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Inhibitory control and working memory predict rhythm production abilities in patients with neurocognitive deficits

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A R T I C L E I N F O

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A B S T R A C T

Deficits in rhythm perception and production have been reported in a variety of psychiatric, neurodevelopmental and neurologic disorders. Since correlations between rhythmic abilities and cognitive functions have been demonstrated in neurotypical individuals, we here investigate whether and how rhythmic abilities are associated with cognitive functions in 35 participants with neurocognitive deficits due to acquired brain lesions. We systematically assessed a diverse set of rhythm perception and production abilities including time and beat perception and finger-tapping tasks. Neuropsychological tests were applied to assess separable cognitive functions. Using multiple regression analyses we show that lower variability in aligning movements to a pacing sequence was predicted by better inhibitory control and better working memory performance. Working memory performance also predicted lower variability of rhythmic movements in the absence of an external pacing sequence and better anticipatory timing to sequences with gradual tempo changes. Importantly, these predictors remained significant for all regression models when controlling for other cognitive variables (i.e., cognitive flexibility, information processing speed, and verbal learning ability) and potential confounders (i.e., age, symptom strength of depression, manual dexterity, duration of illness, severity of cognitive impairment, and musical experience). Thus, all rhythm production abilities were significantly predicted by measures of executive functions. In contrast, rhythm perception abilities (time perception/beat perception) were not predicted by executive functions in this study. Our results, enhancing the understanding of cognitive underpinnings of rhythmic abilities in individuals with neurocognitive deficits, may be a first mandatory step to further potential therapeutic implications of rhythm-based interventions in neuropsychological rehabilitation.

1. Introduction

Nodding the head or clapping hands to the beat of music seems to require minimal cognitive effort. Moreover, there is evidence that the ability to synchronize movements with a rhythm develops in childhood without formal instruction and remains relatively stable until old age (Drewing et al., 2006). The putatively innate perception of rhythms plays a crucial role in social interactions and attachment formation (Provasi et al., 2014). Musical and rhythmic skills have also been suggested to be relevant for a number of motor and language abilities (e.g., Kotz et al., 2018) and may be involved in other cognitive processes (Frischen et al., 2022). Given the documented overarching relations between different aspects of cognition and rhythmicity, it may be unsurprising that rhythmic skills are afforded by a sophisticated machinery housed in widely distributed neural circuits (Repp and Su, 2013). The network includes auditory and sensorimotor areas, the basal ganglia and

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cerebellum, but also prefrontal cortices (Chen et al., 2009; Damm et al., 2020; Hove et al., 2013; Kasdan et al., 2022; Kung et al., 2013; Leow and Grahn, 2014; Miyata et al., 2022; Pecenka et al., 2013; Wiener et al., 2010; Witt et al., 2008).

1.1. Deficits in rhythm perception and production abilities

In correspondence with the wide distribution of the 'rhythm network', a wide range of structural and functional brain alterations have been shown to interfere with rhythm perception and production: Sub-second auditory time perception was reported to be impaired in individuals with traumatic brain injury (Bader et al., 2019; Verga et al., 2021), cerebellar lesions (Ivry and Keele, 1989; Nichelli et al., 1996; but see Harrington et al., 2004 for a contrasting finding), and Parkinson's disease (Benoit et al., 2014; but see Ivry and Keele, 1989; Wearden et al., 2008 for contrasting findings). Additionally, research involving participants with spinocerebellar ataxia highlighted the cerebellum's specific role only in the absolute duration-based timing of single subsecond intervals, but not in the relative timing of rhythmic sequences with a regular beat (Grube et al., 2010). A further study showed that individuals with Multiple System Atrophy (affecting the cerebellum or striatum) and individuals with early symptomatic Huntington's disease exhibited impairments in both absolute and relative timing tasks (Cope et al., 2014). Consistent with this, beat perception was found to be impaired in Parkinson's disease (Benoit et al., 2014; Biswas et al., 2016; Cameron et al., 2016), and also in stroke survivors (Patterson et al., 2018). Deficits in sensorimotor synchronization were reported in individuals with cerebellar lesions and basal ganglia lesions (Schwartze et al., 2011, 2016; van der Steen et al., 2015). Inconsistencies in the literature may be partially due to severity of the disorder, method of recording rhythmic skills, and level of prior musical experience. Beyond neurological disorders, deficits in rhythmic abilities have also been found in schizophrenia (Carroll et al., 2009; Moussa-Tooks et al., 2019), bipolar disorder (Bolbecker et al., 2011), and neurodevelopmental disorders (Bégel et al., 2022; Corriveau and Goswami, 2009; Falk et al., 2015; Falter et al., 2012; Gowen and Miall, 2005; Puyjarinet et al., 2017; Thomson et al., 2006; Toplak and Tannock, 2005). Thus the spectrum of diseases studied is broad, notably, however, in most of these diseases deficits in executive functions are well documented.

1.2. Rhythm and executive functions

Executive functions are high-level cognitive processes that enable individuals to regulate their thoughts and actions during goal-directed behavior (Friedman and Miyake, 2017) and can be divided into three main components: inhibitory control (actively inhibit or delay a dominant response to achieve a goal), cognitive flexibility (flexibly adjusting to new demands, rules, or priorities), and working memory (holding information in mind and manipulating it; Diamond, 2013). A large body of research has shown that musical training leads to advantages in cognitive, especially executive functioning (Bailey and Penhune, 2010; Bialystok and DePape, 2009; Bugos et al., 2007; George and Coch, 2011; Hao et al., 2023; Zuk et al., 2014). Moreover, music therapy has been successfully used in the neurologic rehabilitation of executive functions after traumatic brain injury (Martinez Molina et al., 2022; Siponkoski et al., 2020; Thaut et al., 2009). Research suggests that the rhythmic component of music training is particularly important for improving executive functions (Frischen et al., 2019; Metzler-Baddeley et al., 2014). In accordance, executive functions were found to be associated with separable rhythmic abilities, as detailed below. We here differentiate between aspects of rhythm production (i.e., sensorimotor synchronization, rhythmic-motor stability, anticipatory timing) and rhythm perception (i.e., sub-second time perception and beat perception), as rhythmic competencies are multidimensional and can be captured with different tasks (Dalla Bella et al., 2024b; Fiveash et al., 2022).

First, the ability to synchronize internally generated rhythmic movements with an external beat or rhythm was correlated with inhibitory control and selective attention in a neurotypical sample of musicians and non-musicians (Slater et al., 2018). Moreover, percussionists, who are highly skilled in sensorimotor synchronization, showed superior inhibitory control compared to vocalists and non-musicians (Slater et al., 2017). Conversely, children and adults with attention-deficit/hyperactivity disorder (ADHD), with poorer sensorimotor synchronization and beat perception, also showed poorer performance in tasks assessing inhibitory control and cognitive flexibility (Puyjarinet et al., 2017). Predictive coding and conflict monitoring have been discussed as common cross-domain mechanisms (Slater et al., 2018).

Second, maintaining a given tempo without an external pacing sequence was correlated with working memory and memory span in children (Monier and Droit-Volet, 2019). In line with this, rhythmic-motor stability decreased significantly, under working memory load in the dual-task paradigm in neurotypical adults (Holm et al., 2017). In individuals with cerebellar degeneration, variability in the central timing component (counterpart to the motor component) correlated with working memory capacity (Harrington et al., 2004). The results are consistent with the assumption that tempo-stability requires an internal representation of tempo (Jantzen et al., 2007). It has also been shown that short-term memory capacity predicts unique variance in rhythm reproduction performance (Grahn and Schuit, 2012).

Third, there is evidence of a role for working memory in anticipatory timing during synchronization to sequences with gradual tempo changes in neurotypical adults (Colley et al., 2018). Consistent with this, anticipatory timing significantly decreased as the working memory load increased in a dual-task paradigm among musicians (Pecenka et al., 2013). The term anticipatory timing (also referred to as *temporal prediction ability*; Pecenka and Keller, 2011), describes an individual's capacity to predict the size of temporal intervals between successive events (Colley et al., 2018). Working memory may facilitate the generation of these predictions. This ability is critical for motor actions performed concurrently with external events (Schmidt, 1968) and is especially challenged when the external event is not regular but changes in tempo.

Fourth, sub-second auditory time perception was correlated with working memory processes in neurotypical adults (Zhang et al., 2016) and in adolescents with ADHD (Toplak et al., 2003). Working memory processes may be required to maintain a stable representation of the duration of the preceding sound while the following sound is perceived. We here explicitly focus on sub-second auditory time perception, as this is the timing mechanism most directly involved in the perception and production of musical rhythm. However, it should be mentioned that previous research proposed a distinction between cognitively controlled timing in the supra-second range and automatic timing in the sub-second range (Lewis and Miall, 2003a, 2003b), arguing that processing supra-second time scales (but not sub-second time scales) involves cognitive functions such as working memory and attention (Baudouin et al., 2006; Fortin and Couture, 2002; Lewis and Miall, 2006; Rammsayer et al., 2001).

Fifth, working memory processes were found to be associated with the perception of a beat in a musical rhythm. More specifically, in participants with Parkinson's disease, verbal working memory and focused attention predicted the performance in beat perception among a range of cognitive functions (Biswas et al., 2016). In participants with acute traumatic brain injury, a correlation was found between memory span and rhythm perception performance (Anderson et al., 2021), however, the study did not control for other cognitive functions. Based on the assumption that the perception of a beat in a musical rhythm is a predictive process (Patel and Iversen, 2014), working memory (specifically updating) may be involved in generating that prediction.

