



Tapping polyrhythms in music activates language areas

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ABSTRACT

Music is experienced and understood on the basis of foreground/background relationships and tension created between actual music and the underlying meter. Polyrhythms create tension between a counter meter and the main meter. Previously, we have shown that Brodmann area 47 (BA47), a brain area associated with processing of language, is activated bilaterally when musicians tap the main meter in a polymetric context emphasizing a counter meter, suggesting that processing of metric elements in music relies on brain areas also involved in language processing. In that study, the tension was created entirely by changes in the stimulus while participants were tapping the main meter. Here we find left-hemispheric BA47 activation in response to a self-produced counter meter on top of a main meter provided by an ecological music excerpt. This data indicates that the activation is linked to polyrhythmic tension, regardless of whether it arises from the stimulus or the task.

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Perception of music is related to a complex interplay between local auditory events and the underlying structural context partly inherent to the music, partly mediated by mental structures. According to contemporary music theory [6,11], foreground/background relations creating tension and relief are among the principal means by which music conveys meaning and emotion.

In contemporary styles of music such as jazz, *polyrhythms* create strong sensations of tension between a counter meter (e.g. 3/4) and the main meter (e.g. 4/4), challenging the listener's sense of the metrical background. A typical polyrhythm may be created by evenly tapping 4 times per second with the right hand, and 3 times per second with the left hand. This polyrhythm can be experienced either as a 4/4 meter or a 3/4 meter (a waltz). Since polyrhythms have two different possible interpretations, e.g. as a waltz or a march, they represent auditory percepts in which foreground/background relations may become unstable [15], creating fundamental perceptual challenges to the central nervous system analogous to the bistable visual percept of Rubin's vase [18] where either a vase or the adjacent faces may be perceived as the foreground.

Rhythm perception and production have previously primarily been linked to activation of motor areas of the brain including

the premotor and supplementary motor areas, cerebellum, and basal ganglia [3,10]. In the, until now, only imaging study on polyrhythms, we showed that musicians tapping the main meter during polyrhythmic tensions activate Brodmann area 47 (BA47) bilaterally [23], suggesting that the processing of metric elements of music relies on brain areas also involved in language processing. Musicians in that study were instructed to tap the main meter while the auditory stimulus alternated between emphasizing the main and counter meter.

Here we examine the sensation of polyrhythm from the perspective of the creator of the polyrhythm (e.g. the soloist). We collected participants' reports, behavioral data and fMRI data during musical tension created by alternate tapping of polyrhythm and main meter during identical musical excerpts. Since the activation of BA47 in our previous experiment appeared independently of the tapping task, and as a consequence of polyrhythmic epochs in the musical stimulus, we hypothesized that BA47 should also be active when the polyrhythmic tension was created by participants tapping polyrhythms on top of music with a simple, regular meter. This would indicate that activation of BA47 is specific to polyrhythm, rather than to the origin of this tension (the stimulus or the task).

Twenty native Danish-speaking, right-handed participants volunteered to participate in the study, which was approved by the local Committee on Ethics in Biomedical Research, Aarhus County, in accordance with the Helsinki declaration. Data from two participants were discarded due to image reconstruction errors. The remaining 18 participants (14 M, 4 F, mean age 29 years, SE = 1)

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were professional jazz (10) or rock (8) musicians or active musicians studying jazz/rock at the Royal Academy of Music, Aarhus, Denmark (5 drummers, 4 bassists, 4 guitarists, 5 pianists). All participants had received musical training beginning at a young age (between 5 and 13 years, mean = 8), musical training at conservatory level for an average of 3 years (SE = 0.5), and practiced an average of 1 1/2 h per day (SE = 0.2). All rock musicians were familiar with polyrhythms and played jazz occasionally. Musicians were selected as participants for this study due to the complex nature of the rhythmic task.

