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Strong-Meter and Weak-Meter Rhythm Identification in Spina Bifida Meningomyelocele and Volumetric Parcellation of Rhythm-Relevant Cerebellar Regions

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Abstract

Children with spina bifida meningomyelocele (SBM) are impaired relative to controls in terms of discriminating strong-meter and weak-meter rhythms, so congenital cerebellar dysmorphologies that affect rhythmic movements also disrupt rhythm perception. Cerebellar parcellations in children with SBM showed an abnormal configuration of volume fractions in cerebellar regions important for rhythm function: a smaller inferior-posterior lobe, and larger anterior and superior-posterior lobes.

Keywords

rhythm; metric structure; MRI; cerebellum; spina bifida meningomyelocele

Introduction

Timing and rhythm contribute to the precise, hierarchically organized movements involved in skilled performance,[1] which is often rhythmic.[2] Rhythmicity facilitates control of automatic movements within chunks and non-automatic movements between chunks,

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Conflicts of Interest
The authors declare no conflicts of interest.

allowing motor execution to move smoothly between discontinuous and continuous performance.[2]

The metrical structure of rhythm is established by temporal information creating the perception of strong (accented, or stressed) and weak (unaccented, or unstressed) beats at regularly spaced intervals.[1,3] A rhythm whose strong accents coincide with the strong positions of the metrical structure is unsyncopated or "on the beat" and has smaller integer ratios between event onsets, such as 1:2, 1:3, or 1:4; a rhythm with accented or strong events at weak positions is syncopated or "off the beat" and has larger or noninteger ratios, such as 1:2.5 or 1:3.5.[4] The strong-meter advantage is that strong-meter rhythms are easier than weak-meter rhythms to discriminate, remember, and reproduce.[5–8] Structured rhythms are associated with fMRI activity in the premotor area and the cerebellar anterior lobe, whereas unstructured rhythms are linked to prefrontal cortex and posterior cerebellar lobe activity.[8]

Children and adolescents with spina bifida meningomyelocele (SBM) have deficits in the production and perception of rhythm, including motor speech deficits,[9] impaired rhythm entrainment,[10] and inaccurate discrimination of strong-meter rhythms.[11] In SBM, the posterior fossa is small, the posterior fossa contents are distorted and herniated through the tentorial incisure and foramen magnum, and the cerebellar hemispheres are reduced in volume, although mid-sagittal cerebellar vermis may be linearly enlarged.[12–15]

Building on our behavioral study of rhythm in SBM, this paper measures speed and accuracy of rhythm discrimination in a larger sample, and reports a technique for parcellation of cerebellar regions relevant to rhythm perception.

Materials and Methods

Strong-Meter versus Weak-Meter Function

Participants—Participants were 131 children and adolescents [mean age at test 13.0 (SD = 2.8) years of age, and each with a minimum IQ score of 70]. One hundred and one had been diagnosed at birth with SBM and developed hydrocephalus; of these, 79 had lower spinal cord lesions, and 22 had upper spinal cord lesions, the latter being associated with more cerebral and cerebellar structural loss and more behavioral dysfunction.[13] Thirty typically developing children and adolescents formed a control group.

Materials—The task[7,16] defined an interval as the onset-to-onset duration between successive equal-intensity tones on a snare drum. Intervals varied in a 1:2:3:4 ratio using duration units of 200 ms (interval 1 was 200 ms, intervals 2, 3, and 4 were 400, 600 and 800 ms, respectively). Each rhythm had a permutation of the same set of nine different intervals (111112234). For strong-meter rhythms, onsets of longer intervals occurred on the beat. For weak-meter rhythms, onsets of longer intervals occurred off the beat.

Procedure—In the 40 test trials (20 same and 20 different patterns; 20 strong and 20 weak patterns) presented randomly for each participant and intermixed across the strong-meter and weak-meter conditions, participants judged the two rhythm patterns as same or different by a button press. Each trial involved a 1500-ms fixation stimulus followed by two patterns, a standard pattern and a comparison pattern with an inter-stimulus interval of 1500 ms ("tone 1" or "tone 2" was indicated on screen during presentation). On "same" trials, the standard and comparison patterns were identical. On "different" trials, the comparison differed from the standard because one inter-onset interval of 400 ms (interval 2) was doubled in duration.

