each task separately, testing d-prime values (one d-prime value for pitch-deviant detection; three d-prime values for meter-deviants, one per deviant type) against zero and correlating these with musical training. In addition, we compared the levels of perceived difficulty and fatigue across tasks.

For EEG data, we compared meter standards with meter deviants in attended vs. unattended conditions (2×2 design, meter x attention), focusing on meter effects (meter perception) and meter × attention interactions (modulation of meter perception by attention). We compared each of the 3 m deviants to meter standards (silent deviant against standard, both at trigger 1; early deviant, trigger 2, against standard, trigger 3; late deviant, trigger 4, against standard, trigger 3, see Fig. 1). In the comparison between silent deviants (metrically-relevant silences, placed at the first beat of the bar) and standards, we did an additional control analysis, where we compared silent deviants with the metrically-irrelevant silences of standards (i.e., silences inserted at the second or third beat of bar 2, see Stimulus and Appendix). We named these *standard silences*. The purpose of analyzing standard silences was to cross-check the evidence that the ERPs to silent deviants, which intended to capture meter perception, were actually a response to meter (cf. Stimulus section), and not merely to silence. If the ERPs to standard silences differed from those to silent deviants, this would support the idea that silent deviants were eliciting a meter-deviance-specific response.

Grandaveraged channels were grouped into 6 Regions Of Interest (ROIs, Fig. 2): Left Anterior (FP1, AF7, AF3, F3, F5), Middle Anterior (F1, Fpz, AFz, Fz, F2), Right Anterior (Fp2, AF8, AF4, F4, F6), Left Central (FC5, FC3, C3, C5, CP5, CP3), Middle Central (FC1, C1, CP1, CPz, Cz, FCz, FC2, C2, CP2), Right Central (FC6, FC4, C4, C6, CP6, CP4), Left Posterior (P3, P5, P7, PO7, PO3), Middle Posterior (P1, Oz, POz, Pz, P2), Right Posterior (P4, P6, P8, PO8, PO4). We thus had 3 caudality levels and 3 laterality levels. Each trigger (silent deviants and late deviants) was analyzed with a 2 x 2 x 3 x 3 (attention x meter x caudality x laterality).

We used Cluster Randomization Analysis, a non-parametrical, bottom-up statistical test based on spatiotemporal clustering (Maris and

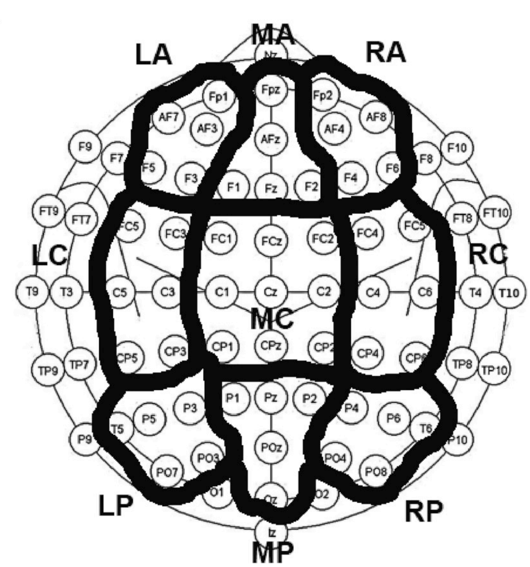

Fig. 2. Regions Of Interest (ROIs) used in EEG analysis (L = Left, M = Middle, R = Right, A = Anterior, C = Central, P = Posterior).

Oostenveld, 2007) in order to detect time windows in which meter effects were observed. The analyses indicated the interval between 280 and 570 ms for trigger 1, and 350–510 ms for trigger 2 (against 3). For trigger 4 (against 3), we saw significant meter effects between 8-280 ms and 320–590 ms. Therefore, we divided the epochs into two time windows: 0–300 ms for early and 300–600 ms for late ERPs. We ran a 2 x 2x3 x 3 (attention x meter x caudality x laterality) repeated measures ANOVA for each, using a critical significance level of 0.05 with Greenhouse-Geiser corrections for sphericity violations. We focused on meter effects (standard vs deviant), breaking down the analysis into caudality and/or laterality levels when interactions with these were seen. We then focused on attention × meter interactions, comparing standards with deviants in each attention level for significant interactions, and then inspecting possible interactions with caudality and/or laterality. Paralleling behavioural analysis, we tested whether musical training (number of years) correlated with ERPs.

