The Preferred Period Hypothesis Revisited: Rhythmic Preferences and Motor Tapping Precision in ADHD Adults and Controls

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Abstract

Many aspects of human behavior are inherently rhythmic, requiring production of rhythmic motor actions as well as synchronizing to rhythms in the environment. It is well-established that individuals with ADHD exhibit deficits in temporal estimation and timing functions, which may impact their ability to accurately produce and interact with rhythmic stimuli. In the current study we seek to understand the specific aspects of rhythmic behavior that are implicated in ADHD. We specifically ask whether they are attributed to imprecision in the internal generation of rhythms or to reduced acuity in rhythm perception. We also test key predictions of the Preferred Period Hypothesis, which suggests that both perceptual and motor rhythmic behaviors are biased towards a specific personal 'default' tempo. To this end, we tested a several aspects of rhythmic behavior, including spontaneous motor tapping (SMT), perceptual preferences (PPT) and synchronization-continuations tapping in a broad range of rhythms, from sub-second to supra-second rates. Moreover, we evaluate the intra-subject consistency of rhythmic preferences, as a means for testing the reality and reliability of personal 'default-rhythms'.

Results indicate that individuals with ADHD are primarily challenged in producing self-generating isochronous motor rhythms, during both spontaneous and memory-paced tapping. However, they nonetheless exhibit a high degree of flexibility in synchronizing to a broad range of external rhythms. These findings suggest that auditory-motor entrainment is preserved in ADHD, and that the presence of an external pacer allows overcoming the inherent difficulty in self-generating isochronous motor rhythms. Interestingly, we find no advantage for performance near so-called 'default' motor or perceptual rhythms, in either ADHD or control groups, as was suggested by the Preferred Period Hypothesis. Moreover, participants in both groups displayed large variability in their SMTs and PPTs across session, raising questions regarding the extent to which all individuals indeed have specific motor and perceptual preferences. Therefore, alongside the insights into the nature of rhythmic deficits in ADHD, this study also challenges some assumptions made previously regarding the prevalence and functional role of default rhythmic preferences in facilitating rhythmic behavior more broadly.

1. Introduction

Rhythm is a central characteristic of many human behaviors. It is expressed through motor actions, such as clapping, walking, dancing and speaking (Bohannon 1997; Williams and Grant 1999; McAuley et al. 2006; Pellegrino et al. 2011). Rhythm also benefits perception, since its inherent temporal predictability allows preempting and preparing for upcoming stimuli (Nobre and Coull 2010; Ten Oever et al. 2017; Haegens and Zion Golumbic 2018; Jones 2019a). Not only is rhythm implicated as important for a wide range of cognitive abilities, but reduced temporal acuity has been linked to difficulties in both attention and language processing (Barkley et al. 1997; Kerns et al. 2001; Smith et al. 2002; Corriveau and Goswami 2009; Noreika et al. 2013). In particular, individuals with ADHD reportedly display reduced precision on a variety of timing-related tasks and rhythmic behaviors (Kerns et al. 2001; Smith et al. 2002; Rubia et al. 2003; Toplak and Tannock 2005a; Zelaznik et al. 2012). However, to date there is much ambiguity regarding the nature of rhythm-related deficits in ADHD adults and their consequences for daily behavior. The current study is a broad investigation of spontaneous and synchronized motor rhythms and the potential link between them, in adults with ADHD as well as within a typical control population.

In order to elucidate the nature of rhythmic deficits in ADHD, it is helpful to differentiate between two types of rhythmic behaviors: The first is spontaneous production of rhythm, generated internally by the motor system (Rimoldi 1951; Fraisse 1982). The second is synchronization to rhythms in the environment, that involves inherent interactions between sensory and motor systems (Repp and Su 2013). However, the relationship between spontaneous generation of motor rhythms and synchronizing motor actions to external rhythms has not been sufficiently characterized, to date. In the current research we were particularly interested in understanding whether the timing deficits observed in ADHD are related to the internal generation of rhythm or rather are linked to deficits in sensory-motor interactions.

1.1 Internal Rhythmic Preferences

A large body of literature suggests that individuals have a default **Spontaneous Motor Tempo (SMT)**, that is consistently produced during free motion (Rimoldi 1951; Fraisse 1982). In humans, spontaneous rhythms are generated in many body parts, including legs, lips, head and hands (Bohannon 1997; MacDougall and Moore 2005; Bobin-Bègue et al. 2006; Todd et al. 2006; Van Dyck et al. 2015) although the SMT literature has predominantly focused on finger-tapping paradigms where participants are instructed to tap their finger “at their most comfortable rate” (Collyer et al. 1994).

Some have argued that these default motor preferences also extend to the realm of auditory perception. Specifically, McAuley and colleagues (2006) report a one-to-one correspondence between individual SMTs and the tempo that individuals indicate is most 'comfortable' for them to listen to, labeled their **Preferred Perceptual Tempo (PPT)**. This finding prompted the *Preferred Period Hypothesis*, suggesting that individuals have a characteristic preferred rhythm, that is generalized across perception and production, and can be attributed to a common internal oscillator (McAuley 2010; Michaelis et al. 2014; Provasi et al. 2014; Schwartze and Kotz 2015). Moreover, according to this perspective, preferred internal rhythms also influence behavior, facilitating perceptual, motor and inter-personal synchronization at rhythms near one's SMT (Styns and Leman 2007; Large and Gray 2015; Zamm et al. 2015). However, to date, the consistency of 'default' motor and perceptual preferences within individuals and the degree to which they indeed generalize across rhythmic behaviors, has been somewhat debated (van der Wel et al. 2009; McPherson et al. 2018; Qi et al. 2019). Moreover, the manifestation of internal motor and perceptual rhythmic preferences in clinical populations who exhibit timing-related deficits, such as ADHD, has not been studied.

1.2 Synchronization to External Stimuli

Synchronizing motor actions to sensory rhythms is carried out through action-perception loops, and relies critically on temporal accuracy within both the sensory (Tierney and Kraus 2013) and motor systems (Schwartze et al. 2011). A potential neural mechanism proposed to underlie sensory-motor synchronization is entrainment of internal neural oscillations, and phase locking between sensory and motor cortices (Schroeder and Lakatos 2009; Morillon et al. 2014; Haegens and Zion Golumbic 2018; Rimmele et al. 2018). In contrast to the notion of SMT, synchronization requires flexible adaptation of internally generated motor rhythms to a wide range of rates, dictated by external sources. Therefore, we might ask whether the Preferred Period Hypothesis bears any relevance for synchronization behavior? Some have suggested that, indeed, motor synchronization to external rhythms is facilitated by internal inclinations, which manifests in improved synchronization accuracy for rhythms near one's preferred rhythm (McAuley et al. 2006; Styns and Leman 2007). However, in many studies, the range of rhythms to test this was tailored around participants' personal SMT or was limited to a small number of rhythms. Moreover, individuals may display large variability in their synchronization abilities, irrespective of the specific rhythm tested. Indeed, several studies report findings that are inconsistent with the prediction that synchronization is specifically improved near one's SMT (van der Wel et al. 2009; Van Dyck et al. 2015; McPherson et al.

2018). Therefore, currently, it is difficult to assert the specific contribution of personal/default rhythmic preferences to motor synchronization capabilities, in explaining individual differences in motor synchronization to external rhythms.

Given the proposed functional role of synchronization in facilitating perception, it is important to understand whether this behavior is indeed biased by internal rhythmic inclinations, as proposed by the Preferred Period Hypothesis. One of the goals of the current experiment was to systematically test this hypothesis, by testing the intra-subject consistency of spontaneous motor and perceptual rhythms, and their relationship to synchronization capabilities across a broad range of tempi, from sub-second intervals (250ms) to supra-second intervals (2.2 sec). This also enabled us to study which aspects of rhythmic behavior are implicated in ADHD, dissociating between internally-generated rhythms and sensory-motor rhythmic interactions.