1.3. Aims and outline of the present study

Given the evidence for associations between rhythmic and cognitive abilities on the one hand and the growing use of music therapy in neuropsychological rehabilitation on the other hand, there is a need to better understand the interplay between rhythmic abilities and cognitive functions in clinical populations. However, studies targeting people with an acquired brain lesion are missing. To help fill this research gap, we here deliberately targeted individuals with a wide range of severities regarding their neurocognitive deficits due to a diverse spectrum of acquired brain lesion etiologies. Our rationale is that a wide range of cognitive and rhythmic performance will allow for a better estimate of the correlations between the two, since our focus is on the behavioral correlates of the acquired brain lesion. Therefore, participants were not selected according to the underlying disease. In addition to reducing bias (e.g., preferential lesion location in stroke) the approach mirrors clinically existing neuropsychological rehabilitation approaches, in which people with acquired brain lesions of different etiologies are treated jointly. In other words, the choice of the therapy method is guided by the cognitive profile rather than the underlying pathology (e.g., attention training for people with attention deficit due to stroke, traumatic brain injury, etc.).

Previous studies on correlations between rhythmic abilities and cognitive functions often targeted only one test for a single cognitive function or only single rhythmic processes. This limits the comparability and may miss important interdependencies between different cognitive domains. In this study, we emphasize the role of various executive functions, importantly also accounting for other cognitive functions such as verbal learning ability and processing speed. Regarding rhythmic abilities, it has been shown that multiple tests with various rhythmic tasks are needed to capture individual differences in multidimensional rhythmic abilities (Dalla Bella et al., 2024b; Fiveash et al., 2022). To our knowledge, no study has assessed a broad range of cognitive functions together with various rhythmic abilities in individuals with neurocognitive deficits. An established tool for the systematic assessment of perceptual and sensorimotor timing abilities is the Battery for the Assessment of Auditory Sensorimotor and Timing Abilities (BAASTA; Dalla Bella et al., 2017; for a tablet version and norms, see Dalla Bella et al., 2024a). BAASTA is a highly sensitive instrument for detecting individual differences as well as timing and rhythm deficits in different patient populations, such as Parkinson's disease (Benoit et al., 2014), traumatic brain injury (Verga et al., 2021), developmental stuttering (Falk et al., 2015), ADHD (Puyjarinet et al., 2017), and dyslexia (Bégel et al., 2022). Test-retest reliability has been tested in neurotypical adult participants and was moderate to excellent for all measures used in this study except for the variability of spontaneous unpaced tapping (Dalla Bella et al., 2024a).

Taken together, the aim of the present study was to investigate associations between rhythmic abilities and cognitive (especially executive) functions in a heterogeneous sample of participants with neurocognitive deficits. To this end, we systematically assessed several cognitive functions, several rhythmic abilities, and potential confounding variables (i.e., age, symptom strength of depression, manual dexterity, duration of illness, severity of cognitive impairment, and musical experience). The cognitive functions were inhibitory control, working memory, cognitive flexibility, information processing speed, and verbal learning ability, which were assessed using established neuropsychological tests. The rhythmic abilities were synchronization consistency (i.e., lower variability in the alignment of internally generated rhythmic movements and an external pacing sequence), rhythmic-motor stability (i.e., lower variability of rhythmic movements in the absence of an external pacing sequence), anticipatory timing (i.e., better temporal prediction of pacing sequences with gradual tempo changes), time perception (i.e., differentiation of two durations in sub-second range), and beat perception (i.e., judgment of whether a metronome is aligned with the musical beat). Rhythmic abilities were assessed using BAASTA and a task measuring anticipatory timing ability (Pecenka et al., 2013).

Based on the reviewed literature we expected that executive functions are systematically related to rhythmic abilities and formulated directed hypotheses. More precisely, we hypothesize that (1) better synchronization consistency is predicted by better inhibitory control, (2) higher rhythmic-motor stability at a given tempo is predicted by better working memory performance, (3) better anticipatory timing is predicted by better working memory performance, (4) more accurate time perception (in the sub-second range) is predicted by better working memory performance, and (5) more accurate beat perception is predicted by better working memory performance. Using multiple regression modeling, we investigated whether rhythmic abilities can be predicted by executive functions, taking into account other cognitive functions and potential confounding variables. In a more exploratory manner, we investigated possible associations with lesion size in a subsample.

2. Material and methods

2.1. Participants

Initially, 43 patients with various neurocognitive disorders participated in the study. Eight patients had to be excluded because of severe fatigue during testing ($n = 2$), behavior contrary to instructions ($n = 1$), severe arthrosis of the fingers ($n = 1$) and severe dominant upper extremity paresis interfering with completion of the production tasks ($n = 4$). The analyses in this study are therefore based on 35 patients (18 men; 17 women) aged 20–79 years ($M = 50$, $SD = 14$). Underlying pathology were mainly ischemic stroke ($n = 10$), cerebral hemorrhage ($n = 6$), brain tumors ($n = 5$), traumatic brain injury ($n = 4$), multiple sclerosis ($n = 2$), and leukoencephalopathy ($n = 2$). For further single diagnosis and epidemiological information including lesion location if applicable see supplementary material, Table S1. Time since onset of the illness ranged from 4 months–13.5 years ($M = 23.2$, $SD = 30.8$ months; onset was defined as the date of first manifestation or the date of diagnosis). 16 of the 35 participants had active musical experience (lay instrumental skills, singing in a choir), but none had been a professional musician (for further parameters describing the sample's prior musical experience see supplementary material, Table S2). 33 participants were right-handed and two participants were left-handed according to the Edinburgh handedness inventory (Oldfield, 1971). Participants had no severe impairment of their dominant hand (i.e., exclusion of participants with paresis of the dominant upper limb) and reported normal or corrected to normal hearing abilities. The study was conducted at the Clinic for Cognitive Neurology at the University Hospital in Leipzig, Germany. Participants gave their written informed consent to participate and were naïve to the hypotheses of the study and the manipulations underlying the rhythmic tasks. The study was performed in accordance with ethical standards compliant with the declaration of Helsinki and had been approved by the local scientific ethics committee (no. 301/20-ek, July 21, 2020).

2.2. Assessment of rhythmic abilities

Rhythmic abilities were assessed with three perceptual tasks (duration discrimination, anisochrony detection, Beat Alignment Test), and four sensorimotor tasks (unpaced/self-paced tapping, externally paced tapping, synchronization-continuation, anticipatory tapping). All tasks except for anticipatory tapping are part of the tablet version of BAASTA (Dalla Bella et al., 2024a), which was implemented as an application (v0.5.2) on a Samsung Galaxy TAB A tablet (8.0″, 2019) running Android 10.0. For the anticipatory tapping task based on Pecenka et al. (2013), participants tapped on a custom-built tapping pad (dimensions: 21 x 15 × 2.5 cm), which recorded the tapping on a 70 × 70 mm surface by means of an air pressure sensor. The tapping pad was connected to a MacBook Pro via a USB MIDI interface (Midiman MIDISPORT 2 x 2 from M-Audio). The stimulus presentation as well as the recording of the tapping times was done with the program MAX/MSP 8 (https://cycling74.com/). Prior to each task, participants received verbal instructions from the experimenter. Auditory stimuli were presented via headphones (Sennheiser HD280 pro), with the volume adjusted to a level comfortable for the participant.

2.2.1. Perceptual tasks

For all perceptual tasks, the experimenter operated the tablet and entered the participants' verbal responses. During the rhythm perception testing, participants were instructed not to move their head, hands, or feet rhythmically. The experimenter monitored the participants to ensure compliance with this instruction. All tasks were preceded by four example trials and four practice trials with feedback from the experimenter.

Duration discrimination. Sub-second time perception was investigated with the task duration discrimination. Participants listened to tone pairs (frequency = 1 kHz) and were asked to judge whether the second tone (variable duration, range = 600–1000 ms) was longer than the first (fixed duration, 600 ms). The stimulus difference was changed in each trial depending on the participant's response (adaptive procedure). Perceptual thresholds of just noticeable difference (JND) were calculated (Weber fraction in ms) based on a 2 down/1 up staircase procedure (for details, see Dalla Bella et al., 2017). The lower the perceptual threshold, the better the performance. The procedure for determining the JND was applied twice and the results were averaged.

Anisochrony detection. The task assessed the ability to perceive a temporal irregularity (i.e., a time shift) within an isochronous sequence of tones (a metronome). Sequences of five piano tones were presented to the participants (frequency = 1047 Hz, tone duration = 150 ms). Isochronous sequences had a constant inter-onset-interval (IOI) of 600 ms, whereas in anisochronous sequences the fourth tone was presented earlier than expected by up to 30% of the IOI. The task was to judge whether the sequence was regular (isochronous) or irregular (anisochronous). JND thresholds were calculated using the same procedure as for duration discrimination. The JND was determined twice, and the results were averaged.

Beat Alignment Test. This task assessed the ability to perceive the beat in 24 musical fragments from Bach's "Badinerie" and from Rossini's "William Tell Overture" (duration of fragments = 20 beats or quarter notes, inter-beat-interval [IBI] = 600 ms). From the 7th musical beat, a metronome with a percussion timbre was superimposed onto the music and aligned or not with the beat (i.e., out of phase by 33% of the music IBI, or with a different period by 10% of the IBI). The task was to judge whether or not the metronome was aligned with the musical beat.

2.2.2. Production tasks

In sensorimotor tasks, participants tapped with their index finger on the tablet or the tapping pad in the anticipatory tapping task. All tasks were performed with the dominant hand and were preceded by one practice trial for paced tapping and synchronization-continuation and three practice trials for the anticipatory tapping task. The unpaced tapping task did not include a practice trial.

Unpaced tapping. To assess spontaneous preferred tempo and rhythmic-motor variability without a pacing stimulus (also referred to as *self-paced tapping*) participants tapped on the tablet as regularly as possible for 60 s, first with their dominant and then with their non-dominant hand. The speed chosen should be as natural as possible and the tapping rate should be maintained as constantly as possible.