3. Results

3.1. Behavioral results

Discrimination between pitch deviants and pitch standards in the deviant-detection task (unattended condition) was significant (d-prime, *M* + *SD*: 3.40 + .30, $t(17) = 47.69$, $p < .001$). Musical training did not correlate with d-prime ($p > .31$).

Discrimination between standard and deviant meter was significant for silent deviants (*M* + *SD*: 1.04 + 0.59; $t(17) = 4.50$, $p < .001$) and late deviants (*M* + *SD*: 0.49 + 0.76; $t(17) = 2.71$, $p = .015$), but not for early deviants (*M* + *SD*: 0.31 + 0.84; $t(17) = 1.55$, $p > .13$). Unlike the pitch deviant-detection task, musical training correlated with d-prime values for silent deviants ($r = 0.485$, $p = .042$), early deviants ($r = 0.700$, $p = .001$) and late deviants ($r = 0.592$, $p = .010$).

Participants rated explicit meter-judgement (mean rate 4.06/5) as significantly more difficult ($t(17) = -5.33$, $p < .001$) than pitch deviant detection (1.89/5). The two tasks generated equivalent levels of fatigue (pitch deviant 2.89/5, explicit meter-judgement, 3.39/5, $p > .24$).

Although participants showed no discrimination between early deviants and standards, we still considered early deviants (trigger 2) in the analysis of EEG.

3.2. EEG: silent deviant onset against standard onset (trigger 1)

No meter effects or interactions with attention for early ERPs (0–300 ms, Fig. 3): the main effects of meter were non-significant ($p = .69$). There was a significant meter x laterality interaction ($F(1.35, 22.98) = 8.05$, $p = .005$, $\eta^2 p = .32$), but meter effects were not significant in any of the three regions (left, middle or right, $ps > .41$).

The attention × meter interaction was not significant ($p = .56$), and there were no third-order interactions with caudality ($p > .35$) or laterality ($p > .39$).

Attention-independent meter effects for late ERPs (300–600 ms, Fig. 3): meter effects were significant (increased positivity for deviants: $F(1,17) = 13.24$, $p = .002$, $\eta^2 p = .44$), and so were meter × caudality interactions ($F(1.07.18.19) = 10.21$, $p = .004$, $\eta^2 p = .38$). The late positivity was stronger for deviants than for standards at anterior ($F(1,17) = 11.76$, $p = .003$, $\eta^2 p = .41$; *standard-deviant* = −4.18, *SE* = 1.22, *CI* (95%) = [-6.65–1.61]) and central electrodes ($F(1,17) = 21.47$, $p < .001$, $\eta^2 p = .56$; *standard-deviant* = −3.34, *SE* = 0.72, *CI* (95%) = [-4.86–1.82]), but not at posterior ones ($p > .17$). Meter effects correlated strongly with d-prime ($r = 0.639$, $p = .006$) and with musical training ($r = 0.599$, $p = .009$).

Attention x meter-related interactions were non-significant (attention x meter, $p = .81$; attention x meter x caudality, $p > .55$; attention x meter x laterality, $p > .39$; attention x meter x caudality x laterality, $p = .78$).

Control analysis (Fig. 4): Between 300 and 600 ms, the comparison between silent onsets at weak metrical positions (silent standards) and silent deviants showed non-significant meter effects (main effect: $p > .43$; meter x caudality: $p > .35$; meter x laterality: $p > .11$) and non-significant interactions with attention ($ps > .31$). We further compared the silent deviant – standard difference (attention levels collapsed) with silent standard – standard, and we saw no differences between the two for meter effects and topographical interactions, $ps > .17$. We found a similar pattern for the early time window (0–300 ms): meter effects and topographical interactions were non-significant ($ps > .43$); attention x meter interactions were also non-significant ($ps > .29$); the silent deviant – standard difference was statistically equivalent to the silent standard – standard difference ($ps > .11$). Overall, these results indicate that silent standards had the same effects as silent deviants. Thus, we cannot be sure that the ERPs reflect meter perception, they may simply indicate the perception of silence.

3.3. Early deviant onset (trigger 2) against standard onset (trigger 3)

No meter effects for early ERPs (0–300 ms, Fig. 5): There were no significant meter effects ($p > .50$), attention x meter interactions ($p > .84$), or any further interactions with caudality ($p > .18$) or laterality ($p > .84$) in early ERPs.