1.3 Timing in ADHD

Timing-related deficits in ADHD have been demonstrated across multiple timescales and on a variety of tasks including sensorimotor synchronization, duration discrimination and reproduction, verbal time estimation and temporal anticipation (Noreika et al. 2013). Timing impairments have been associated with dysfunctions in neural circuitry known to be important for temporal processing, including the cerebellum, basal ganglia and fronto-parietal networks (Valera et al. 2010; Noreika et al. 2013) as well as neurochemical regulation of dopamine, which is strongly linked to timing functions and motor control (Baldwin et al. 2004; Rubia et al. 2009; Luman et al. 2015). In particular, two main phenomena are consistently observed across many timing-related tasks: A tendency toward hastening, i.e. preferring and producing faster rhythms / shorter intervals, and overall increased intra-subject variability (Barkley et al. 1997; Meaux and Chelonis 2003; Rubia et al. 2003; Toplak and Tannock 2005b; Klein et al. 2006; Toplak et al. 2006). However, the majority of these studies all involve forming temporal representations for *external stimuli*, and to date there has been no systematic investigation of spontaneous rhythm production in ADHD. The current study is a broad investigation of both spontaneous and synchronized motor rhythms and the potential link between them, in adults with ADHD as well as within a typical control population. It allows testing whether the deficits in rhythmic behavior observed in ADHD are related to imprecision in internal generation of rhythms or whether they should be attributed to reduced acuity in temporal perception and/or sensory-motor interactions?

To this end, we conducted a multi-stage experiment in ADHD adults and matched controls, assessing several aspects of rhythmic behavior, including: spontaneous motor tapping (SMT), perceptual preferences (PPT), as well as motor synchronization and memory-based rhythm reproduction. Critically we emphasized measures of consistency across trials and sessions, that are key for determining the extent to which motor and perceptual preferences are indeed characteristic for each individual. The procedure used here to evaluate individual SMT and PPT differed somewhat from previous studies in the specific instructions given to participants. Whereas most studies studying personal preferences in rhythms instruct participants to tap "at their most comfortable rate" and to rate perceived rhythms according to "comfort" or "pleasantness" (McAuley et al. 2006), here rhythmic preferences were linked to a more well-defined internal rhythm – counting from 1 to 10. We chose to narrow the operational definition of spontaneous rhythms in this manner for two reasons. First, in a preliminary study from our lab (see supplementary materials) we used the acceptable 'most comfortable' instructions, but failed to find consistency between motor and perceptual preferences. We hypothesized that perhaps this is due to different interpretation of what 'most comfortable' means. Giving more specific 'counting' instructions would supposedly reduce this variability (Grondin et al. 1999) allowing us to more convincingly attribute our results to natural variability in internal rhythmic preferences rather than trivial differences in interpretation or subjective and momentary 'comfort'. Second, we hoped that the current 'counting' instructions would allow us to relate our findings more directly to speech-rhythms, which are often pointed to when considering the ecological relevance of rhythmic preferences and synchronization for everyday behavior (Woodruff Carr et al. 2014; Lagrois et al. 2019).

2. Material and Methods

2.1 Participants

The experiment included two groups: ADHD and Controls, with 19 participants in each (15 women in each, 4 left handed), aged 21-28 (mean 23 in both). The experiment was approved by the Institutional Review Board of Bar Ilan University. Participants provided written informed consent prior to commencement of the experiment and received compensation for participation.

All participants self-reported normal hearing and no history of neurological disorders (besides ADHD). Participants in the ADHD group presented written diagnosis, from a neurologist or psychiatrist (8 participants) or from certified ADHD clinics. Within the ADHD group, 8 participants regularly took medication on a daily or weekly basis, 3 participants took medication at need and 8 did not take medication at all. However, all participants were instructed not to take medication 24 hours before experiment. Administration of an auditory CCPT task confirmed a significant difference between the ADHD and Control groups, complementing their formal diagnosis (see below).

2.2 Procedures and Stimuli

Participants were seated comfortably in a sound attenuated booth, and heard sounds through headphones (Sennheiser HD 280 pro). Finger taps were recorded using a custom-made tapper based on an electro-optic sensor. All other behavioral responses were collected using a response pad (Cedrus, RB-840). The experiment was programmed and controlled using PsychoPy software (www.psychopy.org). All auditory stimuli were prepared using Audacity and Matlab (Mathworks), and consisted of repetitions of pure tones (440Hz, 30ms with ±5ms ramp up/down), presented at different rates. The experiment consisted of four tasks, performed in interleaved order as shown in Figure 1.

Spontaneous Tapping Task: Participants were instructed to tap with the index finger of their dominant hand while counting silently from 1-10 silently. After each trial participants received feedback as to the number of taps performed, which ensured that they indeed counted internally. Participants repeated the spontaneous tapping task in four separate sessions throughout the experiment, with each session containing three consecutive tapping trials. These repetitions were used to test for consistencies in spontaneous tapping rates within and across sessions.

Perceptual Preference Task: Participants listened to sequences of tones and were instructed to adjust the tempo (speed up or slow down) until they reach a tempo that was comfortable for them to count along with (counting from 1-5). Each trial started with an initial tempo that was either very slow (ISI: 1300 or 1400ms) or very fast (ISI: 250 or 350ms), and participants could change the tempo by adjusting the ISI in discrete intervals of ±30ms, ±100ms or ±300ms. They were instructed to use the larger step at first and once they reached a comfortable range to fine-tune their selection using the smaller steps. Once they had reached their preferred counting tempo they pressed a 'stop' button. Participants repeated the PPT task in two separate sessions throughout the experiment, with each session containing four consecutive trials (with interleaved fast and slow initial tempi).

Synchronization-Continuation Task: Participants heard a sequence of 10 tones at a particular tempo and tapped along with them (Synchronization stage). Then a stop sign appeared for 1.5 seconds, after which they were instructed to reproduce the previous tempo and continue tapping 10 times (Continuation stage). Participants received feedback after the continuation stage whether they had indeed tapped 10 times, which ensured internal counting. No feedback was given regarding the temporal accuracy of the tapping. Ten different tempi were used, presented in random order (ISIs: 250, 350, 450, 550, 650, 800, 1000, 1400, 1800 and 2200ms). Participants performed the Synchronization-Continuation task in two separate sessions throughout the experiment, and each tempo was repeated twice in each session.

Auditory CCPT task: Participants completed an auditory version of the Conjunctive Continuous Performance Test (CCPT), in order complement the formal ADHD diagnosis. We followed the design developed and validated by Shalev and colleagues for Hebrew speaking participants (Shalev et al. 2011). Participants listen to a stream of CV syllables, comprised of all 16 combinations of the consonants (*n, s, b, r*) with the four vowels (*a, e, i, u*), which are clearly distinguishable in Hebrew. Syllables were presented for 200 ms, with ISI ranging 1 second, 1.5, 2 or 2.5 seconds. Participants were required to press the response button with their index finger only when they hear the target syllable */ni/*, which appeared at a frequency of 30%. All non-target items were presented with equal frequency. The test consisted of a 10-minute long block, containing 320 trials preceded by 15 practice trials.

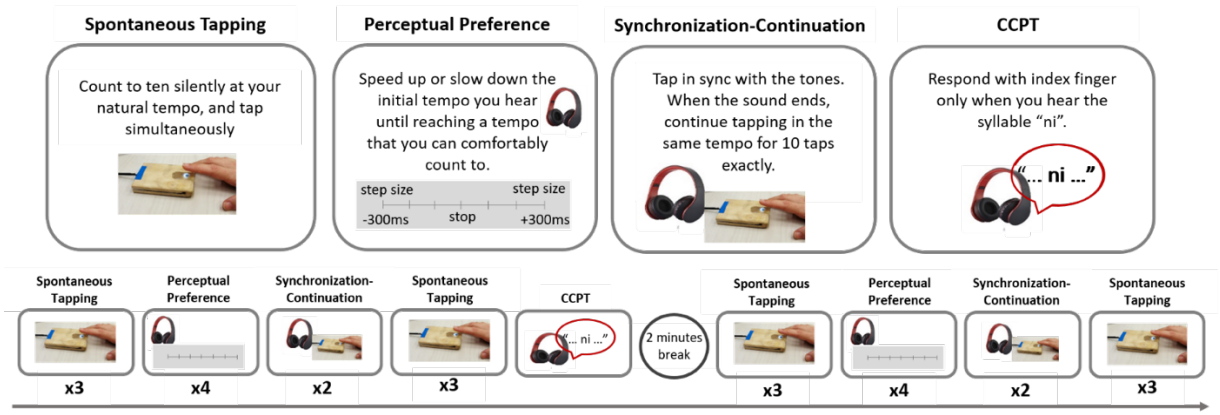


Figure 1. Experimental design. Top: The four tasks performed during the experiment. Bottom: Time line of performing each task and repetition across sessions.