Cerebellar Parcellation

Participants—MRIs were available on 30 participants with SBM and seven typically developing controls.

Procedure—The 3T MRI data acquisition and processing, described elsewhere,[17] used coronally acquired data with voxel size = 0.9375, 0.9375 mm and slice thickness of 1.5 mm. Using FreeSurfer tissue-segmentation modules (www.surfer.nmr.mgh.harvard.edu), a four-compartment model (one white matter and three gray matter) parcellated cerebellums into four units[18]: (1) corpus medullare: central white matter and output nuclei; (2) anterior lobe: lobules–IV, bounded by the most posterior point of the fourth ventricle, corpus medullare, and primary fissure; (3) superior-posterior lobe: lobe VI and crus I of VIIA, bounded by the primary fissure, corpus medullare, and horizontal fissure; and (4) inferior-posterior lobe: crus II of VIIA, VIIB, VIII, IX, and X, bounded by the most posterior point of the fourth ventricle, corpus medullare, and horizontal fissure.

Results

Strong-Meter versus Weak-Meter Function

Accuracy and response times were based on the control group's performance (mean and variability). Each score was scaled so that zero represented the average control performance, and higher scores denoted better performance (e.g., faster response time or greater accuracy), after which the separate z-scores for accuracy and response time were averaged, resulting in one score for strong-meter rhythms, and one score for weak-meter rhythms. Participants with SBM did not differ from controls on age, although age was related to rhythm performance ($r = +0.47$ for strong-meter; $r = +0.36$ for weak-meter, both $P < 0.001$), and was used as a covariate in subsequent analyses. Groups were compared on strong- and weak-meter performance individually, as well as on the difference between strong- and weak-meter performance.

Groups with SBM had negative scores, showing that they performed more poorly than controls (Fig. 1). For strong-meter rhythms, the SBM group with upper spinal cord lesions performed more poorly than both the controls ($P = 0.0016$) and the SBM subjects with lower spinal cord lesions ($P = 0.0062$), who did not differ from each other, $P > 0.05$. For weak-meter rhythms, controls outperformed both SBM upper lesion ($P = 0.0120$) and SBM lower lesion ($P = 0.0373$) groups, and the two groups with SBM did not differ from each other, $P > 0.05$.

To explore the strong-meter advantage, the difference in strong- and weak-meter performance was computed and compared for the SBM groups. Because of the metric used, the difference between strong- and weak-meter performance for controls was approximately zero. Among groups with SBM, the overall effect approached significance, $F(1,98) = 3.30$, $P = 0.0723$. The SBM upper lesion group had relatively better weak- versus strong-meter performance (difference $z = -0.21$); in contrast, the SBM lower lesion group showed a strong-meter advantage (difference $z = +0.16$).

Cerebellar Parcellation

A MANOVA on the cerebellar volumes (Fig. 2) revealed an effect of group, Wilks $\lambda = 0.532$, $F(3,33) = 9.67$, $P < 0.0001$; cerebellar volumes were 25.5% lower in the SBM group relative to controls. In the regional analyses, the groups did not differ in corpus medullare volume fraction (SBM 0.141 versus controls 0.143), but the group with SBM had a smaller volume fraction than controls in the inferior-posterior lobe (SBM 0.331 versus controls 0.430, $t = 5.36$, $P < 0.0001$). The SBM group had a larger volume fraction than controls in

the anterior lobe (SBM 0.135 versus controls 0.074, $t = -4.28$, $P < 0.0001$) as well as in the superior-posterior lobe (SBM 0.392 versus controls 0.353, $t = -2.37$, $P < 0.0233$).