The stimulus consisted of three measures (3*2 s) from Sting's "The Lazarus Heart". It had 120 beats per minute (bpm) and was identical to the first half (the main meter part) of the stimulus used in our previous study [23]. The tempo was constant and the onset of the snare drum beats was accurately played across the entire epoch (SE: 5 ms), as analyzed by a sound-editing program (Adobe Audition), making this ecological stimulus ideal for evaluating the participants' accuracy in tapping different meters.

Musicians were fMRI-scanned while listening to 40 repetitions of the stimulus: during four repetitions of the stimulus (12 measures), they alternated between six measures of listening, three measures of tapping the main meter (M) on a response pad with their right index finger, and three measures of tapping the counter meter (C) at 160 bpm (Fig. 1). This polyrhythm (C against M) is known as '4 against 3', implying that three measures are sufficient and necessary for the downbeats of the two meters to coincide. Prior to scanning, participants practiced the task and performed a rhythm imitation test to assess their rhythmic aptitude [23,24]. Only competent participants (score ≥ 7 (of 30)) were included in the study. Participants completed a post-scanning written questionnaire. A PC using Brainwave (GE Medical Systems, Waukesha, WI, U.S.A.) controlled stimulus presentation and tapping data collection. Participants heard the stimuli through MR compatible stereo headphones (Avotec, Inc., Jensen Beach, FL) and were instructed to remain still and to not count during scans. Scanner noise timing and intensity were identical during the scanning sessions, so that participants were not distracted by abrupt sound changes,

and activations due to scanner noise cancelled out across conditions. All participants reported the ability to ignore the scanner rhythm.

Simple tapping errors were excluded from the tapping data recorded during scanning and standard deviations for tapM and tapC were compared across repetitions for each participant. For each tap, the difference (Td) between the expected time of a tap (Te) and the actual time (Ta) was calculated (i.e. $Td = Ta - Te$), and the block-wise standard deviation of Td was computed. Standard deviations of Td were pooled across participants and blocks for each of the two different tapping modes. We computed a binned kernel density estimate to visualize the distributions of the standard deviations and performed a Wilcoxon rank sum test for equal locations of the distributions. We performed a principal component analysis (PCA) on the standard deviations of tapM, the standard deviations of tapC and the scores from the rhythm imitation test. We used the first eigenvariate of this PCA as a measure of the participants' rhythmic abilities (termed the "RA score").

In each participant, 75 functional MR images were acquired during the stimulus using a 1.5T GE scanner (GE Medical Systems, Waukesha, WI, U.S.A.) across 41 slices to provide whole brain coverage. We used a gradient recalled Echo Planar Imaging sequence (TR = 3200 ms, TE = 40 ms, flip angle = 90°, matrix size 64 × 64, 4 mm slice thickness, FOV = 24 cm). Subsequently, we obtained coplanar high-resolution T1 spoiled gradient-recalled echo images (TR = 30 ms, TE = minimum-full, matrix size 256 × 192, flip angle 45°, FOV = 24 cm), consisting of 124 slices.

Images for each participant were co-registered and spatially normalized into MNI space using linear transformations and polynomial nonlinear warping with AIR. We used a six-parameter rigid body transformation model and a least square cost function with intensity scaling to correct for head motion by realigning and unwarping each participant's functional images to an image created as a mean of all functional images. Images were smoothed using a 12 mm full-width half-maximum isotropic Gaussian kernel.

Statistical comparisons of functional images were performed using SPM2 (<http://www.fil.ucl.ac.uk>) [2] in a fixed boxcar design