Attention-dependent meter effects for late ERPs (300–600 ms, Fig. 5): there was a significant interaction between attention, meter and caudality ($F(2,34) = 9.67$, $p = .005$, $\eta^2 p = .36$). Attention x meter interactions were non-significant at anterior ($p > .26$) and central regions ($p > .79$), but they were marginal at the posterior one ($F(1,17) = 3.22$, $p = .090$, $\eta^2 p = .16$). Posterior electrodes showed no meter effects for the attended condition ($p > .38$), but they did for the unattended one, where early deviants exhibited increased negativity compared to standards ($F(1,17) = 7,35$, $p = .015$, $\eta^2 p = .30$; *standard – earlydeviant* = 1.51, *SE* = 0.56, *CI* (95%) = [0.34 2.68]).

The increased negativity for deviants in the unattended condition did not correlate with d-prime ($p > .34$) nor musical training ($p > .68$).

3.4. Late deviant onset (trigger 4) against standard onset (trigger 3)

Attention-independent meter effects for early ERPs (0–300 ms, Fig. 6), but uncorrelated with behaviour: there was a significant meter effect (increased positivity for deviants: $F(1, 17) = 5.00$, $p = .039$, $\eta^2 p = .23$; *standard – late deviant* = −1.30, *SE* = 0.58, *CI* (95%) = [-2.53–0.07]), not interacting with caudality ($p > .11$) or laterality ($p > .63$). These widespread meter effects did not correlate either with d-prime ($p > .42$) or with musical training ($p > .65$).

Meter effects did not interact with Attention ($p > .10$).

Attention-dependent meter effects for late ERPs (300–600 ms, Fig. 6): meter effects were not significant ($p > .75$), but there was an interaction between attention and meter ($F(1,17) = 4.43$, $p = .05$, $\eta^2 p = .21$): whereas attended trials showed no significant differences between standards and deviants ($p > .16$), unattended trials showed meter x caudality interactions ($F(1.15, 19.57) = 17.84$, $p < .001$, $\eta^2 p = .51$). Breaking down the analysis of unattended trials into caudality levels, we found meter effects at posterior electrodes (increased negativity for deviants: $F(1,17) = 13.34$, $p = .002$, $\eta^2 p = .44$; *standard – early deviant* = 2.15, *SE* = 0.59, *CI* (95%) = [0.91 3.39]). Although there was a meter x laterality interaction ($F(2,34) = 4.15$, $p = .024$, $\eta^2 p = .20$), all posterior regions showed meter effects (left: *F*