Conclusions

Congenital cerebellar dysmorphologies like SBM that disrupt rhythmic movements[10] also disrupt speed and accuracy of rhythm perception, suggesting a central processing disruption of the brain mechanisms for rhythm. Abnormal cerebellar development,[13,15] involving normal volumes in the corpus medullare, decreased volumes in the inferior-posterior lobe and increased volumes in the anterior lobe and superior-posterior lobe may be part of a disruption of the neural control of rhythm.

Rhythm is associated with the accurate timing of movements.[1] Timing deficits in SBM may produce a temporal disconnection between sensation and movement, resulting in asynchrony of feed-forward processes that encode the sensory consequences of motor acts.[10] Although failure of timing and rhythm in SBM does not disrupt motor learning,[19] it does prevent the generation of the predictive motor sequences needed for fine adaptive motor control and movement regulation.[19–21]

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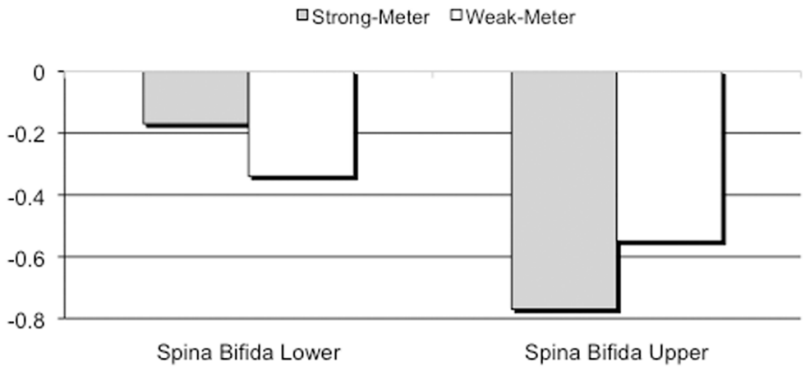

Figure 1.

Performance of groups with SBM upper and lower cord lesions on strong-meter and weak-meter rhythms. Scores were scaled such that 0 represented the average control performance, and higher scores denoted better performance (e.g., lower response time or greater accuracy); then the separate z-scores for accuracy and response time were averaged, resulting in one score for strong-meter rhythms, and one score for weak-meter rhythms. Both groups with SBM had negative scores, showing that they performed more poorly than controls.

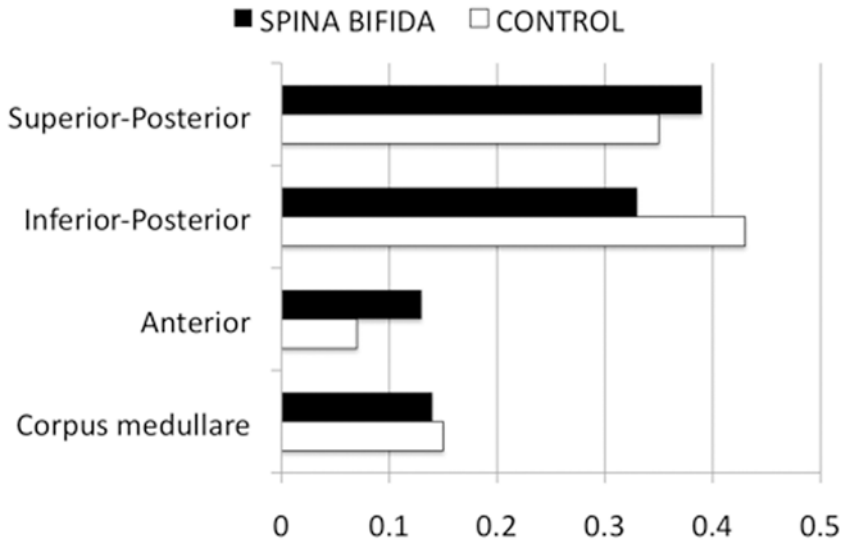

Figure 2.
Cerebellar volume fractions for superior-inferior lobe, inferior-posterior lobe, anterior lobe, and corpus medullare expressed as percent of total cerebellar size.