2.3 Data Analysis

<u>*SMT*</u>

To quantify spontaneous tapping behavior, we assessed both central SMT measures (mean and median values), as well as consistency measures, within and across trials. All calculations were derived from the Inter-Tap-Intervals (ITIs) in individual trials, and are illustrated in Figure 2. All taps were included in the analysis, without excluding initial taps or extremely long or short ITIs, since we regard any such variability as an integral part of tapping behavior.

Consistency measures were all based on the Coefficient of Variation ($CV = \frac{std}{mean}$), to avoid biases due to differences in tempo and allow comparability across tempi. We specifically calculated the following consistency metrics for each participant:

Within-trial tapping consistency (CV_{within_trial}): Represents how isochronous the tapping was within a given trial. This is calculated using the ITIs across all ten taps in a given trial (Figure 2, row 1).

$$CV_{within_trial} = \frac{std(ITI_{within_trial})}{mean(ITI_{within_trial})}$$

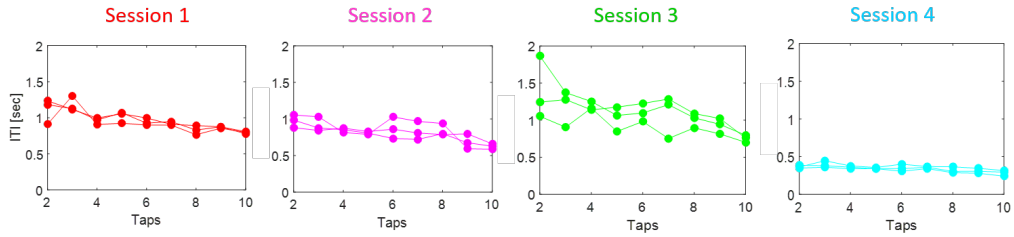
Within-session tapping consistency ($CV_{within_session}$): Represents whether participant replicate the same median rhythm in consecutive trials within a session. This is calculated using the median ITI values from the three trials within each session (Figure 2, rows 2,3):

$$CV_{within_session} = \frac{std(Median_ITI_{per_trial})}{mean(Median_ITI_{per_trial})}$$

Across-session tapping consistency ($CV_{across_session}$): Represents whether participant replicate the same median rhythm in different sessions throughout the experiment. This is calculated using the median ITI values from the three sessions (Figure 2, rows 4, 5).

$$CV_{across_session} = \frac{std(Median_ITI_{per_session})}{mean(Median_ITI_{per_session})}$$

Finally, the average **Spontaneous Motor Tempo (SMT)** was calculated by averaging the median ITIs across all four sessions (Figure 2, row 6).



	Trial 1	Trial 2	Trial 3	Trial 1	Trial 2	Trial 3	Trial 1	Trial 2	Trial 3	Trial 1	Trial 2	Trial 3
CV within trial	0.14	0.13	0.16	0.2	0.14	0.08	0.14	0.16	0.26	0.07	0.15	0.09
Median ITI per trial	0.94	0.99	0.89	0.94	0.80	0.83	1.18	0.90	1.1	0.34	0.34	0.36
CV within session	0.05			0.09			0.13			0.04		
Median ITI per session	0.95			0.83			1.10			0.34		
CV across sessions	0.4											
SMT	0.8											

Figure 2. Analysis of Spontaneous Tapping Behavior - example from one participant. *Top:* Tapping ITIs in single trials (10 taps per trial, three trials per session), across all four sessions of the SMT task. *Bottom:* Table summarizing the derivation of central and consistency metrics (median/mean and CV, respectively) from tapping ITIs, within and across session, used for characterizing different aspects of spontaneous tapping.

PPT

To quantify perceptual rhythmic preferences, we used the 8 tempi that participants indicated were 'comfortable to count with' across all PPT-task trials. The average of these tempi was considered as the participants' Preferred Perceptual Tempo (PPT), and PPT Consistency was calculated as the CV of these 8 tempi.

Synchronization-Continuation

Tapping accuracy relative to the prescribed tempo in each trial was assessed by calculating the mean ITI and comparing it to the ISI of the stimulus, separately for the Synchronization and Continuation stages. We estimated tapping consistency by calculating the CV within trials separately for the Synchronization and Continuation stages. Moreover, for the Synchronization

stage we also calculated the Negative Mean Asynchrony (NMA) which is the timing difference between sound and tap onset.

Statistical Analysis

In order to compare results between the two groups we conducted several statistical tests. Differences between the distribution and consistency of SMT and PPT values between the groups were tested using Wilcoxon rank sum test and Kolmogorov-Smirnov test. We tested for correlation between the median SMT and PPT values using a Linear regression analysis. In the Synchronization-Continuation analysis, we tested for main effects and interactions between group and tempo using mixed-model ANOVAs on the average tapping rates and tapping-CV within trials.

3. Results

3.1 CCPT Results

Before analyzing the difference between groups in the main experiment, we used the CCPT task to verify the distinction between the two groups. Following common practice in the clinical diagnosis of ADHD (Di Martino et al. 2008; Shalev et al. 2011), we quantified the variability in reaction times (RT standard deviation; RT-std) for each participant across the entire task, as a measure for sustained attention. As expected, we found that RT variability was greater in the ADHD group relative to the control group (p=0.033, Wilcoxon rank sum test; Figure 3). This pattern confirmed the ADHD group selection, complementing their clinical diagnoses.

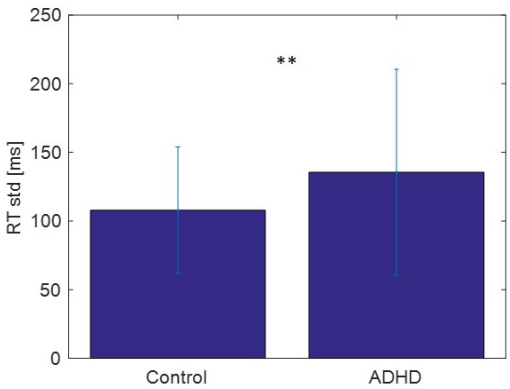


Figure 3. **CCPT results**. Reaction Time variability (RT std) on the CCPT tasks for the two groups.

3.2 Spontaneous Motor Tapping

Both groups exhibited a broad range of median SMT values, between 0.4 - 1.5 seconds ITIs (median = 0.83; Figure 4A). Distribution of SMT values did not differ significantly between the Control and ADHD groups (p=0.24, Wilcoxon rank sum test), although the median SMT tempo in the ADHD group was slightly faster (Figure 4B).

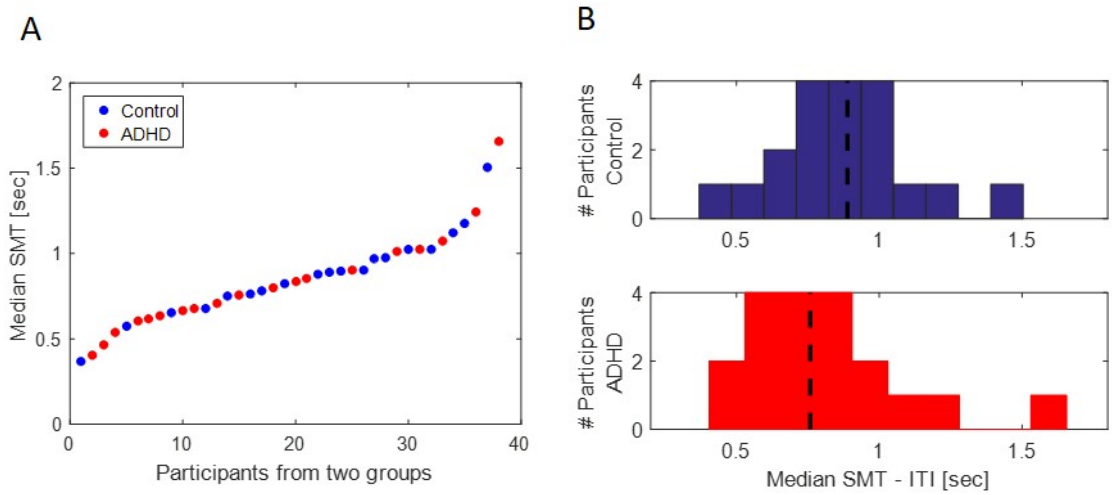


Figure 4. SMT distribution A) SMT values for all participants, color coded by group (blue – control; red – ADHD). B) Distribution of SMT values by group. Dashed line indicates the median group SMT. No significant differences in SMT distributions was observed between the two groups.

Although previous literature focuses primarily on a single SMT rate per participant, spontaneous tapping within individual participants was in fact often inconsistent, as illustrated in Figure 5B. To characterize this variability, we quantified tapping consistency at three levels: within trial, within session and across sessions.