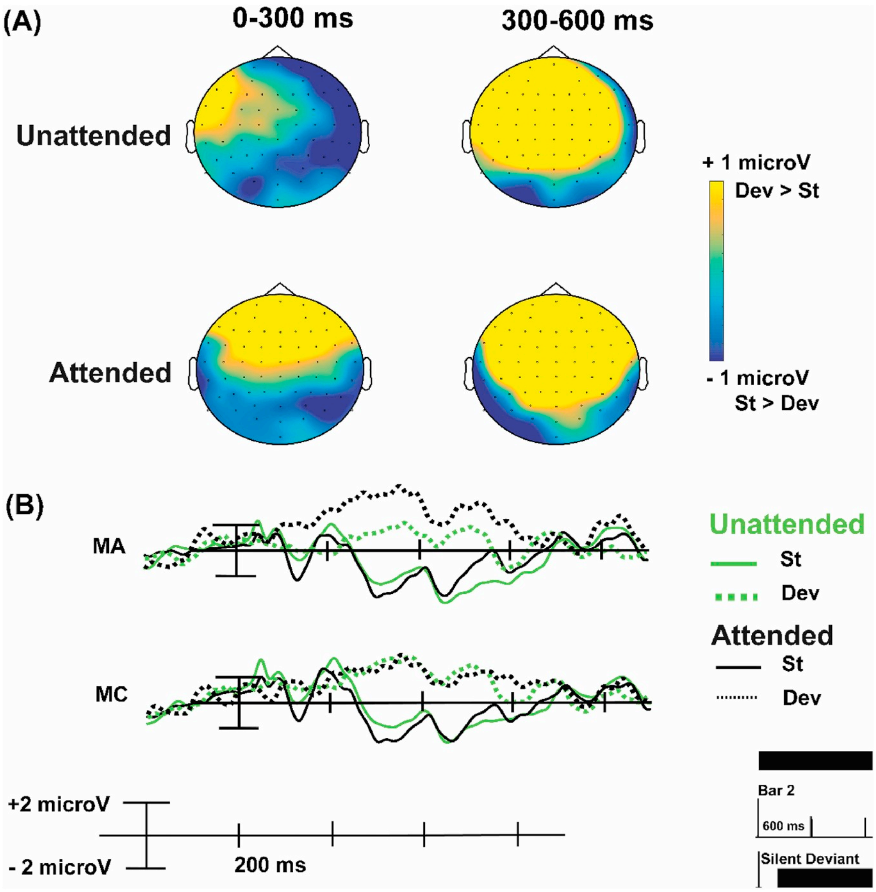

Fig. 3. Topographic maps (A) and illustrative waveforms (B) of meter effects (deviant-standard) under unattended vs. attended conditions for silent deviants (hierarchy violations, trigger 1). Both unattended and attended showed a late (300–600 ms) anterior-central positivity for silent deviants. MA = Mid-anterior region; MC = Mid-central region.

(1,17) = 9.91, p = .006, η^2p = .37; middle: F(1,17) = 14.44, p = .001, η^2p = .46; right: F(1,17) = 14.75, p = .001, η^2p = .47). At central electrodes, there was a significant meter x laterality interaction (F (2,34) = 10.19, p < .001, η^2p = .38), with middle-central electrodes showing meter effects (F(1,17) = 5.41, p = .033, η^2p = .24; *standard – late deviant* = 1.80, *SE* = 0.77, *CI* (95%) = [0.17 3.43]), but not left-central (p > .22) or right-central ones (p > .19). Anterior electrodes showed no meter effects (p > .40) or meter x laterality interactions (p > .24).

The mid-central and bilateral-posterior late negativity for unattended deviants correlated marginally with d-prime (r = - 0.422, p = .081) as well as with musical training (r = - 0.443, p = .066).

4. Discussion

We investigated whether there are effects of attention on meter perception by examining EEG correlates of meter perception in novel ways: first, we have directly compared the two dimensions of meter perception – beat-hierarchy (silent deviants) and cycle-length perception (early and late deviants); second, we probed structural meter-processing by making listeners abstract meter from surface-varying rhythmic patterns; third, we tested the correlation between EEG and behavioral data in order to better identify proper meter-related ERPs.

Based only on the available studies, which used surface-based approaches to meter, our prediction would be that cycle-length meter

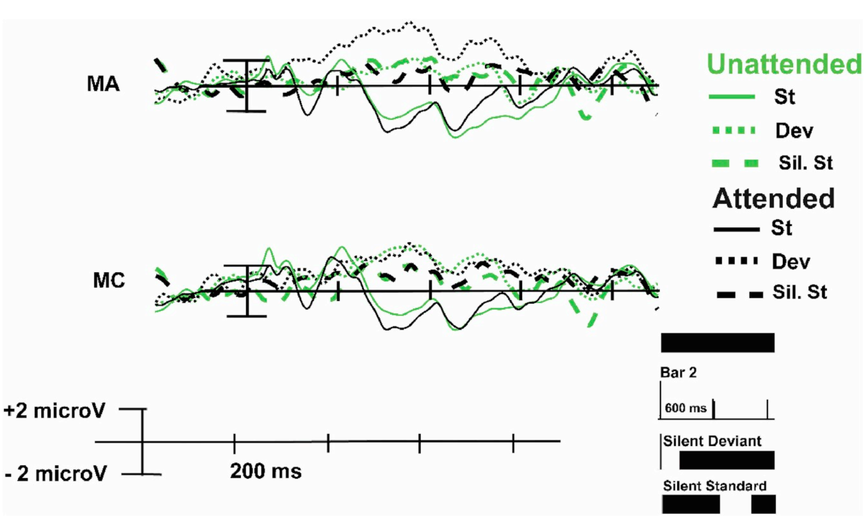

Fig. 4. Illustrative waveforms of silent standards (silences at weak beats, thick dashed line) superimposed on the waveforms of silent deviants against standards (hierarchy violations, trigger 1, cf. Fig. 3). There were no significant differences between silent standards and silent deviants, suggesting that ERPs did not capture meter perception proper. MA = Mid-anterior region; MC = Mid-central region.