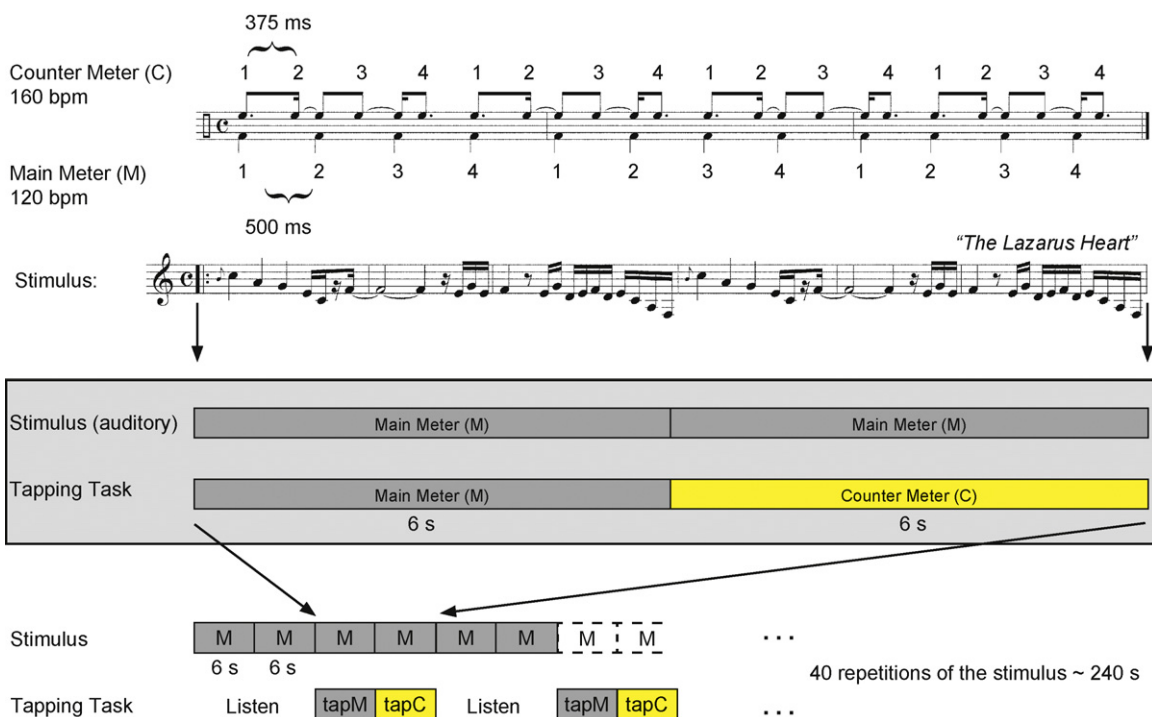


Fig. 1. Musicians alternate between listening and tapping to Sting's: "The Lazarus Heart". Tapping the counter meter while listening to the main meter (tapC) is contrasted to tapping the main meter (tapM).

(4 blocks of each 6 s: listenM, listenM, tapM/M, tapC/M) convolved with a canonical hemodynamic response function (splitting the listening condition into two makes a comparison possible between a pre and post-tapping epoch). In each participant, whole brain contrast images were made between the tapC/M and the tapM/M conditions. Individual difference images were taken to a second level random effects analysis. Images were corrected for multiple comparisons using Family-Wise Error correction with a threshold of $P < 0.05$, and only activations with a cluster size larger than 15 voxels were reported. FWE-correction is the most conservative procedure provided with the SPM package, minimizing the probability of false positives. The coordinates of the most significant voxels for each cluster were anatomically localized using the Talairach Daemon 1.04, with a query range of 5 mm. Beta-values for the most significant voxel in each cluster for each participant, compared to the average of the beta-values from the two listening blocks, were used as an indication of whether neural effect of tapC/M could be caused by activation or deactivation. We used the contrast estimates (tapC versus tapM) for the most significant voxel in each of the clusters for each participant for regression analyses with the participant's RA score.

According to the reports, participants received enough information to perform the tasks (4.6 (scale 1–5) SE = 0.029), found the tasks interesting (4.35 (scale 1–5) SE = 0.029), moderately easy (3.4 (scale 1–5) SE = 0.047) and neither physically (2.1 (scale 1–5) SE = 0.03)) nor emotionally unpleasant (2.0 (scale 1–5), SE = 0.04). The majority of the participants (11 of 13) that answered regarding their emotions in relation to the polyrhythm task, used words related to tension such as “stressful”, “challenging”, “frustrating”, “off balance” “demanding concentration”.