CV_{within_trial} reflects the degree to which spontaneous tapping is isochronous, i.e. whether participants produce a constant rate. We found a significant difference in CV_{within_trial} between the two groups ($p<0.03$, Wilcoxon rank sum), indicating reduced isochrony in the ADHD group (figure 5B).

The ADHD group also displayed reduced consistency in the median tapping-rates they produced in different trials within the same session ($CV_{within_session}$) and across-sessions ($CV_{across_session}$), as reflected by a more wide-spread distribution (Kolmogorov-Smirnov test; p=0.048 and p=0.018105 respectively) and a trend toward higher median CV values (Wilcoxon rank sum test; p=0.054 for both $CV_{within_session}$ and $CV_{across_session}$; Figure 5C). Using a cutoff of $CV_{across_session} > 0.25$ used previously by McAuley et al. 2006 to exclude participants with

inconsistent SMTs, 42% of participants in the ADHD group (8/19) did not produce consistent SMTs across sessions. SMT consistency across session in the Control group was somewhat improved, but nonetheless ~30% of the participants (6/19) demonstrated inconsistent spontaneous tapping across sessions.

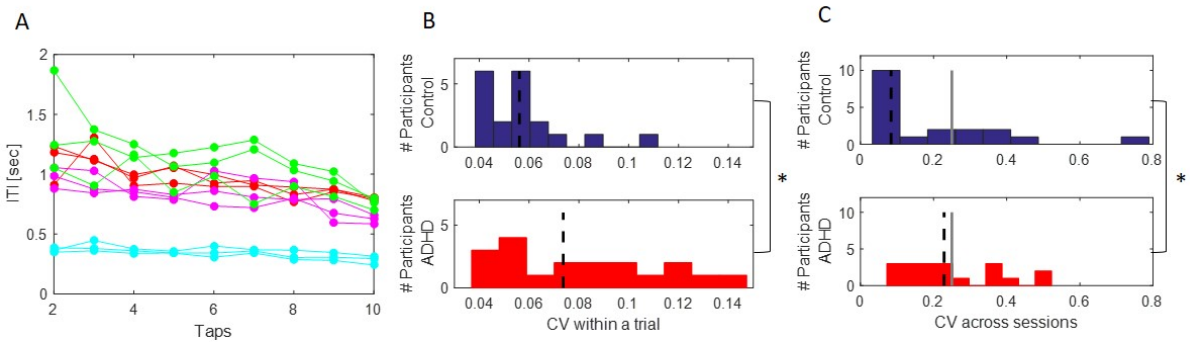


Figure 5. Spontaneous Tapping Consistency. A) Spontaneous tapping times in a single participant across all trials, color coded by session (three trials per session; same data as shown in Figure 2). This example illustrates both within trial variability (e.g., tapping ITIs within the green trials varied within a large range) and across session variability (e.g., tapping in the cyan session was substantially faster than the rest) often observed within participant. B) Distribution of within-trial CV in the Control and ADHD groups. The dashed line represents the groups median. Tapping consistency was reduced in the ADHD group relative to Controls. C) Distribution of across-session CV in both groups. The dashed line represents the groups median, and the gray line indicates the cutoff of CV>0.25 used previously to classify participants with inconsistent SMT across sessions. Inconsistencies in SMT across sessions were significantly more prevalent in the ADHD group relative to controls.

3.3 Preferred Perceptual Tempi

The tempi that participants indicated as most "comfortable to count with" (mean PPT across sessions) ranged broadly between 0.26-1.46 sec ITI (median 0.84). Comparison between the groups indicated that mean PPT values were significantly faster in the ADHD group ($p<0.03$, Wilcoxon rank sum test; Figure 6A). 57% (11/19) of the participants in the ADHD group displayed inconsistent preferences across trials (using the same CV>0.25 cutoff as above), whereas in the Control group inconsistent preferences were observed in ~30% of participants (6/19). However, the distribution of PPT rating consistency did not differ significantly between the groups (Kolmogorov-Smirnov test $p = 0.11$; Wilcoxon rank sum test, $p=0.16$; Figure 6B).

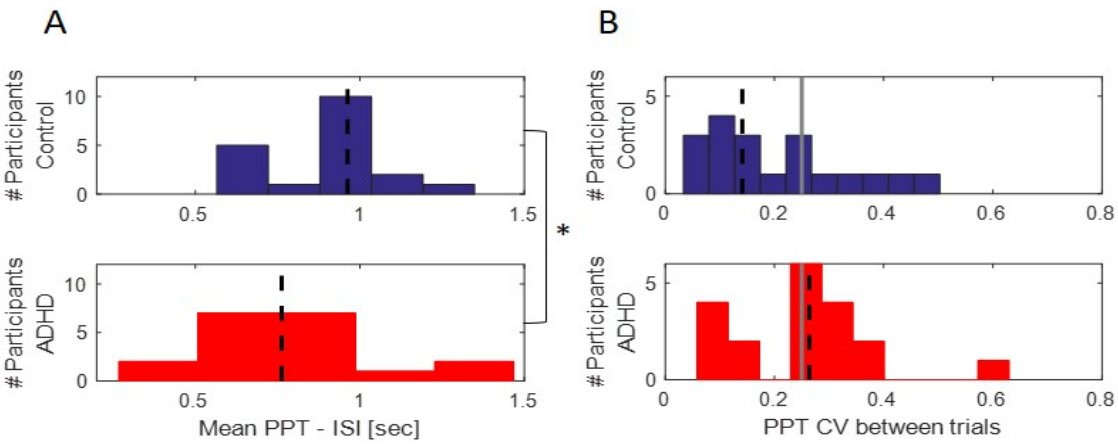


Figure 6. **PPT distribution and consistency.** (A) Distribution of mean PPT values and (B) their consistency across trials in the ADHD and Control groups. The ADHD groups showed overall preference for faster tempi relative to controls. The dashed line represents the groups median, and the gray line indicates the cutoff of CV>0.25 indicating participants with inconsistent perceptual preferences across trials.

3.4 SMT-PPT correlation

A key claim of the Preferred Period Hypothesis is that perceptual preferences and motor preferences can be attributed to a common underlying oscillator. We tested the relationship between the rhythms generated spontaneously by each participant and the rhythms they indicated as perceptually preferable using a linear regression between the median SMT and PPT values (across all sessions). We found that indeed these values were positively correlated ($r=0.678$, $p<0.001$), however the regression line did not fall on the diagonal which is inconsistent with the hypothesized one-to-one correspondence (Figure 7A&B). Similar non-one slope values were found when fitting the data separately for the two groups (control group: $y=0.53x+0.44$, $r=0.67$, $p<0.002$; ADHD group: $y=0.67x+0.2$, $r=0.68$, $p<0.002$). Interestingly, there was also no correlation between the variability displayed on the two tasks ($r = 0.27$, $p=0.099$; Figure 7C), indicating that some participants could have a highly consistent PPT and yet a variable SMT.