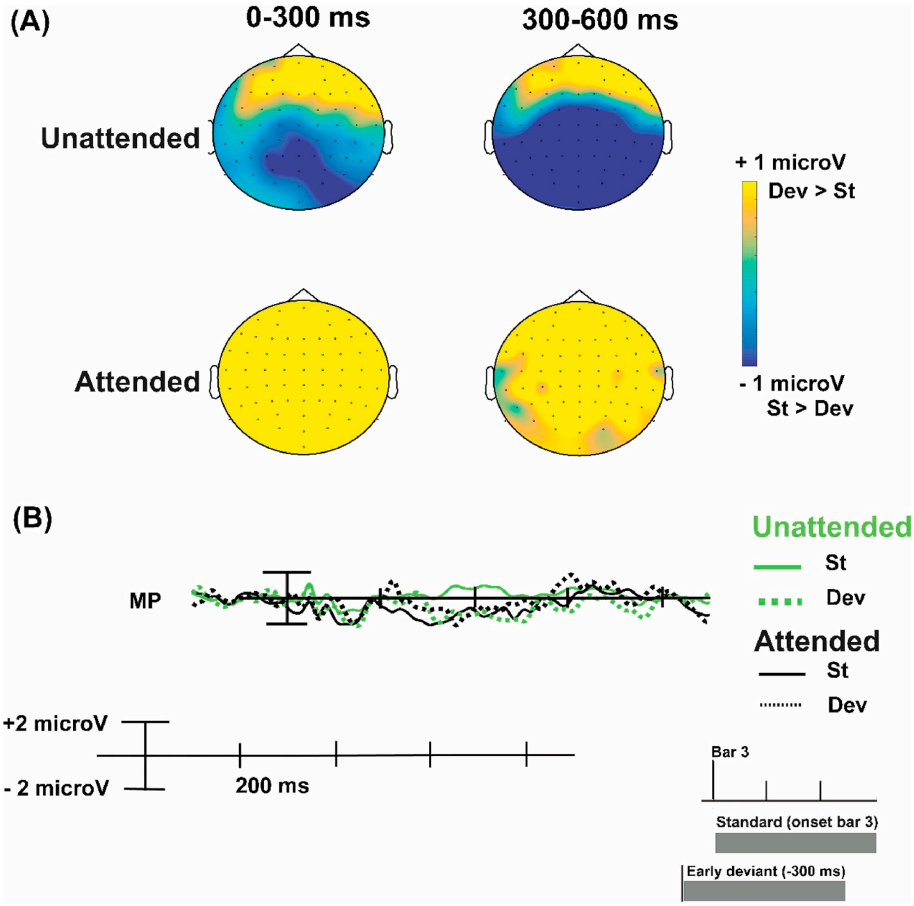

Fig. 5. Topographic maps (A) and illustrative waveforms (B) of meter effects (deviant-standard) under unattended vs. attended conditions for early deviants (cycle length violations, trigger 2 for standard and 4 for deviant). While unattended showed a late (300–600 ms) posterior negativity for late deviants, attended showed no significant meter effects. MP = Mid-posterior region.

violations impact EEG responses only under attention to meter, while hierarchy violations would be able to do it with and without attention to meter However, we approached meter from a structure-based viewpoint instead of a surface-based one. Our question was: will this shift in perspective invalidate the predictions arising from surface-based studies?

The answer was yes: unlike anything seen in surface-based studies, structural meter processing was *pre-attentive but not attentive*. This was clear for cycle-length violations, where we found a late central-posterior (300–600 ms) negative response that occurred only in the unattended condition. This late negativity was seen in both early deviants (shorter cycle length) and late ones (longer cycle). The fact that we saw the same type of ERPs (late negativity) in both unattended late deviants and unattended early deviants strengthens the evidence for a cycle-length-violation-specific ERP signature. In early deviants, the correlation between ERPs and behavior was non-significant, but that was probably due to the poor performance levels in early deviants, which showed no significant behavioral discrimination from standards.