Density plots revealed larger location (Wilcoxon rank sum test, $P \ll 0.0001$) and substantially higher dispersion for tapC compared to tapM. This effect was unidirectional except for in 1 participant showing that tapC was a more difficult task to perform than tapM.

TapC (6 s) > tapM (6 s) showed a strong activation of the left inferior frontal gyrus (IFG), localized to BA47, and the anterior cingulate cortex (ACC) with local peak activations in BA32 (Table 1). Plotting the beta-values for the peak voxels of tapC and tapM versus rest (baseline) indicated that this was activation rather than deactivation (Fig. 2). The left hemispheric BA47 activation was in contrast with the bilateral activation during polyrhythmic tension in our earlier study [23].

To examine putative right hemispheric BA47 activation, we used the WFU-pickatlas SPM toolbox for defining this structure as a region-of-interest. Contrasting tapC with tapM at the default level of $P < 0.05$ (FWE-corrected), we found activation within the right BA47, peaking at [38,36,-2] ($z = 4.02$) and [30,26,-16] ($Z = 3.99$). Combined with our previous findings these results indicate that production of polyrhythm causes bilateral BA47 activation.

No correlation was found between the rhythmic accuracy of the participants and BA32 activation, indicating that the observed activation of ACC is not linked to rhythmic competence. There was a correlation between the RA score and the activation in BA47 hemisphere ($P < 0.03$, Fig. 3) indicating that rhythmically competent musicians require less activation of this area when performing polyrhythms.

TapM > tapC yielded no significant activation, just as no activations/deactivations were observed in motor or premotor areas in the tapC > tapM contrast. This indicates that from a pure motor

Table 1

Column H indicates left (L) and right (R) hemisphere. BA, Brodmann's area of peak activation, obtained from the Talairach Daemon. MNI-coordinates are in millimeters, reflecting distance from the anterior commissure, and express peak activation of a cluster of voxels in a particular anatomical region, as determined by one-sample t -tests. Cluster size reflects the number of activated voxels above the chosen threshold.

Brain activations									
Location	Cluster		Significance			Coordinates			
	H	BA	Size	T	Z	FWE	X	Y	Z
TapC > tapM									
Inferior frontal gyrus	L	47	38	9.62	5.56	0.001	-42	42	-4
Anterior cingulate	R	32	69	7.47	4.91	0.021	12	10	38
	R	32		7.39	4.88	0.023	8	22	32
TapM > tapC									
No activation									
Tap > listen									
Cerebellum	R		1358	14.78	6.61	0.000	34	-56	-40
Vermis	L/R			11.87	6.08	0.000	0	-64	-22
Cerebellum	R			10.42	5.76	0.000	22	-58	-34
Thalamus (ventral anterior nucleus)	L		340	11.08	5.91	0.000	-14	-8	14
Precentral gyrus	L	6	562	9.36	5.49	0.002	-4	-10	62
	L	4	687	8.65	5.29	0.004	-52	-8	44
	L	4		8.42	5.22	0.005	-58	-22	44
	L	4		7.93	5.06	0.010	-46	-22	50
Superior temporal gyrus	L	22	213	8.06	5.10	0.008	-48	8	0
Inferior frontal gyrus	L	47		7.39	4.88	0.021	-38	16	-10
Lateral globus pallidus	R		36	7.37	4.87	0.027	16	-2	10
Anterior cingulate	L	32	20	7.32	4.86	0.022	-2	4	46
Listen > tap									
Precuneus	R	7	136	9.90	5.77	0.001	8	-46	28
	R	7		8.37	5.20	0.005	22	-64	64
	R	7	544	9.16	5.43	0.002	8	-68	44
	R	7		8.98	5.38	0.003	10	-60	46
	L	7		7.93	5.06	0.010	-2	-58	46
TOP	R	19/39	24	8.43	5.22	0.005	36	-84	22
Prepare to tap > relax after tap									
Precentral gyrus	L	6	94	12.02	6.11	0.000	-2	-18	64
Postcentral gyrus	L	3	1559	10.58	5.80	0.000	-42	-30	60
Postcentral gyrus	L	1		7.81	5.02	0.011	-28	-34	72
Relax after tap > prepare to tap									
No activation									