Paced tapping. Synchronization accuracy and consistency were assessed with an externally paced tapping task, in which participants were asked to tap in synchrony with an isochronous pacing sequence (metronome) or music. The metronome consisted of a regular sequence of 60 piano tones (frequency = 1319 Hz) presented at three different tempos (IOI = 600 ms, 450 ms, 750 ms). Each trial at a given tempo was performed twice. Synchronization to music used a musical excerpt from Bach's "Badinerie". The music excerpt had a length of 64 beats (= quarter notes) and a tempo corresponding to an IBI of 600 ms. Tapping to the music was also performed twice.

Synchronization-continuation. This task assessed rhythmic-motor variability at a given tempo. A metronome (10 isochronous tones) was first presented in one of three tempos (IOI = 600 ms, 450 ms, 750 ms). The participants synchronized with the metronome and continued tapping at the same rate after the sequence stopped for a duration corresponding to 30 IOIs of the pacing stimulus. Each trial at a given tempo was performed twice.

Anticipatory tapping. To assess anticipatory timing participants were asked to tap in synchrony to a tempo-changing pacing sequence (IOI = 382–601 ms; Pecenka and Keller, 2011). Six trials of 60 tones (bongo sounds) were presented. The first six tones of each trial were isochronous with an IOI of 600 ms, whereas the tempo changed successively for the following 54 tones. The tempo changes included both accelerations (accelerando) and decelerations (ritardando) and followed a quadratic function. The end of each trial was signaled by an auditory stop signal.

2.3. Neuropsychological assessment

Standardized neuropsychological test procedures were used to assess executive functions (inhibitory control, working memory, cognitive flexibility) and other cognitive functions.

Inhibitory control. We assessed inhibitory control with a Simon task implemented as the *incompatibility* test of the software package Test of Attentional Performance (TAP; version 2.3; Zimmermann and Fimm, 2014). This task measured interference tendency by stimulus-response incompatibility. White arrows were presented on a black computer screen in the left or right visual field. The arrows pointed either to the right or to the left. Two keys were placed in front of the participant. When an arrow appeared, the participant was supposed to press the key in the direction of the arrow, regardless of whether the arrow was presented in the left or right visual field. 30 compatible and 30 incompatible trials were performed, with the number of trials balanced in the left and right visual fields. In the compatible conditions, the side of the stimulus in the visual field matched the direction of the arrow (= responding hand). In incompatible conditions, the direction of the arrow did not match the side in which the arrow appeared creating a conflict situation. The incompatibility effect refers to the difference between the median reaction times of the incompatible minus the compatible condition. We corrected for the influence of overall processing speed by dividing the difference by the median reaction time of the compatible condition [(Incompatible - Compatible)/Compatible].

Working memory. We conducted the digit span backwards task from the Wechsler Memory Scale (WMS-R; German Version; Härting et al., 2000). Participants were asked to recall sequences of digits of increasing length in reverse order. The total score of correct answers was used as a measure of working memory performance.

Cognitive flexibility. The Trail Making Test (TMT; Reitan, 1992) in a modified paper-pencil version according to Rodewald et al. (2012) was used. In TMT-A, the participants connect the numbers 1 to 25 (arranged in a pseudorandomized manner) in ascending order as quickly as possible. In TMT-B, they connect the numbers 1 to 13 and the letters A to L alternately in ascending order as quickly as possible. Using the absolute processing times, an index was calculated according to the formula [(B - A)/A] (see Periáñez et al., 2007; Stuss et al., 2001)

Verbal learning ability. This ability was assessed with the California Verbal Learning Test (CVLT; Niemann et al., 2008). We used learning slope as a measure of learning growth over five learning cycles of a word list. The slope measure was obtained by fitting a regression line to the free recall values over the five runs.

Processing speed. The tonic condition of the Alertness task of the Test of Attentional Performance (Zimmermann and Fimm, 2014) was used to assess general processing speed. At random intervals, a white X appeared on a black screen. The participants' task was to respond as quickly as possible with the index finger of the dominant hand by pressing a key when the cross appeared. The median reaction time of two runs with 20 trials each was used for the analyses.

Severity of cognitive impairment. Trained clinical neuropsychologists from the Clinic for Cognitive Neurology at the University Hospital in Leipzig made an assessment regarding the severity of the cognitive impairment (no/mild/moderate/severe) based on defined criteria applied to the results of comprehensive neuropsychological diagnostics (Frei et al., 2016).

2.4. Assessment of confounding variables

Manual dexterity. We measured unimanual finger and hand dexterity with the 9-Hole Peg Test (9HPT; Rolyan®). The participants were asked to pick up nine pegs with their dominant hand and insert them into a pegboard as quickly as possible. Subsequently, the pegs should be picked up again and returned to the container as quickly as possible. The final score was the mean processing time over two trials.

Musical experience. Participants were asked about their musical activity during lifetime (i.e., playing an instrument, singing). A score for musical experience was calculated, reflecting the total number of hours a participant had been musically active throughout his/her life. Specifically, it was asked how many hours per week over how many years one was involved in performing music. Music performance included any form of playing an instrument or singing, whether alone, in class, in an ensemble, or in a band.

Symptom strength of depression. The revised version of the German Beck Depression Inventory (BDI-II; Hautzinger et al., 2009) was administered to assess the symptom strength of depression. For analysis, we used the total score of the BDI-II.

Debriefing. After study completion, a debriefing took place on strategies and other aspects (i.e., interest, motivation, concentration) of task performance.

Lesion sizes. In 27 participants brain images were available: $n = 9$ in-house high-resolution images from 3T Siemens Magnetic Resonance Imaging (MRI) scanner (T1 1 mm^3 isovoxel and FLAIR); $n = 12$ clinically motivated MRIs (various scanners, partially different MR-sequences) and $n = 6$ Computer tomography (CT) scans. 24 of these participants showed circumscribed structural lesions, while three participants showed no focal lesion. Lesions were delineated manually using MRIcron (Rorden and Brett, 2000) on T1-images with Fluid-attenuated inversion recovery (FLAIR) as reference or Computer tomography (CT) images. The lesion masks were then standardized to stereotactic space (MNI) using the *clinical toolbox* (www.nitrc.org/projects/clinicaltbx/) in SPM12 (https://www.fil.ion.ucl.ac.uk/spm/software/spm12/), applying the unified segmentation approach (Ashburner and Friston, 2005) and restricting estimation of normalization parameters to healthy tissue (Brett et al., 2001).

2.5. Data acquisition procedure

The assessment of rhythmic abilities together with the inhibition task, the assessment of the musical experience, and a debriefing about strategies was done in two sessions with a duration of 45 min taking place on different days (interval between sessions: 3–9 days). Neuropsychological assessment and manual dexterity testing were done by trained neuropsychologists and therapists as part of the clinical diagnostics. All tests were performed within the first two weeks of the diagnostic phase for a therapeutic stay at the Clinic for Cognitive Neurology at the University Hospital in Leipzig, Germany.

2.6. Data analysis

BAASTA perceptual tasks. The thresholds for the duration discrimination and anisochrony detection tasks were calculated by averaging the JND thresholds obtained in two blocks. Blocks were rejected when they contained more than 50% of false alarms (i.e., participants incorrectly indicated a difference in a no-difference trial). For the Beat Alignment Test, the discriminability index (d') from signal detection theory was calculated, defined as the difference between the z-transformed hit rates (when unaligned tones were correctly detected) and false alarm rates (when lack of alignment was incorrectly reported).

BAASTA production tasks. Pre-processing of the tapping data followed the procedure described in Bégel et al. (2018b), Dalla Bella et al. (2017) and Dalla Bella et al. (2024a). Mean inter-tap-intervals (ITI) and their coefficient of variation (*CV*, obtained by dividing the ITIs *SD* by the mean) as a measure of rhythmic-motor variability were calculated for unpaced tapping and the continuation phase of the synchronization-continuation task. Before statistical analyses, the *CV* of the ITI of the synchronization-continuation task was submitted to a ln transformation. For the paced tapping tasks, we calculated circular statistics as in previous studies (Bégel et al., 2022; Bégel et al., 2018b; Dalla Bella et al., 2017; Puyjarinet et al., 2017). Each finger tap is represented by an angle (unitary vector) on a 360° polar scale, in which the circle represents the IOI (or IBI for music) of the stimuli. The length of the resultant vector *R* is referred to as the synchronization consistency (i.e., stability in taps in opposite to variability) and was considered in our study as the main index for synchronization. Its value varies between 0 (no synchronization) and 1 (perfect synchronization). Before statistical analyses, synchronization consistency was submitted to a logit transformation. The direction of *R* is expressed in percent of the IOI and represents the accuracy of synchronization performance. If the participant's synchronization was below chance level, as assessed by the Rayleigh test for circular uniformity (Fisher, 1995; Wilkie, 1983), accuracy was not calculated. The mean performance of the two trials was calculated for paced tapping and synchronization-continuation.

Anticipatory tapping. The data analysis of this task followed the procedure described in Pecenka et al. (2013) and was conducted using MATLAB (Version R2021a). First, the initial six taps of each trial were deleted. Then, each tap was assigned to the nearest beat of the pacing sequence within a time window of ±200 ms (linear statistics). Taps that fell outside the time window were defined as outliers (missing data). Trials with more than 25% missing data points were excluded from the analysis. Missing data points resulted from missing or unrecorded taps as well as outliers and associated further missing data points due to the calculation of ITI. Participants with less than three valid trials were excluded from the analysis. We computed a measure of anticipatory tendencies based on the lag-0 and lag-1 cross-correlations (CC) between the ITIs produced by the participant and the IOIs of the pacing signal. Both the prediction index (lag-0 CC) and the tracking index (lag-1 CC) were computed in relation to the lag-1 autocorrelation (AC) of the timing sequence (CC - AC/1 - AC) as suggested by Repp (2002). The ratio of lag-1 CC/lag-0 CC indicates whether a participant anticipates tempo changes (Ratio >1) or reacts to tempo changes (Ratio ≤1) and is referred to as the prediction/tracking ratio. The ratio was calculated separately for each trial, Fisher-z transformed, and averaged over all valid trials. (Note that this measure is different from the so-called negative mean asynchrony typically observed in paced tapping, whereby taps occur earlier than tones, to the extent that the prediction/tracking ratio reflects the extrapolation of changes in successive IOIs.)