The possibility of pre-attentive processing is not surprising, since it consistent with previous findings of passive entrainment to meter (Cirelli et al., 2016), of pre-attentive processing of hypermeter – referring to 4-bar phrases (Silva et al., 2014a, 2014b), as well as with studies showing that (pre-attentive) meter structure guides the processing of target events (Bolger et al., 2013). In our study, the presence of pre-attentive but not attentive meter processing may have been due to the fact that we elicited increased levels of meter abstraction (structural processing) relative to previous studies (surface processing), thus changing the dynamics of meter perception and rendering our findings not comparable with previous ones. Specifically, it is likely that, under strong abstraction requirements such as the ones we induced, meter perception becomes so complex that it is better handled by the implicit processing system. This would meet the long-known principles that complexity benefits from implicit processing (Reber et al., 1980), and explicit instructions often hinder performance in complex tasks (Masters, 1992). Therefore, when dealing with structural meter processing, pre-attentive processing may not just be possible: it may be necessary, and previous studies may have missed this point due to the surface-based approach to meter. In order to move forward with this hypothesis, future studies should perform a direct contrast structural and surface-based meter processing.

Supporting our prediction concerning EEG components, we saw *late* EEG responses (300–600 ms) to our meter deviants, which required deep, structural processing in order to allow meter abstraction. The fact that we did not see any MMN or N1-like response to meter deviants, paralleling previous EEG meter studies (e.g., Geiser et al., 2009; Ladinig et al., 2009; Vuust et al., 2005, 2009), may be, thus, related to the structural processing mode we elicited, even though other explanations may exist: for instance,.the absence of an MMN-like component may relate to the fact that our meter deviants were not a minority within stimuli (infrequent deviants), as it happens in a typical MMN paradigm (Näätänen et al., 2007). Instead, we had as many deviants as we had standards (87 per class), which may have been responsible for our divergent pattern of ERPs. It has been suggested that MMN is a response to the minority status of stimuli (infrequent deviants) and not to deviance itself (Ruusuvirta, 2001). If this is the case, maybe MMN paradigms are not the most adequate tool to investigate meter perception, since meter perception is a matter of incongruity (the basic expectation is that of regularity) rather than a matter of rarity. Apart from the

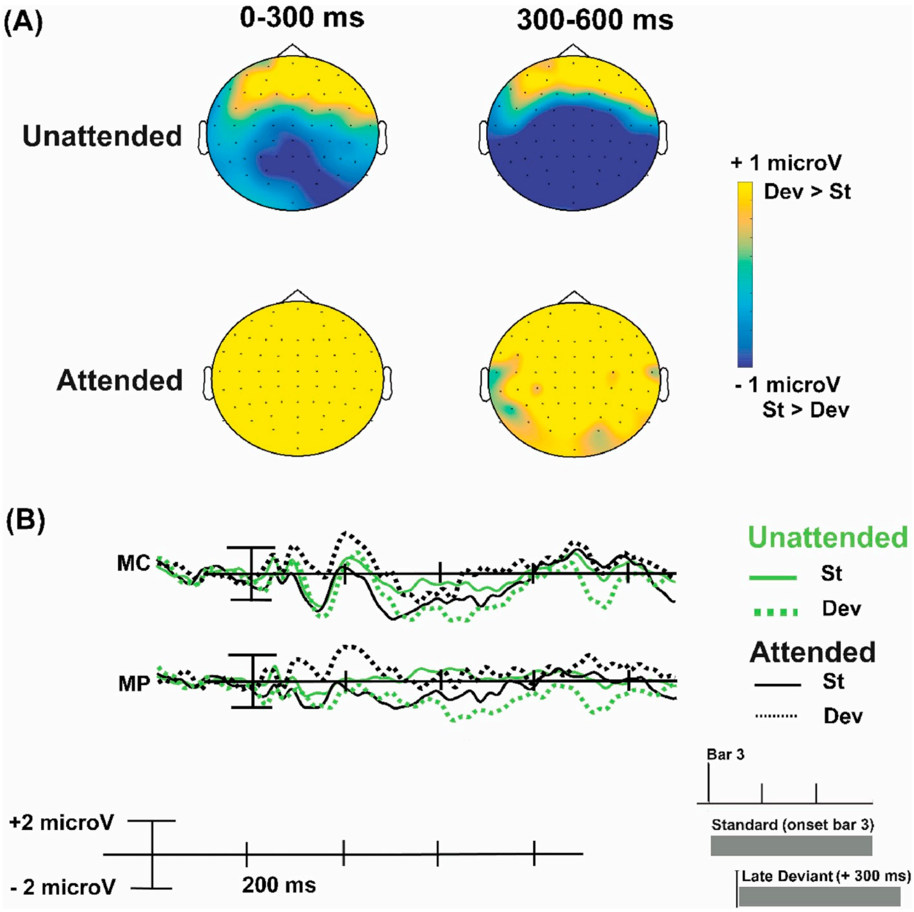

Fig. 6. Topographic maps (A) and illustrative waveforms (B) of meter effects (deviant-standard) under unattended vs. attended conditions for late deviants (cycle length violations, trigger 3 for standard and 4 for deviant). While unattended showed a late (300–600 ms) central-posterior negativity for late deviants, attended showed no significant meter effects. MC = Mid-central region; MP = Mid-posterior region.