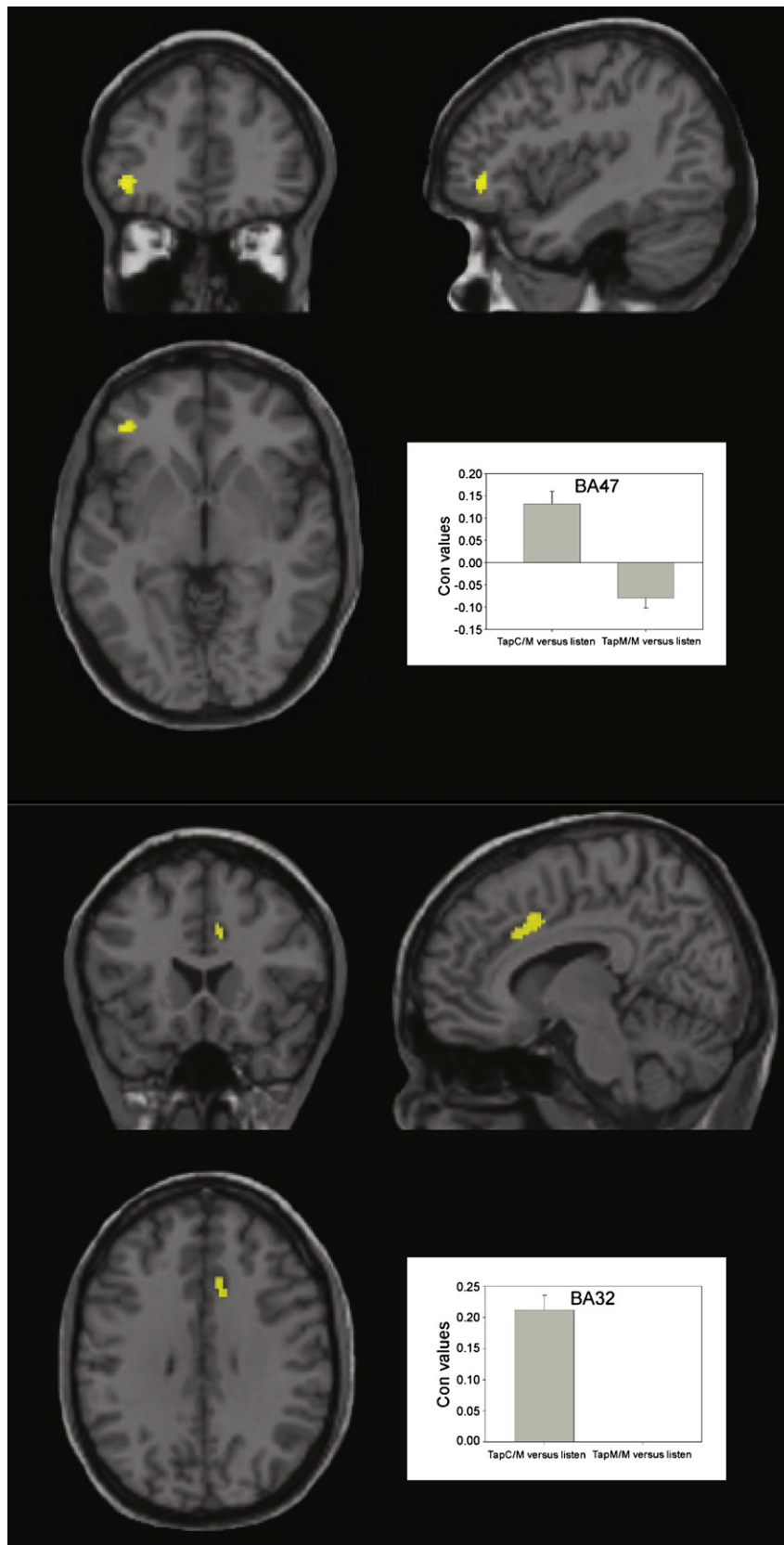


Fig. 2. Bold activations of the contrast tapC > tapM, overlaid on the single participant T1 image provided with the SPM2 package. Bar chart indicates the contrast estimates for the two different conditions (tapC and tapM) versus baseline in the peak voxels of BA47 and BA 22.