Image analysis in participants with focal brain lesions. The overlay of the lesions shows widely distributed lesion patterns affecting both hemispheres. The maximal number of overlapping lesions in a given voxel was three. Fig. 1 provides a tomographic and 3D illustration of the lesion overlay. As a measure of individual lesion load, we calculated the diameter of a sphere corresponding to the overall lesion volume. Exploratory analyses were conducted to examine whether there are significant correlations between the overall lesion volume and the performance in rhythmic abilities. Moreover, we used the WFU Pick-Atlas v3.0 (Maldjian et al., 2003), to assess the lesion load in the 12 lobar regions provided by the atlas in both hemispheres (frontal, parietal, temporal, limbic and occipital lobes, frontal-temporal space, medulla, midbrain, pons, sub-lobar, cerebellum anterior, cerebellum posterior). In 6 of the 24 regions none of the participants had any lesion. For the 18 remaining regions the number of participants showing lesions ranged

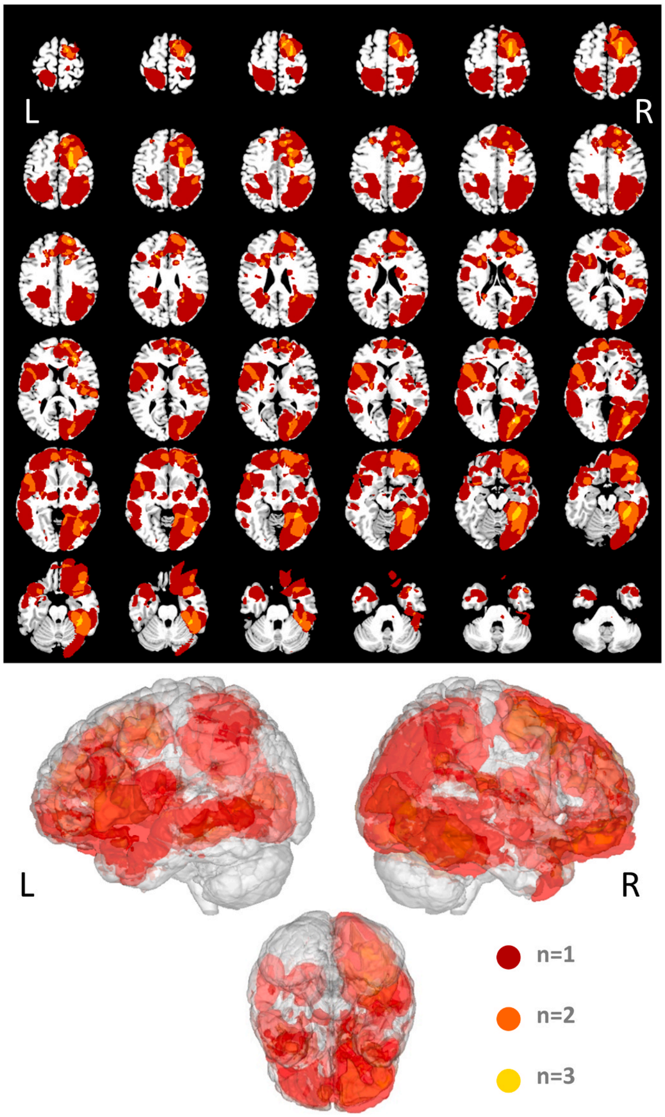

Fig. 1. Overlay of all circumscribed lesions (n = 24 participants). The lesions show a wide distribution over both hemispheres. Overlap is low, maximally 3 participants show overlap (yellow areas).

from 1 to 18. Supplementary material Table S3 provides the total, hemispheric, and regional volumes as well as neurological diagnoses of all participants with a circumscribed lesion (n = 24).

2.7. Statistical analyses

To investigate the results of the rhythmic tasks with a clinical sample and evaluate data quality, comparison of means of different tasks and task conditions were calculated: Paired t-tests were employed to compare (1) the thresholds of duration discrimination and anisochrony detection, (2) the results of unpaced tapping with the dominant hand and non-dominant hand, and (3) the results of paced tapping to metronome and paced tapping to music. To analyze whether the performance of paced tapping and synchronization-continuation differed depending on the rate of the pacing stimulus (IOI), separate analyses of variance (ANOVA) with repeated measurement were calculated. When the assumption of sphericity was not met, the Greenhouse-Geisser correction (on the degrees of freedom) was applied. In addition, Pearson's correlations were calculated between all rhythmic tasks.

We tested whether and to what extent executive functions (i.e., inhibitory control, working memory, cognitive flexibility) can predict the performance in rhythm perception and production tasks by using multiple regression modeling. The dependent variables were (i) synchronization consistency (i.e., vector length of the task paced tapping to metronome), (ii) rhythmic-motor variability (i.e., *CV* of the ITI of the task synchronization-continuation), (iii) anticipatory timing (i.e., prediction/tracking ratio of the task anticipatory tapping), (iv) sub-second time perception (i.e., threshold of the task duration discrimination), and (v) beat perception (i.e., *d'* in the Beat Alignment Test). Regression analyses were limited to five rhythmic tasks as there were no hypothesized relations between executive functions and anisochrony detection and unpaced tapping.

The predictors in each model were (i) the relativized reaction time of the Simon task to assess inhibitory control, (ii) the total score of correct responses in the digit span backward task to assess working memory, and (iii) the relativized processing time of the TMT A and B to assess cognitive flexibility. We applied model selection based on Akaike's information criterion corrected for small sample size (AICc; Burnham and Anderson, 2002) which is a standard measure to arbitrate between complexity and explanatory power of the models. Subjects with missing values in the Simon Task, the digit span backward and the TMT A or B had to be excluded from the regression analysis, as for a model comparison using AICc all models must have the same sample size. We report the best-fitting models with the lowest AICc. For those models that can significantly predict the criterion, the contribution of other cognitive variables (verbal learning ability, information processing speed) and potentially confounding variables (demographic, clinical, and neuropsychological) was tested by successively entering and removing these additional predictors from the models. Potentially confounding variables were age, musical experience, manual dexterity, duration of illness, symptom strength of depression, and severity of cognitive impairment. Severity of cognitive impairment was entered as a binary variable (0 = *no* to *mild* cognitive impairment [n = 20], 1 = *mild/moderate* to *moderate/severe* cognitive impairment [n = 15]). All other predictors were continuous.

Residual plots were visually inspected for all models to test for the assumptions of normal distribution, linearity, and heteroscedasticity of the data. No obvious patterns were observed, and residuals did not appear to deviate from a straight line in any of the models, therefore meeting the required assumptions. Multicollinearity was checked by calculating variance inflation factors (all VIF <1.3). For the reported models Cook's distance metric was calculated. If data points with Cook's distance scores above 0.5 appeared, we repeated the analyses after discarding these participants. The results were replicated after removal of the outliers. All regression analyses were conducted with RStudio (v2021.09.0) supporting R (v4.1.1) using lm() function for modeling and the *MuMIn* (v1.46.0) package for calculating the AICc. All significant effects were set at $p < 0.05$.

3. Results

3.1. Demographic, clinical, and neuropsychological measures

Descriptive statistics for demographic, clinical, and neuropsychological measures, as well as results on concentration and motivation during the rhythm tasks and interest in the study, are summarized in Table 1 (see supplementary material S4 for data presented according to etiological subgroups). Note that two participants provided self-responses in the BDI that would suggest major depression. However, debriefing with detailed clinical assessment of symptom strength, evaluated by trained psychologists, revealed a moderate depressive episode according to ICD-10, which did not restrict participation in the study.

3.2. Rhythmic abilities

3.2.1. Perceptual tasks

The results of the perceptual tasks are presented in Fig. 2. Duration

Table 1
Demographic, clinical, and neuropsychological measures of the participants.

Measure/Task	Variable	*M* (*SD*)	Range	*n*
Demographics				
Age	Years	50 (14)	20–79	35
Men/women [a]				18/17
Right/left-handed				33/2
Musical experience	Hours	1017 (2402)	0–10839	34
Clinical measures				
Duration of illness	Month	23.2 (30.8)	4–162	35
Lesion load	DiaS in mm	14.1 (8.7)	0–29.3	27
9HPT dominant hand	Seconds	22.7 (8.5)	13.6–63.0	35
BDI-II	Total score	12.6 (9.4)	0–44	35
Neuropsychological measures				
TAP Incompatibility	Relativized RT [b]	0.12 (0.13)	−0.09–0.45	33
Digit span backward	Total score	5.63 (1.52)	3–10	35
Trail Making Test	Relativized PT [c]	1.00 (0.55)	−0.15–2.17	32
CVLT	Learning slope	1.20 (0.76)	0–2.5	33
TAP tonic Alertness	Median in ms	307.23 (142.54)	198–896	35
Compliance				
Motivation	5-Point Likert Scale	4.4 (0.7)	2–5	35
Concentration	5-Point Likert Scale	4.3 (0.8)	2–5	35
Interest	5-Point Likert Scale	3.7 (0.1)	1–5	35

Note. 9HPT = Nine-Hole Peg Test. BDI-II = Beck Depression Inventory II. CVLT = California Verbal Learning Test. DiaS = Diameter of a sphere. TAP = Test of Attentional Performance. CVLT = California Verbal Learning Test. *n* = Number of participants whose data could be used for the analysis.
[a] sex assigned at birth.
[b] the medians of the reaction times (RT) of the task conditions were relativized as follows: [(incompatible - compatible)/compatible].
[c] the absolute processing times (PT) were relativized as follows: [(B - A)/A].

discrimination thresholds were significantly higher (~74.8 ms) than anisochrony detection thresholds, $t_{(28)} = -8.32$, $p < .001$, $n = 29$; Fig. 2a. The figures contain additional information about the participants' performance in comparison to a normative sample from Canada (Dalla Bella et al., 2024a), which comprises 108 healthy adults 18–87 years old. Highlighted areas indicate below-average (red) and above-average (green) performance (percentile rank 16 and 84 of the normative sample). Note that thresholds for duration discrimination could not be determined in six participants and for anisochrony detection in two participants, as the highest possible threshold was reached. d' in the Beat Alignment Test was missing for one participant, who terminated the task prematurely. Still, a substantial percentage of participants demonstrated below-average performance in duration discrimination (24.1%), anisochrony detection (39.4%), and the Beat Alignment Test (26.5%). The percentages for above-average performance were 20.7% of participants for duration discrimination, 6.1% for anisochrony detection, and 26.5% for the Beat Alignment Test.