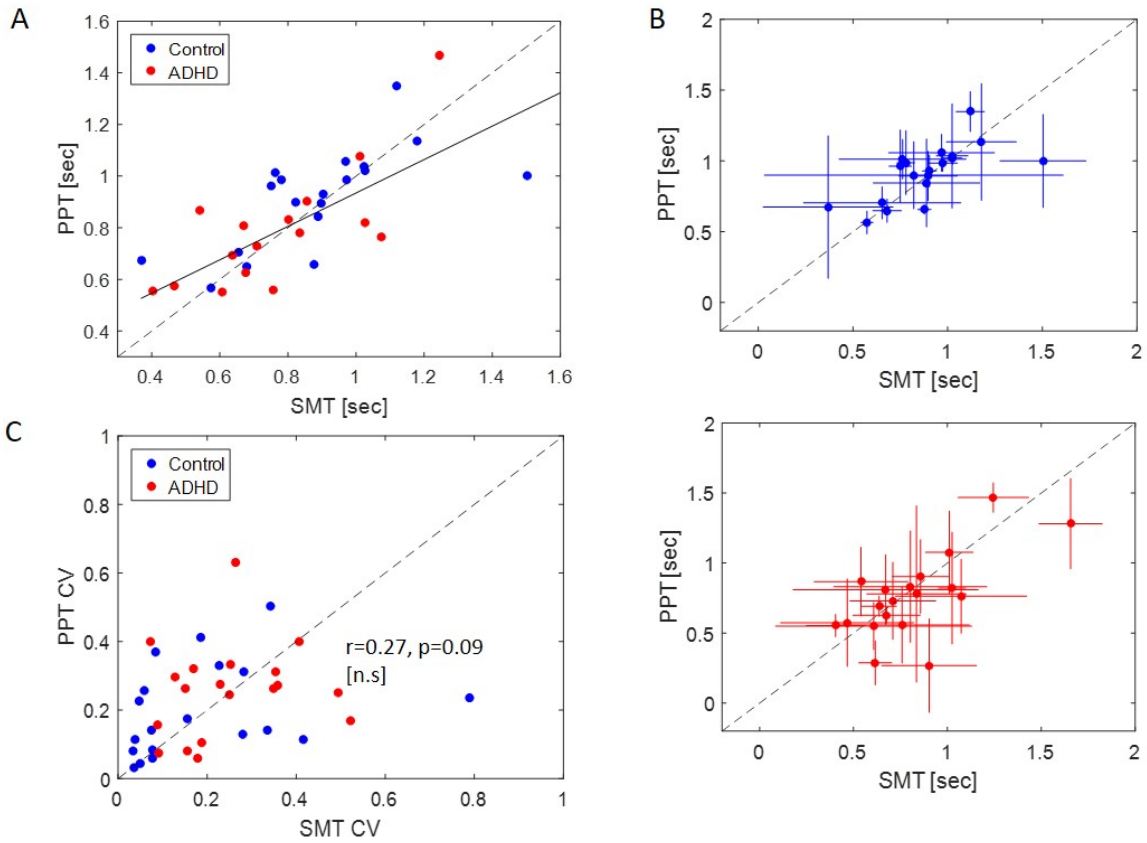


Figure 7. Correspondence between SMT and PPT. A) Linear Regression between the median SMT and PPT values within individuals, color coded by group (blue – control; red - ADHD). The dashed line is the diagonal, and full line represents the regression estimation between SMT and PPT values. Although the two measures are strongly correlated (r=0.67; y=0.647x+0.288), the regression line does not fall on the diagonal indicating a deviation from one-to-one correspondence of preferred motor and perceptual rates. B) Correspondence of SMT and PPT values, separately for the Control (top) and ADHD groups (bottom). Cross-hairs indicate the range of SMT and PPT values observed for each participant across trials. C. A) Linear Regression between the CV of SMT and PPT between session, color coded by groups (Red-ADHD; blue – Control). The correlation is not significant, meaning that different participants showed consistency or inconsistency in the two tests.

3.5 Synchronization - Continuation

Both groups showed highly accurate tapping to a wide-range of rhythms during the Synchronization stage (Figure 8A), with no significant different found across tempi or groups (mixed-model ANOVA; all n.s.). In the Continuation stage tapping remained highly accurate for the faster rhythms (ISI < 1 sec). However, for slower rhythms both groups tapped faster than the prescribed rhythm (Figure 8B), as indicated by a significant effect of Tempo [$F(1,9)=17$, $p<10^{-6}$]. The overall difference in tapping accuracy between the groups tended toward significance [$F(1,36)=3.52$, $p=0.068$], and there was a significant interaction between Tempo x Group [$F(9,324)=3.09$, $p<0.002$, mixed-model ANOVA], indicating that the hastening observed at slower rhythms was more prominent in the ADHD group.

Tapping variability within trial was also larger for slower rhythms, as reflected by a main effect of tempo, in both the Synchronization and Continuation stages [$F(9,36) = 4.99$, $F(9,36) = 4.53$; $p = 2.8*10^{-6}$, $p = 1.25*10^{-5}$ respectively; Figure XC&D]. No effects of Group or interactions were observed for tapping variability in the Synchronization stage, however tapping variability in the Continuation stage was higher in the ADHD group [Group main effect, $F(1,36) = 4.48$, $p < 0.05$]. The interaction between Tempo and Group was not significant [$F(9,324) < 1.0$ for both.

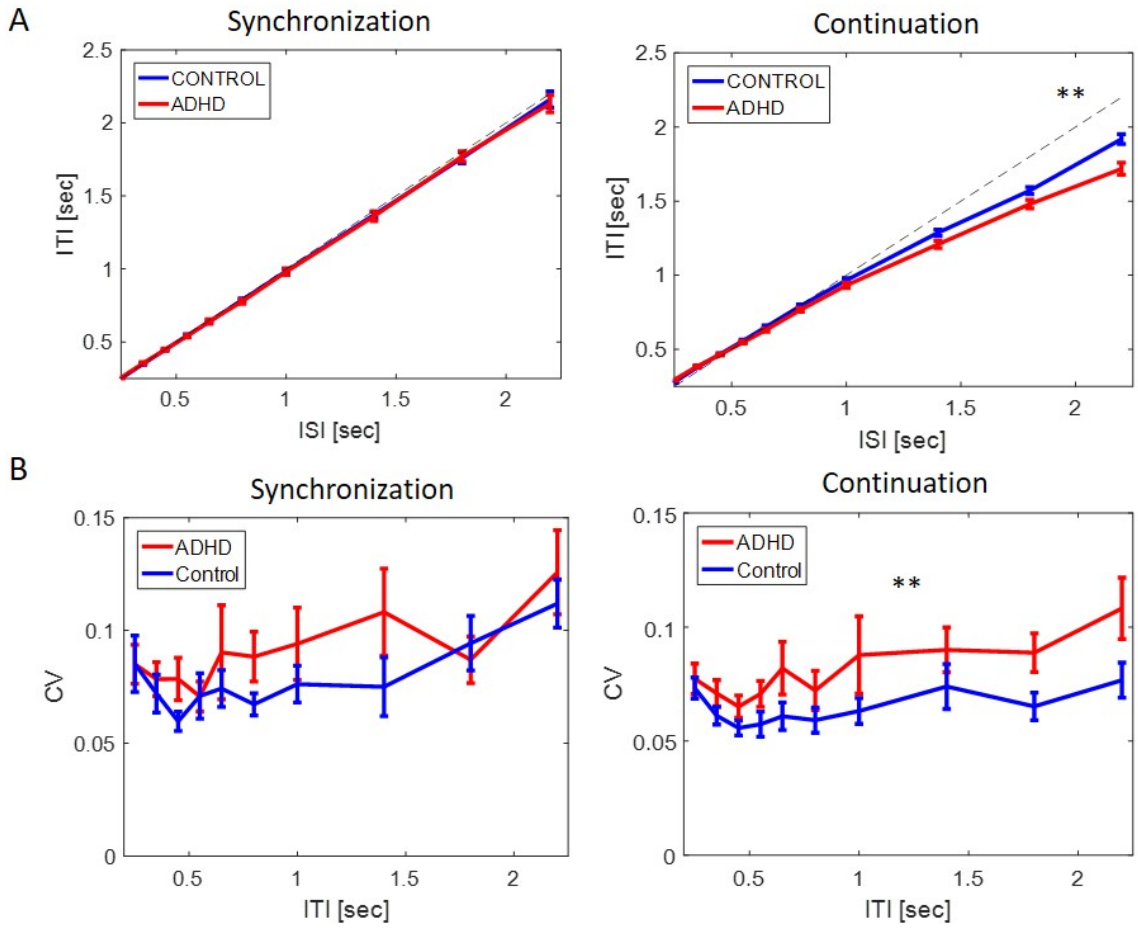


Figure 8. Synchronization-Continuation tapping. A) Correspondence between the mean tapping ITI and the prescribed ISI across tempi in the Synchronization stage, in both groups. B) Same as A for the Continuation Stage. C) Within trial tapping variability (CV) in the Synchronization stage across tempi, in both groups. D) Same as C for the Continuation Stage

We additionally calculated the Mean Asynchrony of tapping in the Synchronization stage. Mean Asynchrony was negative for all tempi, indicating true synchronization and entrainment rather than a sequence of responses. As expected, Mean Asynchrony was negative (NMA) for all tempi, indicating true synchronization (Figure 9). There was a significant main effect of tempo [$F(9,324) = 6.4$, $p<0.0001$], indicating smaller NMA at faster rates, but there was no significant main effect of group or interaction between group X tempo ($F < 1$ for both, mixed model ANOVA).