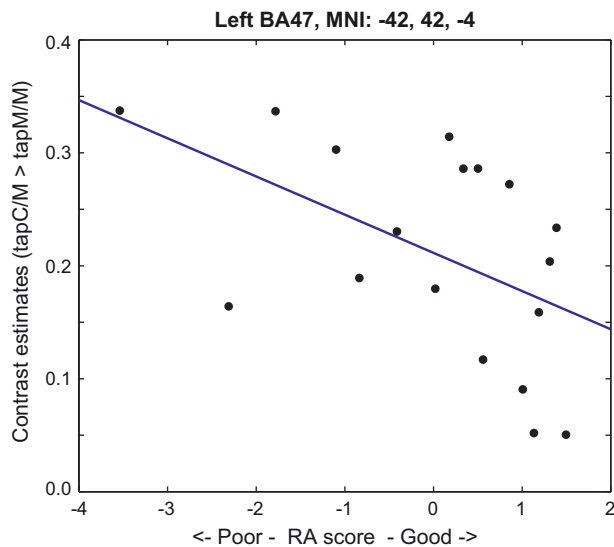


Fig. 3. Correlation between the participants' overall rhythmic abilities (RA score) and the contrast estimates in the peak voxel of BA 47 ($P < 0.03$, $r^2 = 0.26$).

output perspective, the tapping task was similar during the two modes.

Contrasting tapping (12 s) to listening (12 s), we found highly significant activation patterns corresponding to premotor and primary motor cortex in the left hemisphere, thalamus, right cerebellum and vermis. We also found perisylvian activation (BA22, superior temporal lobe), previously associated with synchronization of motor response to a steady rhythm [20], activation of the left BA47, as well as the left ACC (BA32) in this contrast, probably driven by the tapC component in the 12 s tapping block, as indicated by the plot of the contrast-values for these areas (Fig. 2).

Listening > tapping showed activation of the precuneus bilaterally and the temporo-occipito-parietal (TOP) junction, which are considered to be visual association areas. In line with previous authors [9,16] we interpret this as a reflection of deactivations related to goal-directed tasks. Contrasting the listening blocks (6 s preparing for the tapping task > 6 s relaxing after the tapping task), we found significant activation of the left pre-motor (BA6), sensory (BA3) and primary motor (BA1) cortices. We interpret these activations as motor planning. The opposite contrast yielded no significant activation.

According to contemporary musicologists, anticipatory structures creating tension and relief are at the heart of what allows music to be meaningful and convey emotion. In an earlier study, we found activation of BA47 when manipulating musical tension using auditory polyrhythms. In that study, the participants were tapping the main meter in two conditions: one in which the music emphasized a counter meter, another where the music reinforced the main meter. Thus, the tapping task remained the same across conditions. In the present study, we have found that BA47 remains activated when the polyrhythmic tension is created by participants tapping a polyrhythm on top of the main meter part of the stimulus from the earlier study. Here, the tension is created by the tapping task while the auditory stimulation remains the same across conditions. In combination, these two studies indicate that polyrhythmic tension is associated with activation of BA47, independently of whether the tension is created by the stimulus or the task. In addition, we found activation of the ACC.

The terminology to describe polyrhythms used by the participants indicated that tension was indeed felt, which is further substantiated by the fact that all but one participant displayed a decrease in tapping accuracy when tapping the counter meter [for

similar results see 17]. In our previous study [23], we found activation of BA47 in relation to keeping the main meter during intense polyrhythmic tension emerging from the musical stimulus. In the present study, this tension was not present in the music but was self-induced by tapping a counter meter that was 1 1/3 times as fast as the main meter. Hence, in combination with the former study, the present study indicates that the activation of BA47 is linked to polyrhythmic tension, and this appears to be independent of whether tension is created by a tapping task or provoked by the musical stimulus.