3.2.2. Production tasks

The results obtained in the production tasks are presented in Fig. 3. If available, values from the normative sample are provided for comparison. Note that for the variables *mean of the ITI* and *vector direction*, a deviation in either direction (i.e., high and low values) indicates poor performance. For an overview of the descriptive results of all rhythmic parameters as well as all proportions of above-average and below-average performances, see Tables S5 and S6 in the supplementary material.

Unpaced tapping. Performance with the non-dominant hand in the unpaced tapping task could not be evaluated for six participants due to motor impairments caused by (residual) hemiparesis. For the other participants there were no significant differences between unpaced tapping with dominant and non-dominant hand, neither in the mean of the ITI indicating spontaneous preferred tempo ($t_{(28)} = -1.06$, $p = .298$, $n = 29$; Fig. 3a) nor in the *CV* of the ITI indicating rhythmic-motor variability ($t_{(28)} = -1.52$, $p = .139$, $n = 29$; Fig. 3b). Participants showed a preferred tapping rate in the vicinity of 650 ms. For the CV of the ITI (dominant hand) 28.6% of the participants were below average, whereas 5.7% were above average.

Paced tapping. Vector direction indicating synchronization accuracy could not be calculated for three participants in the metronome condition and for one participant in the music condition, as vector direction was only calculated when the synchronization performance was above chance level (tested by the Rayleigh test). No significant differences were found between the three metronome rates for both vector directions ($F_{(1.66,\ 46.36)} = 0.62$, $p = .515$, $n = 29$; Greenhouse-Geisser corrected; Fig. 3d) and vector length ($F_{(1.63,\ 55.53)} = 0.99$, $p = .364$, $n = 35$; Greenhouse-Geisser corrected; Fig. 3e). Average scores of the three tempos (mean of the IOI) were calculated for both variables. There was a significant difference for vector direction depending on the pacing stimulus (metronome vs. music), $t_{(30)} = -4.88$, $p < .001$, $n = 31$; Fig. 3d. However, there was no significant difference between the vector length of paced tapping to the metronome (mean the IOI) and to music, $t_{(34)} = 1.14$, $p = .263$, $n = 35$; Fig. 3e. The range and standard deviation of vector length were larger for tapping to music ($SD = 1.73$) than for tapping to the metronome ($SD = 0.88$). In terms of vector length, the comparison with the normative sample shows higher proportions of below-average performance in our clinical population (ranging from 22.9% to 37.1% of participants for the paced tapping tasks) than above-average performance (ranging from 2.9% to 20.0% of participants).

Synchronization-continuation. Fig. 3f (mean of the ITI) shows, that participants successfully continued the pace set in the synchronization phase. The *CV* of the ITI indicating rhythmic-motor variability at a given tempo did not differ significantly depending on the rate of the pacing stimulus (IOI), $F_{(2,68)} = 0.663$, $p = .519$, $n = 35$; Fig. 3g. Average scores of the three tempos (mean of the IOI) were calculated for the *CV* of the ITI. Again, the comparison with the normative sample shows higher proportions of below-average performance (ranging from 37.1% to 42.9% of our participants) than above-average performance (ranging from 5.7% to 20.0% of our participants).

Anticipatory tapping. Results are shown in Fig. 3c. The prediction/tracking ratio could not be calculated for two participants due to missing data points resulting in more than three invalid trials. Note that no normative data is available, as this task is not part of BAASTA. Prediction/tracking ratios indicated that 73% of the participants tended to anticipate the tempo changes in the tapping task (ratio >1), whereas the remaining participants followed the tempo changes, i.e., responded to the change at a lag (ratio ≤1).

3.2.3. Relations between rhythmic tasks

The performance profiles of participants exhibit considerable heterogeneity, with no coherent pattern of below-average performance among the same individuals. In fact, only one participant consistently demonstrated below-average performance across all tasks, and conversely, only one participant performed average or above-average across all tasks. Focusing solely on rhythm perception tasks, 4 individuals (11.4%) consistently performed below average. A correlation matrix, depicted in Fig. 4a, offers a comprehensive overview of the relationships between various rhythmic tasks. Notably, a strong correlation is observed between the tasks anisochrony detection and duration discrimination. Additionally, there are notable correlations between distinct rhythm production tasks.

When examining the correlations between rhythm perception and rhythm production tasks, two conspicuous high correlations emerge between the Beat Alignment Test and Synchronization Consistency (Vector Length). Fig. 4b illustrates the significant correlation between

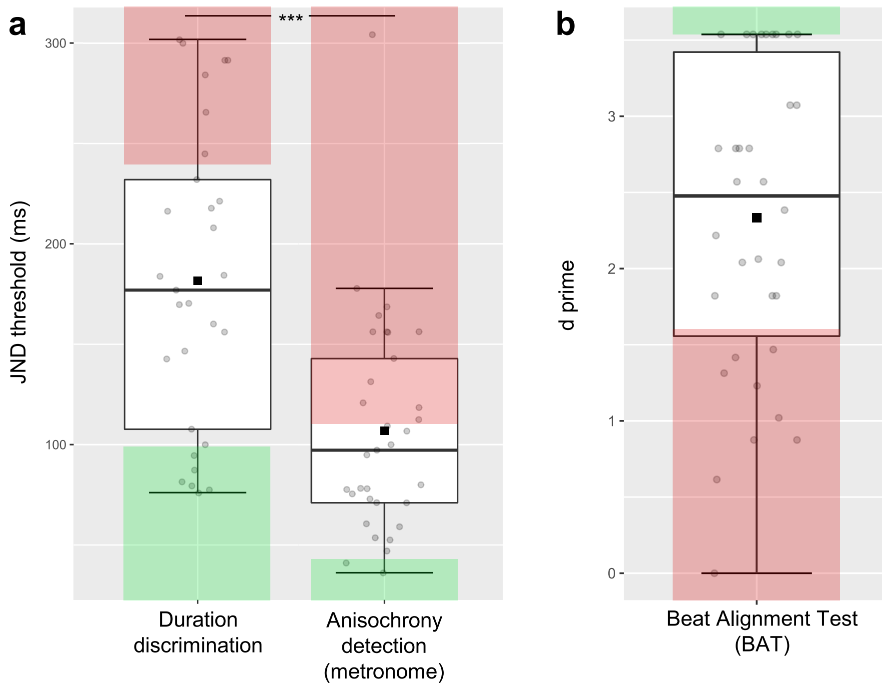

Fig. 2. Performance in the perceptual tasks. Boxplots with median (crossbar), mean (black square), and individual values (gray dots). Error bars indicate 1.5 interquartile range. The areas highlighted indicate poor (red) and high (green) performance, i.e., percentile rank [PR] < 16 and >84 of the normative data from BAASTA. The exact cut-off values are **a:** duration discrimination PR 16 = 98.40; PR 84 = 238.20; anisochrony detection PR 16 = 43.81; PR 84 = 110.26. **b:** Beat Alignment Test PR 16 = 1.60; PR 84 = 3.54. JND = just noticeable difference. ***$p < .001$.

the Beat Alignment Test and synchronization consistency to music. The inclusion of normative data reveals that 5 participants (14.7%) exhibited below-average performance in both tasks, while 7 participants (20.6%) exhibited below-average performance in only one of the two tasks. The majority of participants (64.7%) showed average to above-average performances on both tasks.

3.3. Relations between rhythmic abilities and executive functions

We used multiple linear regression modeling to assess whether timing and rhythmic abilities can be predicted by executive functions and to quantify the strength of associations for different functions (i.e., inhibitory control, working memory, cognitive flexibility). Analyses showed that executive tasks (i.e., inhibitory control, indicated by the Simon task and/or working memory, indicated by the digit span backward) predicted performance in the rhythm production tasks (see Table 2).

(i) Synchronization consistency (vector length of the paced tapping task) was predicted significantly by both inhibitory control and working memory (we reported the model without two outliers here, for the results of the initial model with all participants see supplementary material, Table S8). A scatterplot showing the negative correlation between inhibitory control and synchronization consistency is shown in Fig. 5a, indicating that a higher synchronization consistency is related to a smaller interference effect. The positive correlation between working memory and synchronization consistency is shown in Fig. 5b.

(ii) Rhythmic-motor variability (*CV* of the ITI of the synchronization-continuation task) was predicted significantly by working memory. A scatterplot showing the negative correlation between working memory and rhythmic-motor variability is shown in Fig. 5c.

(iii) Anticipatory timing (prediction/tracking ratio of the anticipatory tapping task) was predicted marginally significantly by working memory. Due to missing values in the Simon task and the TMT A/B, two participants had to be excluded for the regression analyses. When repeating the best-fitting regression model with all possible participants, anticipatory timing was predicted significantly by working memory. A scatterplot showing the positive correlation between working memory and the anticipatory timing is shown in Fig. 5d.