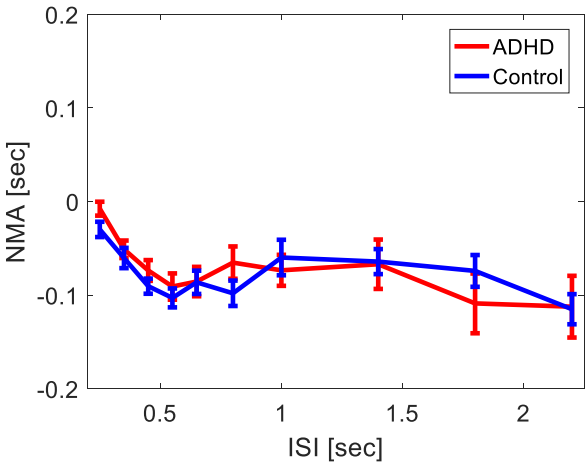


Figure 9. Negative Mean Asynchrony. Negative Mean Asynchrony during the Synchronization stage for all tempi, separately for the two groups.

3.6 Lack of Correlation between SMT/PPT and Continuation Tapping

Last, we directly tested the prediction of the Preferred Rhythm Hypothesis that motor synchronization is improved optimal near ones' individual preferred motor and/or perceptual rhythms. Since performance on the synchronization task was at ceiling for all tempi, this analysis focused only on the Continuations stage. Figure 10 shows the performance in the Continuation stage for all participants, and relates them to individual spontaneous tapping rhythms and perceptual preferences. Each subplot depicts ITI accuracy relative to the prescribed ISI across tempi, overlaid with each participants' SMT mean and range (cyan line and shaded area) and PPT mean and range (magenta line and shaded area). This figure allows appreciating the great variability across individuals in their preferences, tapping consistencies and the relationship (or lack thereof) between the different rhythmic tasks compared here.

As observed in the group-level data (Figure X- above), most participants demonstrate good continuation-tapping for sub-second tempi, and hastening at slower rates. However, we fail to observe any systematic benefit for continuation-tapping at one's SMT or PPT rate per se, nor

is that necessarily the point where accurate tapping breaks down for slower rates. Rather, many participants maintained good tapping accuracy outside the SMT/PPT range. The is quantified at the group-level, by comparing the tapping accuracy at the tempo closest to each participant's average-SMT, relative to faster or slower tempi. Results show that tapping was similarly accurate at the SMT relative to faster tempi (rank sum test, $p=0.38$), but was systematically less accurate for slower tempi (rank sum test, $p<10^{-6}$; Figure X). This pattern is not consistent with a specific preference for the SMT rate, and it more easily explained by a general reduced accuracy for slower rhythms, regardless of personal preferences.

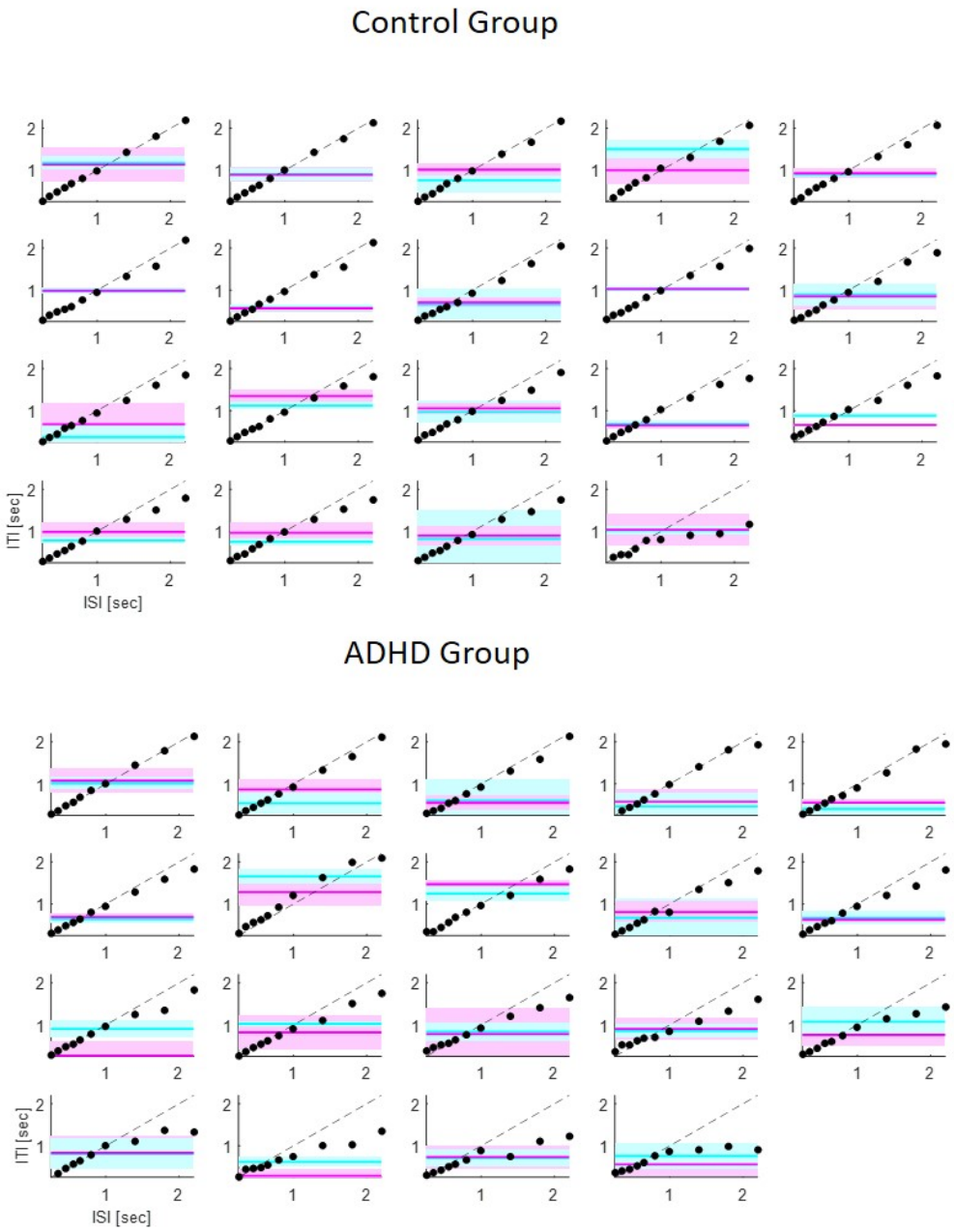


Figure 10 Individual Continuation Data for all participants. ITI as a function of ISI, graphs ordered according to ascending sum of square error. SMT and CV range marked in light blue, PPT and CV range marked in pink. a) Control group participants b) ADHD group participants.

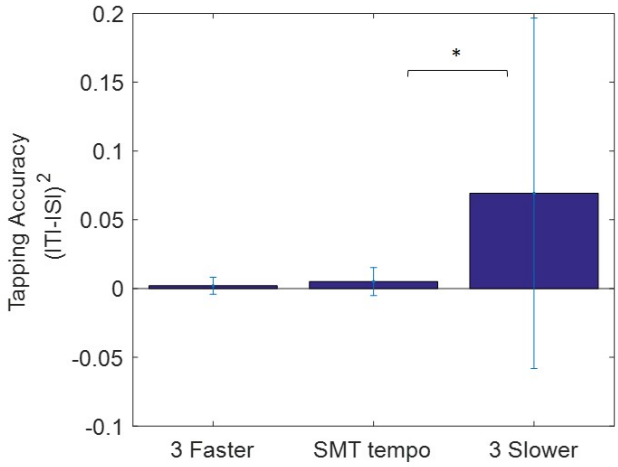


Figure 11. Continuation-Tapping Accuracy vs. SMT. Tapping accuracy during the Continuation stage was quantified for the tempo closes to each participant's SMT, and across three faster and slower rhythms (collapsed across both groups). Accuracy was defined as the squared difference between the mean ITI produced during the continuation stage, relative to the prescribed ISI, averaged across all trials. Reduced tapping accuracy was observed for rhythms slower than the SMT, consistent with the general hastening pattern for slow rhythms. However, no benefit was observed for continuation-tapping near one's SMT relative to faster rhythms.

4. Discussion

The current study provides a broad characterization of spontaneous rhythmic preferences and synchronization to external rhythms in adults with ADHD as well as within a typical control population. It sheds light on the nature of rhythmic deficits observed in ADHD, whose primary challenge seems to be with internal generation and representation of rhythms, but are nonetheless accurate at synchronizing to a wide range of external rhythms. In addition, our results challenge some of the assumptions of the Preferred Period Hypothesis regarding the consistency of motor and perceptual 'default' rhythms, as well as their significance for rhythmic behavior more broadly. In the following sections we discuss the contribution of the current findings to understanding nature of rhythmic deficits in ADHD, and their implications regarding the domain-generality of spontaneous rhythmic preferences.