In accordance with our previous study, a small volume correction analysis of the right BA47 revealed that the activation of the left hemispheric BA47 was bilateral. The activation of BA47 in the left hemisphere tended to be less prominent according to subjective rhythmic skills, suggesting that for rhythmic competent musicians less neural resources especially in BA47 are needed in order to produce the complex polyrhythmic pattern in this study. Note, however, that task difficulty is integral to the polyrhythmic experience and hence to the observed activation. Task difficulty, however, cannot exhaustively explain our results since tapping the main meter caused a decrease of activation in BA47 relative to the listening condition although tapping must be more difficult than mere listening (see Fig. 2).

In contrast to our former study, we found significant activation of the ACC in addition to the activation of BA47. Recent research suggests that the ACC acts as a monitor of conflict occurring between incompatible streams of information processing [21], supporting appropriate actions in an uncertain or dynamic environment [8]. Accordingly, the ACC is believed to be the source of the error-related negativity (ERN) [5], a component of the event-related potential (ERP) of the EEG, elicited in relation to discrepancy between stimulus and action. The tasks of the present and former study differ in terms of the action in relation to the 'conflicting' main meter and a counter meter: keeping the rhythm in a polyrhythmic environment may primarily require suppression of the counter meter, while the production of polyrhythms in the current task requires careful auditory monitoring of the main meter while tapping the counter meter, which may explain the ACC activation.

The involvement of BA47, thought to be a higher language area, in monitoring figure/ground relations such as polyrhythms in music is intriguing. The cognitive linguist Talmy [19] has suggested figure/ground relations to be fundamental to human cognition in general, and semantics in particular. In this understanding, "figure" indicates a percept or concept that needs anchoring, whereas "ground" refers to the percept or concept that does the anchoring. The IFG, which contains the BA47, has been implicated in a range of studies of both music [14] and language [1] in very different paradigms. Koelsch and colleagues have suggested a similarity between brain processing of syntax errors in music and language [7]. A unifying feature of the paradigms used in these studies is a tension created between the anticipatory model and features relevant to communication of the incoming stimuli (e.g. unexpected events), which typically associates stronger brain-processing (greater ERP-amplitude/BOLD-signal) to higher degree of experienced discrepancy or tension. This is consistent with our findings of a reverse correlation between rhythmic competence and BOLD-signal in BA47. In our former study, we observed this reverse correlation between competence and the BOLD signal in only the right hemisphere. Further studies are needed to clarify whether the competence dependency of the activation of the left versus the right BA47 may differentiate the production from the experience of polyrhythms.

In relation to language, it has been proposed that cognition of syntax, phonology and semantics are interdependent, and that the IFG comprising Brodmann areas 44, 45 and 47 is a unification center with areas 44/45 responsible for syntactic processing, and area 47,

for semantic processing [4]. In this view, the IFG is not language specific but acts as a single unification space, integrating the semantic consequences of a broader range of cognitive domains e.g. gestures [13]. The present study extends these domains to music processing of polyrhythmic tension [see also 9]. Arguments in favor of the unification theory include the fact that the IFG is well-connected to other major parts of the neocortex, and that the prefrontal cortex in general has the capacity to sustain activity elicited by a transient event for many seconds [12]. In line with this, performing the polyrhythms requires the ability to sustain the two different meters over three measures.

In conclusion, we have found activation of the left hemispheric BA47 in relation to a self-produced polyrhythm on top of a regular meter, as well as when participants keep the rhythm when listening to polyrhythms, indicating that this activation is linked to the tension of the polyrhythm, independently of whether this tension is created by the stimulus or the task. Polyrhythms are auditory analogues to visual figure/ground relations [22]. We speculate that the inferior frontal lobe is crucially involved in processing discrepancy or tension between the anticipatory neuronal model and relevant features of the incoming stimuli, be it in language, music or other communicational systems.

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