In contrast, performance in tests for executive function did not predict performance in rhythm perception tasks, i.e., duration discrimination and Beat Alignment Test (for all models $p > .2$; see supplementary material, Table S7).

All (relevant) predictors in the reported models above remained significant when controlling for other cognitive variables, i.e., information processing speed, verbal learning ability (i.e., after adding tonic information processing speed, CVLT [learning slope] to the model), and possible confounding variables, i.e., age, symptom strength of depression (BDI), manual dexterity (9HPT), duration of illness, severity of cognitive impairment and musical experience. Musical experience significantly contributed to the model for predicting synchronization consistency ($\beta = 0.40$, $p = .013$), but still, both inhibitory control ($\beta = -0.44$, $p = .008$) and working memory ($\beta = 0.44$, $p = .006$) were significant predictors. In all other models, the demographic, clinical, or neuropsychological variables considered were not significant predictors (for detailed results of the regression analyses, see supplementary material, Tables S8, S9, and S10).

3.4. Post-hoc exploratory analysis on the relationship between lesion size and rhythmic abilities

Post-hoc exploratory analysis showed that there were no significant correlations between lesion size (represented as the diameter of a sphere corresponding to the overall lesion volume) and (i) synchronization consistency ($r = 0.02$, $p = .93$), (ii) rhythmic-motor variability ($r = -0.56$, $p = .80$), (iii) anticipatory timing ($r = -0.05$, $p = .82$), (iv) the

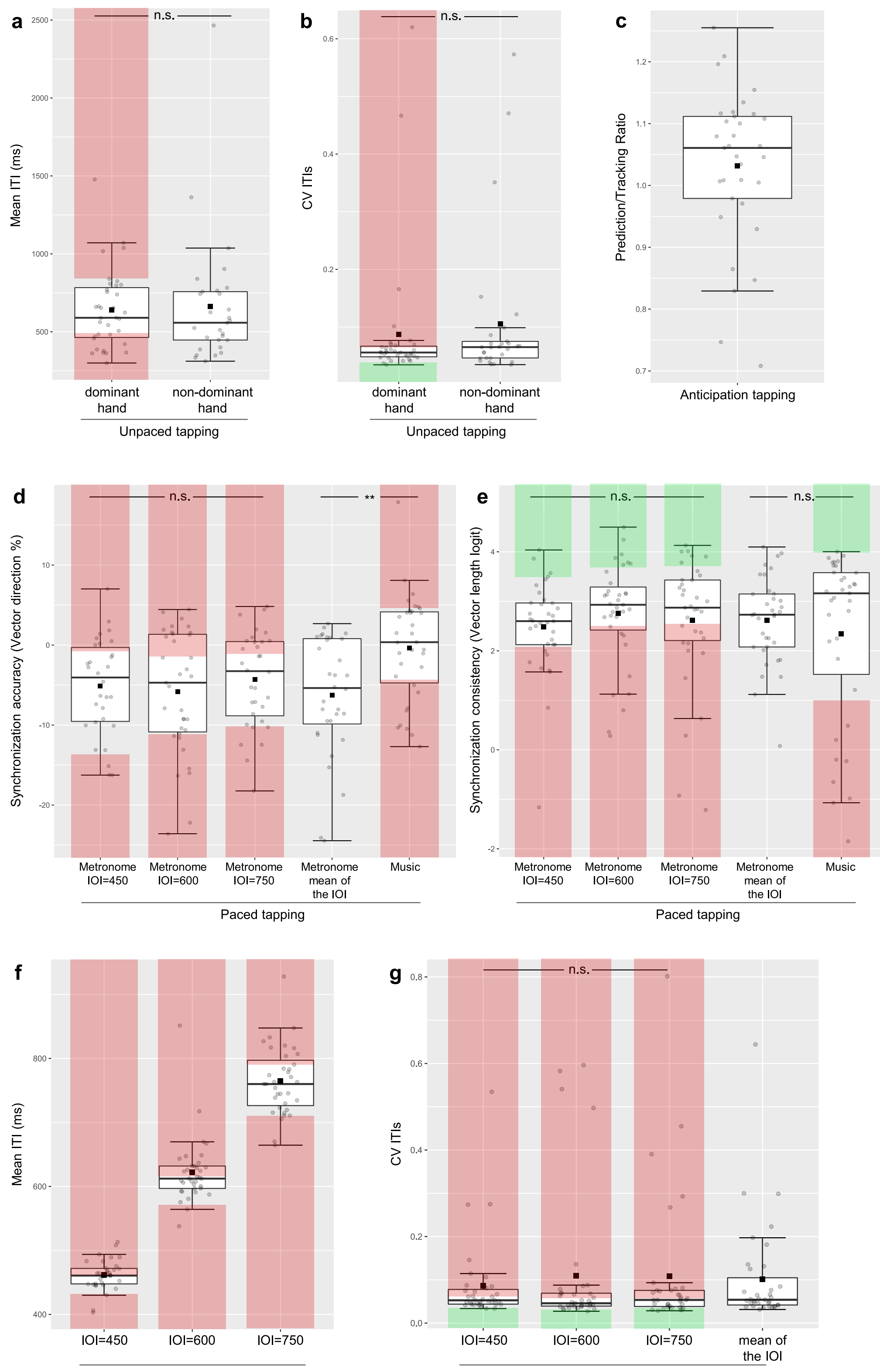

Fig. 3. Performance in the production tasks. Boxplots with median (crossbar), mean (black square), and individual values (gray dots). Error bars indicate 1.5 interquartile range. The areas highlighted indicate poor (red) and high (green) performance if available (percentile rank [PR] < 16 and >84 of the normative data from the BAASTA). The exact cut-off values are **a**: unpaced tapping with dominant hand PR 16 = 495.29; PR 84 = 843.48. **b**: unpaced tapping with dominant hand PR 16 = 0.038; PR 84 = 0.065. **d**: paced tapping inter-onset-interval (IOI) 450 PR 16 = −13.39; PR 84 = −0.87; IOI 600 PR 16 = −11.19; PR 84 = −1.50; IOI 750 PR 16 = −10.15; PR 84 = −1.14; music PR 16 = −4.26; PR 84 = 4.49. **e**: paced tapping IOI 450 PR 16 = 2.08; PR 84 = 3.49; IOI 600 PR 16 = 2.49; PR 84 = 3.67; IOI 750 PR 16 = 2.54; PR 84 = 3.70; music PR 16 = 0.99; PR 84 = 3.98. **f**: synchronization-continuation IOI 450 PR 16 = 432.31; PR 84 = 463.43; IOI 600 PR 16 = 573.55; PR 84 = 616.46; IOI 750 PR 16 = 710.63; PR 84 = 789.33. **g:** synchronization-continuation IOI 450 PR 16 = 0.034; PR 84 = 0.062; IOI 600 PR 16 = 0.032; PR 84 = 0.059; IOI 750 PR 16 = 0.036; PR 84 = 0.058. ITI = inter-tap-interval. CV = coefficient of variation. n.s. = not significant. $^{**}p < .01$.