distinction between surface and structural meter processing, there is also the fact that previous research neglected late ERPs, focusing only on early ones. For instance, Geiser et al. (2009) noted discrepancies between EEG and behavioral data, with behavioral but not EEG data showing musical expertise effects. The authors suggested that the processes of interest may not have been properly captured in the analyzed ERPs, which were restricted to early (0–200 ms) time windows. Thus, one recommendation for future studies could be that researchers keep their focus open to late ERPs.

Even though we highlighted the need to distinguish between surface- and structure-based approaches to meter (one of our two major goals), we failed in clarifying the hypothesis of dissociation between hierarchy- and cycle-length-related deviations concerning attention effects on meter processing (our other goal). For hierarchy-related meter violations, our exam of attention effects on meter perception was inconclusive because we could not fully demonstrate that participants responded to meter violations proper, rather than to mere silence. On the one hand, we inserted silences at weak beats (2nd, 3rd beat) in half of our standard stimuli, and demonstrated that our participants showed above-chance discrimination between standards and silent deviants (meter deviants with silence at 1st beat). We reasoned that, if participants had merely detected silences, successful behavioral performance would have been hard to achieve. However, when we compared EEG responses to sound omissions at strong (silent deviants) vs. weak beats (silent standards) for cross-check, we saw no differences between the two. This leaves us without firm evidence for meter-specific responses concerning hierarchy violations. One explanation for the lack of meter-specific effects may be the short entrainment time: participants were exposed to only 1 bar before the violation, and maybe they were unable to build up the metrical context. Future studies could investigate this possibility by expanding the entrainment time.

Finally, we saw expertise effects on meter perception – measured both behaviorally (significant effects) and with ERPs (marginal ones). The co-occurrence of expertise effects in these two different measures not only reflects the consistency of our findings, as it also stands in line with findings from previous research (e.g., Yates et al., 2017).

5. Conclusion

We examined attention effects on the EEG correlates of structural meter-processing, thus going beyond the dominant surface-based approach to meter of previous studies. Contrasting with findings from surface-based studies (attentive, but not pre-attentive processing), we found that – at least for cycle-length meter violations – meter perception benefits from lack of attention, in that it occurs pre-attentively but not attentively. The EEG correlates of perceived cycle-length violation corresponded to late ERPs, strengthening the idea that deep, structural meter-processing was elicited. Future research should compare structural with surface meter-processing, in order to determine the extent to which these two levels of meter processing dissociate.

Declaration of interests

None.

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Appendix A. Stimulus Materials (second bar)

A - Standards that generated silent deviants (n = 29) by omitting first sound, e.g.,

 generates 

No Silences	PD	Silences at 2nd/3rd beat	PD
			D
	SD		SD
			
			S
	D		
	S		D
			
	D		
			
	D		
	D		
	S		
			S
			
			SD
			

PD = Phrase contained Pitch Deviant at 3rd bar
S = Pitch Deviant at Standard version
D= Pitch Deviant at meter Deviant version

B - Standards that generated early deviants (n = 29) by shortening by an eighth-note, e.g.,

 generates 

No Silences	PD	Silences at 2nd/3rd beat	PD
			
	D		
	S		S
	D		S
			
	S		
	D		S
	D		
	S		SD
	SD		
	D		
			S
			S
	D		
			

PD = Phrase contained Pitch Deviant at 3rd bar
S = Pitch Deviant at Standard version
D= Pitch Deviant at meter Deviant version

C - Standards that generated late deviants (n = 29) by lengthening by an eighth-note, e.g.,

 generates 

No Silences	PD	Silences at 2nd/3rd beat	PD
	D		S
			SD
			
	D		D
			
			SD
	D		
			
	D		S
			S
	D		S
	D		S
	S		
			D
PD = Phrase contained Pitch Deviant at 3rd bar S = Pitch Deviant at Standard version D= Pitch Deviant at meter Deviant version			S

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.neuropsychologia.2019.107184.

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