4.1 Distinctions Between Spontaneous and Synchronized Motor Rhythms

The first aspect of motor rhythms addressed here focuses on the ability to produce isochronous tapping. This was studied under three conditions: Spontaneous finger tapping, paced-synchronized tapping to an external rhythm, and continuation tapping at a prescribed rhythm. All three types of behavior manifest in similar motor outcomes, and engage a network of timing-related motor regions ('temporal hub'), primarily including the supplementary motor area (SMA), inferior prefrontal cortex, the cerebellum, and the basal ganglia (Matell and Meck 2004; Witt et al. 2008; Wiener et al. 2010; Schwartze et al. 2011, 2016; Merchant et al. 2013, 2015). However, there are also important distinctions regarding the processes and neural circuitry they involve.

The isochronous nature of spontaneous, or self-paced, movement has been attributed to the involvement of neural oscillations in motor control (Fraisse 1982; McAuley 2010; Bichsel et al. 2018). The tendency toward isochrony is so strong, in fact, that it is quite difficult to produce arrhythmic motor gestures, particularly by the hand, head and legs (Larsson 2014). In contrast, motor synchronization is not internally generated, but is guided by sensory perception and involves complex interactions between the auditory and motor systems. Synchronization abilities are usually very good in humans, and can be observed in children as early as 3-4 years old (Fraisse 1982; Fujii et al. 2014). Synchronization is observed for both simple and complex rhythms in a wide range of tempi (Large et al. 2002; Keller and Repp 2005; Jacoby and Repp 2012; Repp and Su 2013), and the urge to 'move to the beat' is often considered near-automatic (Large 2000; Snyder and Krumhansl 2001; Janata et al. 2012; Tal et al. 2017; Nozaradan et al.

402 2018). These is arguably achieved through entrainment of motor neural oscillations to the
403 rhythm of external stimuli to guide and control motor actions (Morillon et al. 2014; Yoles-
404 Frenkel et al. 2016; Haegens and Zion Golumbic 2018; Rimmele et al. 2018). The idea of
405 entrainment is supported by the well-documented phenomena of negative mean asynchrony
406 (NMA) in synchronization tasks, observed here as well, which indicates that synchronization
407 is not merely sequential responses to rhythmic input but involves temporal prediction and
408 generalization (Repp and Moseley 2012).

409 Thus, the key distinction between spontaneous tapping and synchronization is whether
410 they are guided by an internal or external pace. This is also reflected in differential involvement
411 of brain regions within the 'temporal hub' when performing these two tasks (Chauvigné et al.
412 2014; Bichsel et al. 2018). Besides the obvious engagement of bilateral auditory regions in
413 synchronization tasks, there is notable functional connectivity between motor and auditory
414 regions (Grahn & Rowe 2009, Chen, Zattore and Penhune 2006, Chen, Penhune and Zattore
415 2008). Difficulties in synchronization are associated with deficits in low-level auditory
416 encoding (Tierney and Kraus 2013; Nozaradan et al. 2016) and in perception-action coupling
417 (Phillips-Silver et al. 2011; Repp and Su 2013; Sowiński and Dalla Bella 2013; Palmer et al.
418 2014; Schwartze et al. 2016). In contrast, self-paced tapping depends more heavily on the basal
419 ganglia and is substantially impaired in individuals with basal ganglia lesions or with
420 neurological motor disorders such as Parkinson's disease (Kornysheva and Schubotz 2011;
421 Schwartze et al. 2011; Chauvigné et al. 2014; De Pretto et al. 2018). Intriguingly, clinical
422 populations who suffer from difficulty in maintaining self-generated motion, are greatly
423 improved by listening to rhythms and are able to synchronize with them quite well (Thaut et
424 al. 2001; Nombela et al. 2013; Schaefer 2014; Ghai et al. 2018). This further supports the
425 dissociation between internally and externally paced tapping and points to a critical role of
426 auditory entrainment in engaging motor oscillations and 'propelling them into action'.

427 The case of continuation-tapping is an interesting one, serving as an intermediate
428 between spontaneous and synchronized tapping. Although many studies refer to continuation-
429 tapping as "unpaced" (e.g., Hove et al. 2017), we find that this terminology can be somewhat
430 misleading since continuation tapping is in fact guided by an internal representation or mental
431 imagery of the rhythm previously synchronized to. Some have suggested referring to
432 continuation-tapping as "memory pacing", emphasizing the important role that temporal
433 working-memory plays in perfoming this task, and distinguishing it from spontaneous motor
434 tapping (Chauvigné et al. 2014). Interpretations vary as to whether the brain regions involved
435 in continuation-tapping are more similar to synchronization (Chauvigné et al. 2014) or to

spontaneous tapping (Witt et al. 2008). However several studies have pointed specifically to increased activation specifically in the basal ganglia and SMA (Lewis et al. 2004; Toyomura et al. 2012; Koshimori et al. 2019) in continuation vs. synchronization tasks. Given that these regions are also hypothesized to be important for temporal working memory (Lustig et al. 2005; McNab and Klingberg 2008; Wiener et al. 2010; Teki et al. 2017; Marvel et al. 2019; Schmidt et al. 2019), it is possible their engagement in continuation tasks reflects auditory imagery of a rhythm that is used to entrain motor oscillations (Halpern and Zatorre 1999; Schaefer et al. 2014; Harrison et al. 2018).

4.2 Motor Tapping Deficits in ADHD

After establishing the distinctions between spontaneous, synchronized and continuation tapping, we now turn to discuss performance on these tasks in individuals with ADHD. We found that spontaneous tapping in individuals with ADHD was more variable and less isochronous relative to controls. To the best of our knowledge only one previous study by Rubia et al. (2003) tested spontaneous tapping in ADHD, focusing on young children (ages 6-12), and similarly found increased variability in the ability to produce isochronous rhythms. Moreover, the current study provides a more complete characterization of synchronization-continuation performance in ADHD relative to previous studies, given the broad range of rhythms tested.

Despite their instable spontaneous tapping, sensorimotor synchronization was nonetheless highly accurate in the ADHD group across a wide-range of tempi, in a manner similar to controls. Mean Asynchrony during synchronization was negative for all tempi, indicating true synchronization and entrainment, and here too no significant difference was found between the groups. Previous studies on sensorimotor synchronization in ADHD have yielded mixed results. Results by Tiffin-Richards et al. (2004) are comparable to ours, showing accurate synchronization performance in ADHD group across multiple sub-second rates. However, Hove et al. (2017) report higher synchronization-tapping variability in ADHD, at two out of four tempi tested (though not adjacent in rate) (see also Pitcher et al. 2002; Ben-Pazi et al. 2003; Rubia et al. 2003; Valera et al. 2010). Indeed, even in our results variability was slightly higher in the ADHD group at least at some tempi, although this was not statistically significant. Therefore, a conservative interpretation would be that variability in synchronization might be slightly enhanced in ADHD, in some cases, but mean tapping rate is nonetheless relatively stable.

This is in contrast to continuation tapping where both the mean tapping rates and variability were significantly worse in the ADHD group relative to controls. This is consistent with several previous studies reporting that individuals with ADHD generally exhibit more variability in continuation-tapping vs. synchronization and are also more variable relative to controls (Rubia et al. 2003; Toplak and Tannock 2005b; Gilden and Marusich 2009; Valera et al. 2010; Zelaznik et al. 2012; Hove et al. 2017). As discussed above, continuation tapping requires maintaining an internal memory-representation of the rhythm previously synchronized and thus can be considered an intermediate task, sharing some properties with both spontaneous and synchronized tapping.

Continuation tapping was notably less accurate for rhythms slower than 1Hz (supra-second rhythms) in both groups, in line with the scalar property of timing (Allman et al. 2014; Gámez et al. 2019), however this was more prominent in ADHD. Previous studies have found similar hastening in ADHD during continuation tapping for supra-second rhythms (Gilden and Marusich 2009; Zelaznik et al. 2012), which has been attributed to a tendency to under-estimate supra-second time intervals. This is consistent with the broader tendency toward hastening in ADHD (manifest here also in their perceptual preferences for faster rhythms (PPT), although SMTs were not significantly faster (see also Ben-Pazi et al. 2003). Temporal estimation of long intervals relies more heavily on temporal working memory, and has been associated with engagement of specific brain regions, including the basal ganglia, frontal cortex and fronto-parietal networks (Nenadic et al. 2003; Lewis et al. 2004; Wiener et al. 2010; Marvel et al. 2019). Individuals with ADHD show reduced activation in these regions during continuation tapping, coinciding with their reduced performance (Valera et al. 2010).