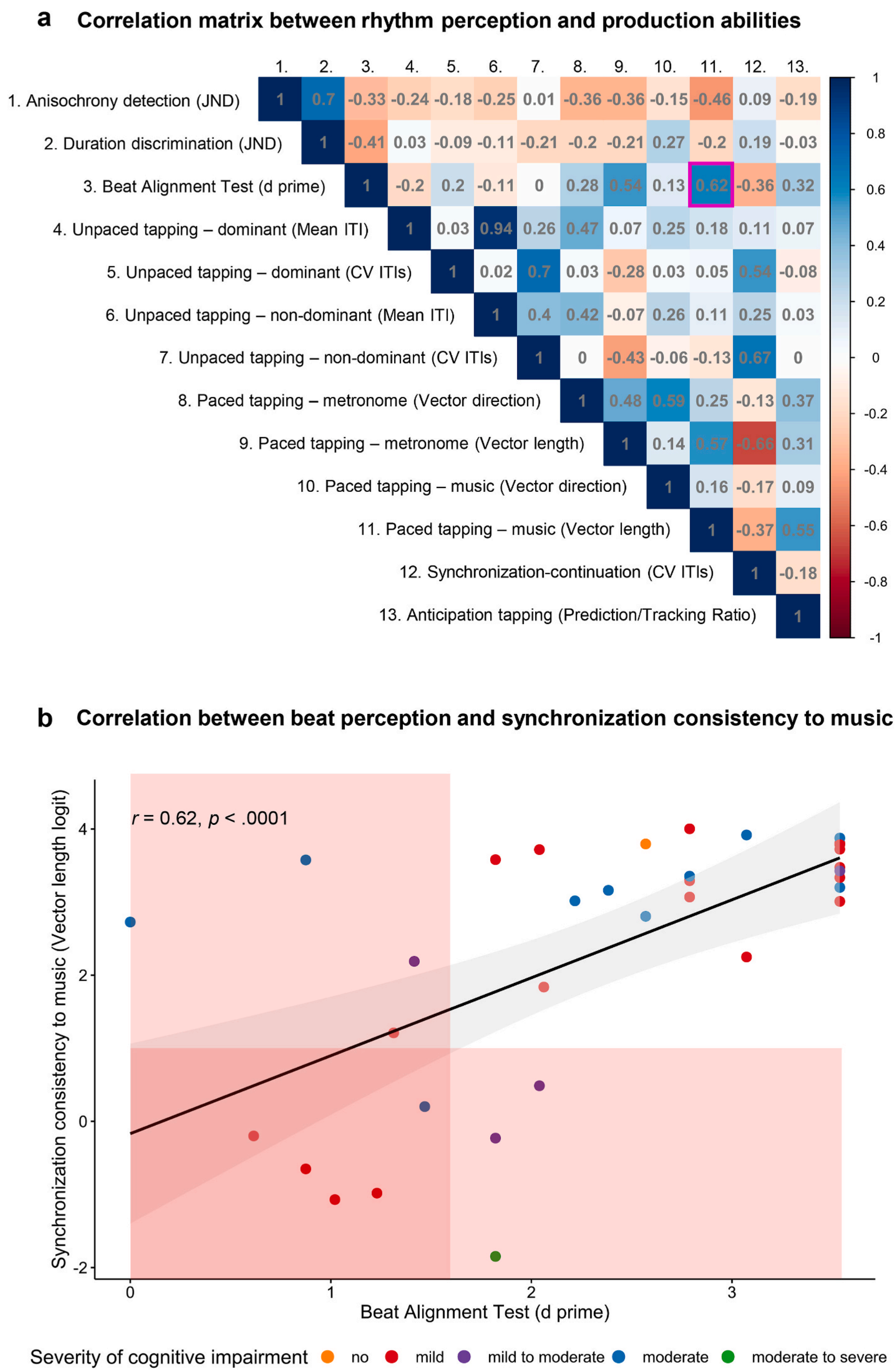

Fig. 4. Correlations between rhythm perception and rhythm production. a. Correlation matrix using all rhythmic variables. Pearson's correlation coefficients are reported according to the color coding. The pink-framed correlation is visualized in b. For Fig. 4b, the areas highlighted in red indicate poor performance (percentile rank [PR] < 16). Exact cut-off values: Beat Alignment Test PR 16 = 1.60; Vector length PR 16 = 0.99.

threshold of the task duration discrimination ($r = -0.14$, $p = .56$) and (v) d' in the Beat Alignment Test ($r = 0.17$, $p = .44$).

4. Discussion

Here we investigated associations between rhythmic abilities and cognitive especially executive functions in participants with neurocognitive deficits. Confirming hypothesis 1, we showed that better synchronization consistency in a paced tapping task was predicted by better inhibitory control. Confirming hypothesis 2 and 3, we showed that higher rhythmic-motor stability at a given tempo and better anticipatory timing to sequences with gradual tempo changes were predicted by better working memory performance. We did not confirm hypotheses 4 and 5: perceptual rhythmic abilities (sub-second time perception/beat perception) were not predicted by working memory in our study. Moreover, we found that besides inhibitory control, better synchronization consistency was also predicted by better working memory performance and higher musical experience, with all factors providing independent contributions. Cognitive flexibility did not emerge as a significant predictor in the best-fitting models. Importantly, all rhythm production abilities were significantly predicted by inhibitory control and/or working memory even when potential contributions

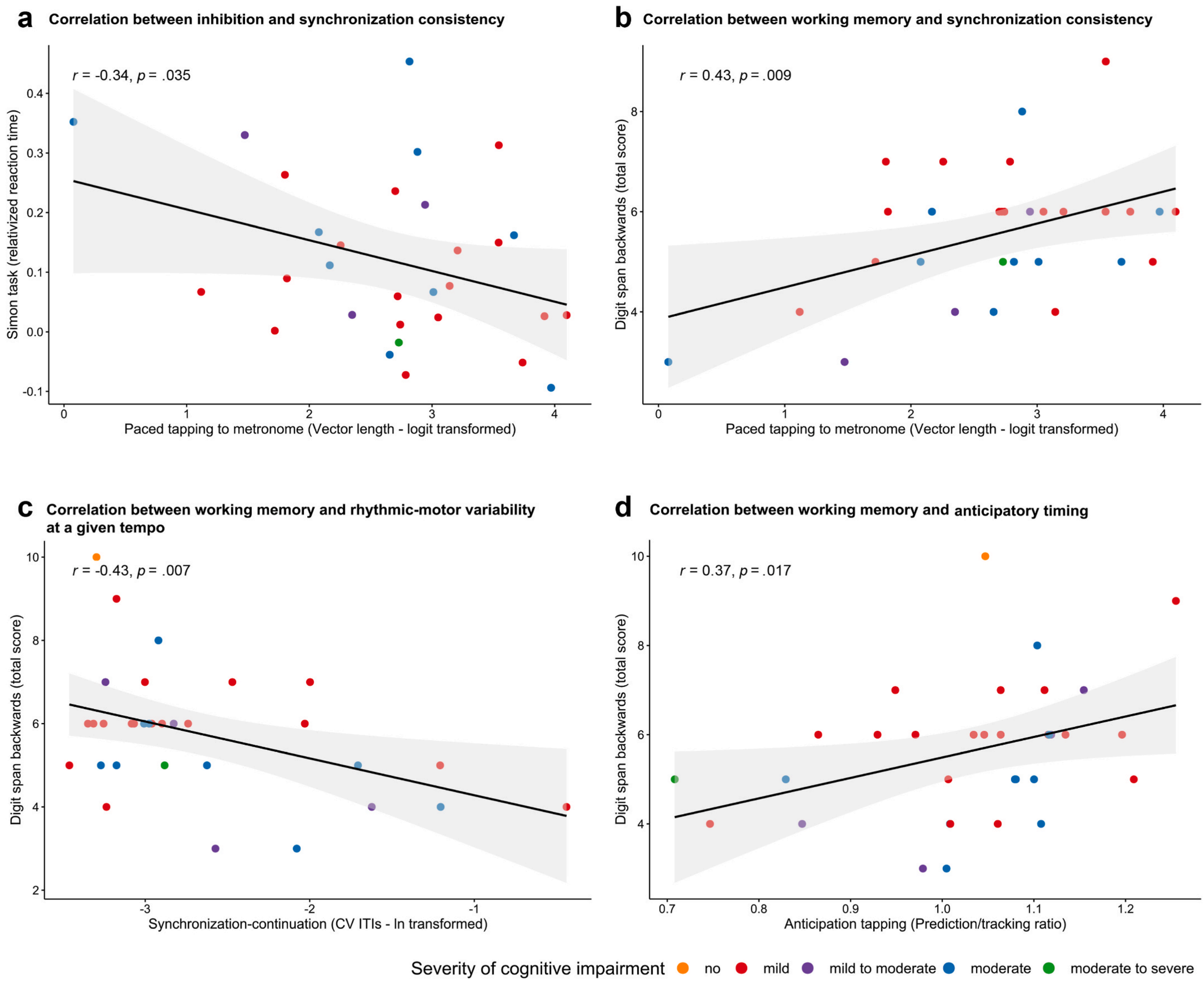

Fig. 5. Correlations between rhythmic abilities and executive functions with a 95% confidence interval (shadowed) and a color code indicating cognitive impairment.

Table 2
Regression analyses using executive functions (inhibitory control, working memory, and cognitive flexibility) to predict rhythm production abilities. The best-fitting models based on Akaike's information criterion (AICc) are reported.

Term	Estimate (*SE*)	ß-value	*t*-value	*p*-value
Synchronization consistency (model without outliers)				
Model fit: $R^2 = .31$, $R^2_{corr} = .26$, $F_{(2,\ 27)} = 6.18$, $p = .006$				
(Intercept)	1.27 (0.63)	–	2.03	.053
Inhibitory control	−2.33 (1.04)	−0.36	−2.24	**.034**
Working memory	0.30 (0.11)	0.45	2.81	**.009**
Rhythmic-motor variability				
Model fit: $R^2 = .19$, $R^2_{corr} = .16$, $F_{(1,\ 30)} = 6.93$, $p = .013$				
(Intercept)	−1.44 (0.48)	–	−3.02	**.005**
Working memory	−0.21 (0.08)	−0.43	−2.63	**.013**
Anticipatory timing ($n = 33$)				
Model fit: $R^2 = .13$, $R^2_{corr} = .10$, $F_{(1,\ 29)} = 4.18$, $p = .050$				
(Intercept)	0.88 (0.08)	–	11.33	**< .001**
Working memory	0.03 (0.01)	0.36	2.05	.050
Anticipatory timing (model including all 35 participants)				
Model fit: $R^2 = .14$, $R^2_{corr} = .11$, $F_{(1,\ 31)} = 4.87$, $p = .035$				
(Intercept)	0.87 (0.08)	–	11.04	**< .001**
Working memory	0.03 (0.01)	0.37	2.21	**.035**

by other cognitive functions (information processing speed, verbal learning ability) and possible confounding variables (i.e., age, symptom strength of depression, manual dexterity, duration of illness, severity of cognitive impairment, and musical experience) were taken into account.

The relationship between inhibitory control and sensorimotor synchronization ability is in line with studies including neurotypical populations (e.g., Slater et al., 2018). Our present study extends this to individuals with acquired neurocognitive deficits. Based on these results it is tempting to speculate that a rhythmic training intervention in patients might also impact cognitive abilities in this population. Inhibitory control is linked to predictive processing and conflict monitoring, as the suppression of irrelevant stimuli or action tendencies usually conflicts with what was predicted or planned. Synchronization ability also depends on prediction, conflict monitoring, and reactive error correction, as individuals anticipate the next stimulus, verify its alignment with their actions, and make necessary adjustments (see Slater et al., 2018; Vuust et al., 2009). In this vein, our results are consistent with the notion that cross-domain predictive processing may be a central mechanism bridging rhythm processing and cognitive-motor abilities (Frischen et al., 2022).

Besides inhibitory control, we found working memory abilities to be a significant predictor for all production-related rhythmic abilities. Rhythmic-motor stability when maintaining a given tempo requires upholding an internal representation of the tempo. Anticipatory timing requires a manipulation of the internal representation of tempo. Furthermore, working memory also emerged in our results as a significant predictor of synchronization consistency independently of inhibitory control and musical experience. This finding seems to contradict with the assumption that the continuation of a given tempo is more cognitively demanding than the synchronization to a pacing sequence and therefore working memory processes are predominantly involved in the former (Jantzen et al., 2007; Monier and Droit-Volet, 2019). However, considering the requirements of sensorimotor synchronization, the involvement of working memory processes is reasonable. Precise sensorimotor synchronization requires the interplay of both anticipatory mechanisms (predictive processes) and adaptive mechanisms (reactive error correction) (van der Steen and Keller, 2013). Working memory likely supports the generation of predictions while updating the internal representation of tempo and monitoring ongoing motor actions. Thus, working memory may facilitate the prediction of the next action interval while simultaneously engaging in actions corresponding to the current time interval (see also Colley et al., 2018). Indeed, a previous study demonstrated that the synchronization performance of neurotypical participants decreases with increasing working memory load (Bååth et al., 2016). In summary, our results in a clinical population support the notion that working memory is not only involved in maintaining a given tempo (synchronization-continuation paradigm) and tempo-adaptive sensorimotor synchronization but also supports tempo-stable sensorimotor synchronization.

The extent of prior musical experience was a significant predictor for higher synchronization consistency. Such an influence of musical experience on sensorimotor synchronization is well attested (Krause et al., 2010; Repp, 2010), however, it should be emphasized that both inhibitory control and working memory significantly predicted synchronization consistency even when musical experience was factored out. Remarkably, rhythmic-motor stability when maintaining a given tempo and anticipatory timing were not significantly predicted by prior musical experience. Neither were other variables, including cognitive flexibility, information processing speed, verbal learning ability, age, symptom strength of depression, manual dexterity, duration of illness, and severity of cognitive impairment predictors of rhythm production abilities. The lack of influence of these variables underscores the robustness of the correlations found despite the heterogeneous characteristics of the participants. Importantly, the overall severity of cognitive impairment as assessed by clinical neuropsychologists on the basis of defined criteria applied to the results of comprehensive neuropsychological diagnostics (Frei et al., 2016) was not a predictor of rhythmic abilities. This indicates that rhythm production is linked to two domains of executive functioning, namely inhibitory control and working memory.

Moreover, lesion size as a surrogate marker of overall severity of the acquired brain lesion was not correlated with rhythmic abilities in the subsample in which the lesion could be delineated ($n = 24$). Due to the exploratory nature of this analysis and the small number of overlapping lesions, this result should be interpreted with caution. A more fine-grained analysis regarding the relevance of specific (sub)cortical lesion sites which can be expected to afford rhythmic abilities was not possible (e.g., auditory and sensorimotor areas, the basal ganglia, prefrontal cortices). In individuals with cerebellar lesions, larger lesions have been shown to be associated with more variable tapping (Schwartze et al., 2016). However, in our sample rhythmic motor performance was specifically related to executive functions, an association that is not better explained by any other variable and cannot be attributed to an artifact due to the general severity of the disease.

Contrary to previous studies (Biswas et al., 2016; Toplak et al., 2003; Zhang et al., 2016) we did not find any support for associations between working memory and rhythm perception (sub-second time perception/beat perception). Moreover, neither time perception nor beat perception was predicted by executive functions. This may partially stem from differences in the task. We used a standard tone of 600 ms (1000 Hz) for the duration discrimination paradigm, while Toplak et al. (2003) used unfilled time intervals with a standard duration of 400 ms, and Zhang et al. (2016) used standard durations of only 100 ms (900–1100 Hz). The different properties of the standard tone could influence the result, as the mechanisms in time perception differ depending on the interval length. Also, the task may have been too difficult for our participants, as the threshold for duration discrimination could not be determined for six participants. However, previous research emphasized that demands on higher cognitive functions, such as sustained attention and working memory, are required only when time intervals exceed a certain length (typically 1 s; Baudouin et al., 2006; Fortin and Couture, 2002; Lewis and Miall, 2006; Rammsayer et al., 2001). The results of our study also indicate that working memory processes are less relevant for sub-second auditory time perception in individuals with neurocognitive disorder. To substantiate this, a larger cohort may be mandatory.

Concerning beat perception, we were unable to replicate the association with working memory (Biswas et al., 2016), although beat perception and synchronization consistency are significantly correlated. The correlation between beat perception and tapping variability is consistent with previous studies (e.g., Dalla Bella et al., 2017; Puyjarinet et al., 2017). One explanation for the absence of a correlation between working memory and beat perception may be attributed to a lower sensitivity of the Beat Alignment Test in detecting rhythmic deficits in our sample. This proposition is further supported by a comparison with normative data, showing that performance in the Beat Alignment Test was evenly distributed between below- and above-average performance, with a typical ceiling effect. Production-related tasks, on the other hand, consistently show a higher prevalence of below-average performance than above-average performance. Moreover, the association between beat perception and working memory documented in Parkinson's disease (Biswas et al., 2016) might be due to a progressive deterioration of both rhythmic abilities and cognitive functions, which may be related to the degeneration of dopaminergic neurons and dysfunction of the basal ganglia loop (Brown et al., 1997; Grahn et al., 2009; Middleton and Strick, 2000). To our knowledge, there are no studies on associations between rhythmic abilities and cognitive functions in other patient groups with more diverse brain dysfunction or neurotypical participants. Pending further research, our results do not support the assumption that differences in beat perception are related to executive functions in individuals with neurocognitive disorders. Such sparing of function is consistent with a degree of modularity.

By including normative data from BAASTA (Dalla Bella et al., 2024a), it was possible to compare the individual performance of participants to a normative sample comprising 108 neurotypical adults between 18 and 87 years recruited in the Montreal area. We consider this comparison to be valid, as we do not expect any general differences in rhythmic abilities due to linguistic or cultural aspects (Germany vs. Canada). Our present sample showed a broad distribution with below-average, average to above-average performance. This is consistent with the fact that we deliberately chose a broad range of severities and diseases. However, conclusions about the overall rhythmic performance of our heterogeneous group of participants are not warranted. Future studies may address more specifically whether specific lesion sites (e.g., basal ganglia and premotor cortices) cause more uniform impairment of rhythmic abilities. Descriptively, we see patterns of performance in rhythmic tasks that are similar to previous studies using the same tasks, indicating good data quality and valid results: The average perceptual threshold for duration discrimination was about 10% higher than the average perceptual threshold for anisochrony detection (Dalla Bella et al., 2017; Puyjarinet et al., 2017). The preferred tempo (IOI) was on average around 650 ms (Dalla Bella et al., 2017), and there were no significant differences between the right and left hand in the unpaced tapping task (Verga et al., 2021). The typical anticipatory tendency, as evident in negative asynchrony for paced tapping (i.e., the time point of the tap is earlier than the time point of the external stimulus) was observed and was smaller for music than for metronome (Dalla Bella et al., 2017). About two-thirds of the participants were able to anticipate tempo changes (Pecenka et al., 2013; Pecenka and Keller, 2009). Notably, the result of our regression analysis on anticipatory timing with working memory as a predictor was very similar to a previous study with neurotypical individuals ($\beta = 0.40$; $R^2 = 0.40$) conducted by Colley et al. (2018). Participants' motivation and concentration during the performance of the rhythmic tasks were subjectively rated as high to very high.

Taken together, our results suggest that executive functions, such as inhibitory control and working memory, might play a role in rhythmic motor performance. The regression analyses yield relations between the different variables but importantly do not allow for ascribing a causal role. Theoretically, it would also be a reasonable approach to predict performance in executive functions based on rhythmic abilities. However, we decided against this for methodological reasons (high intercorrelation of rhythmic abilities and thus poorer interpretation of beta weights). Generally, we speculate that higher-level mechanisms influence both rhythm production and executive functions (e.g., predictive coding, error correction, conflict monitoring). Likely, rhythmic motor performance is based on an interplay of both automatic and cognitively controlled processes (see also Fischinger, 2011; Honing, 2012).

While our study is primarily of scientific nature, a clinical perspective pertains to the increased use of music-based therapies in people with neurocognitive deficits. Our confirmation of associations between rhythmic abilities and cognitive functions in individuals with neurocognitive deficits provides a basis for investigations on therapeutic intervention strategies in neuropsychological rehabilitation, such as the use of music-based interventions, e.g., Neurologic Music Therapy (Thaut et al., 2009), and serious games to train rhythmic skills (Bégel et al., 2018a; Puyjarinet et al., 2022). However, no clinical implications or recommendations can be drawn from this study alone.

In conclusion, this study delved into the relationship between rhythmic abilities and cognitive functions in individuals with neurocognitive deficits. By conducting a comprehensive assessment of cognitive and rhythmic skills, the research aimed to uncover the interplay between these domains. The findings shed light on several significant associations between specific executive functions and distinct rhythmic-motor abilities. Inhibitory control and working memory independently predicted rhythm production abilities, whereas better cognitive performance was associated with a more stable (precise) rhythmic performance. Here we found no significant associations between executive functions and sub-second time perception or beat perception. Overall, our results contribute to a more nuanced understanding of the cognitive underpinnings of rhythmic abilities, particularly in individuals with neurocognitive deficits.

Additional information

Declarations of interest: SDB is on the board of the BeatHealth company dedicated to the design and commercialization of technological tools for assessing rhythm capacity such as BAASTA tablet and implementing rhythm-based interventions. Other authors have no competing interest to disclose.

The study was performed in accordance with ethical standards compliant with the declaration of Helsinki and had been approved by the local scientific ethics committee.

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CRediT authorship contribution statement

Alina S. Löser: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation. **Simone Dalla Bella:** Writing – review & editing, Software, Methodology. **Peter E. Keller:** Writing – review & editing, Software, Methodology. **Arno Villringer:** Writing – review & editing, Resources. **Hellmuth Obrig:** Writing – review & editing, Writing – original draft, Supervision, Resources, Methodology, Conceptualization. **Annerose Engel:** Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Formal analysis, Conceptualization.

Data availability

The authors do not have permission to share data.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.neuropsychologia.2024.109009.

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