The overall emerging pattern from studying these three types of motor tapping behaviors suggests the following: Individuals with ADHD seem to have an inherent deficit in maintaining internal timing and generating isochronous rhythms based on internal motor-oscillations alone. This manifests both in their reduced ability to produce isochronous spontaneous tapping as well as in increased variability in continuation tapping, that imposes high demands on temporal working memory and/or internal representation of time (Barkley et al. 1997; Mioni et al. 2019). At the same time, auditory-motor entrainment is preserved in ADHD and is utilized to correct tapping times allowing participant to accurately synchronize to external rhythms, even at extremely slow rates (Thaut et al. 2015; Ahissar and Assa 2016). Supporting this distinction, a recent study suggest that the timing impairments in ADHD stem from higher level factors such as sustained attention, rather than low-level sensorimotor timing (Hove et al. 2017).

503 The pattern observed here in the ADHD group, who show impaired self-generated
504 tapping that is substantially improved by the presence of an external pacer, is somewhat
505 analogous to the improvement found in Parkinson's disease for sensorimotor synchronization
506 (refs from above). Although these are highly distinct clinical conditions, they do share some
507 commonalities. Most notably they both involve abnormal regulation of dopamine levels (Pine
508 et al. 2010; Vaughan and Foster 2013) and implicate deficits in basal ganglia function (among
509 other neural substrates) (Curtin et al. 2018; Lu et al. 2019), both of which are important for
510 timing-functions (Pine et al. 2010; Allman and Meck 2012). Linking these, a recent PET study
511 showing that synchronized finger tapping to rhythmic sounds modulates dopamine levels in
512 the basal ganglia (Koshimori et al. 2019), suggesting that the behavioral advantages of an
513 external rhythmic pacer are mediated through modulating dopamine-related timing functions.
514 Moreover, treatment of ADHD symptoms with Methylphenidate, a dopamine agonist,
515 reportedly improves temporal estimation in individuals with ADHD (Baldwin et al. 2004;
516 Rubia et al. 2009; Luman et al. 2015; Fostick 2017). Fully exploiting the link between timing
517 deficits in dopamine-related diseases, and the compensation provided by synchronization to
518 external rhythms is beyond the scope of the current paper. However, these similarities compel
519 further research for understanding the cognitive and neural mechanisms underlying the
520 observed improvement of timing-related functions brought about through synchronization.
521 To summarize, our study is the first to directly compare all three types of motor tapping
522 in ADHD adults, and results support a general impairment in the motor production of
523 isochronous rhythms, manifest both in spontaneous tapping and in continuation (reproduction),
524 in a broad range of sub and supra-second rhythms. Nonetheless, we also find that the use of an
525 external pace-maker can substantially assist in overcoming the difficulties of internal timing,
526 as the ADHD successfully adjusted tap-to-tap intervals to maintain the requested global rate in
527 the synchronization task. Taken together, the emerging pattern suggests that the temporal
528 deficits in ADHD may be more generally related to difficulties in maintaining an internal
529 representation of a rhythm, or of temporal intervals. These results shed new light on the specific
530 type of temporal processing that are implicated in ADHD adults, and indicate that the use of
531 external pace-makers can assist in overcoming some of these difficulties.
532
533 ***4.3 Preferred motor and perceptual rhythms***
534 A second aspect of rhythmic behavior studied here pertains specifically to the Preferred
535 Period Hypothesis, suggesting that individuals have a characteristic preferred rhythm,

536 generalized across perception and production (Fraisse 1982; Collyer et al. 1994; McAuley et
537 al. 2006; Michaelis et al. 2014; Schwartze and Kotz 2015). Here we tested several key
538 assumptions of this hypothesis, primarily the stability of spontaneous preferences over time,
539 the correspondence between perceptual and motor rhythmic preferences, as well as the
540 generalization between spontaneous preferences and synchronization to external rhythms.

541 Before discussing the results obtained here, it is important to note two important
542 differences in the procedure used here to evaluate individual SMT and PPT relative to most
543 previous studies. First, whereas most studies instruct participants to indicate their most
544 'comfortable' rhythm, in the current study instructions were linked to a more well-defined task
545 – counting from 1 to 10 (Grondin et al. 1999). As mentioned above, this choice arguably
546 reduces variability related to differences in interpretation or subjective "comfort", which could
547 have potentially explained the large differences found in our preliminary study (see
548 supplementary material). Second, in some studies, the rhythms used for PPT assessment and
549 for synchronization-continuation testing were tailored specifically around each participants'
550 personal SMT (e.g., McAuley et al. 2006). This may have biased results toward the central
551 rhythm used, overestimating the correspondence between spontaneous motor and perceptual
552 preferences. To overcome this, in the current study we tested a broad and constant range of
553 rhythms in the PPT and synchronization-continuation tasks (see also Michaelis et al. 2014).

554 For both SMT and PPT, in the current 'counting rhythm' task individuals were more
555 likely to reproduce the same motor and perceptual preferences across trials and sessions
556 (relative to our preliminary study using the common 'most comfortable rhythm' task). This
557 indicates that the specific instructions given to participants impact performance, affecting both
558 within and between subject variability, which may interfere with interpretation of the results
559 (for similar criticism, see Hinton and Rao 2004). However, even using the more specific
560 'counting rhythm' tasks, many participants still display substantial variability across sessions.
561 Using the cutoff of CV>0.25, used in previous studies to indicate inconsistent performance
562 (McAuley et al. 2006), in the control group ~30% of participants showed inconsistent SMT or
563 PPT across sessions, and the proportion was higher in the ADHD group (43% with inconsistent
564 SMT and 57% with inconsistent PPT). Moreover, there was no correlation in the variability
565 across the two tasks, with some participants showing consistent preferences in one modality
566 but not in the other. The notion of a personal tempo has been around for decades (Rimoldi
567 1951), but although some studies look at within-subject consistency across trials, this is often
568 limited to a small number of trials/sessions (Schwartze and Kotz 2015) and individual
569 differences in test-retest reliability are rarely reported. Indeed, similar to the current findings,

570 a recent study showed that individuals vary substantially in the degree of isochrony during
571 spontaneous tapping, although in that study SMT replicability across trials/session was not
572 tested (McPherson et al. 2018). Test-retest replicability of PPT is even less prevalent, and as
573 mentioned above, measurement of the PPT itself is often skewed toward the SMT by
574 experimental design. While the current results do indicate that some, or even most, individuals
575 have consistent motor and perceptual rhythmic preferences, they also clearly demonstrate that
576 this is not universal. Many individuals feel comfortable tapping at, counting at and listening to
577 a wide range of rhythms, and the notion that rhythmic preferences are limited to one singular
578 tempo might be an overstatement.

579 This holds true also when testing the correspondence between the SMT and PPT. The
580 positive correlation observed here between median SMT and mean PPT values suggest that
581 individuals do have a broad tendency for preferring faster or slower rates. However, counter to
582 the predictions of a singular oscillator underlying both preferences, we did not find a 1:1
583 correspondence between SMT and PPT (regression diagonal < 1). Although some previous
584 studies have found closer correspondence between SMT and PPT values, testing of perceptual
585 preferences is often tailored specifically around each participant's personal SMT which may
586 artificially increase the similarity between them (McAuley et al. 2006; Michaelis et al. 2014).

587 Another prediction of the Preferred Tempo Hypothesis that is also not supported by the
588 current data is that performance on synchronization-continuation tapping is better at one's
589 preferred tempo. Synchronization performance was at ceiling for all tempo, across both groups.
590 This nicely demonstrates the large range within which individuals (ADHD and controls alike)
591 flexibly modulate motor activity to match the rhythm of external rhythms. Indeed, previous
592 studies have shown similarly good synchronization ability to a wide range of rhythms, on a
593 variety of motor tasks, such as finger tapping (Repp and Su 2013), dance movements (Phillips-
594 Silver et al. 2011) and running (Van Dyck et al. 2015). Therefore, no additional benefit of
595 personal rhythmic preferences required.

596 The pattern of continuation-tapping also did not follow the predictions of the Preferred
597 Period Hypothesis. Despite the highly accurate synchronization performance, this precision
598 was not maintained during memory-paced continuation tapping (London et al. 2019).
599 Consistent with previous findings, our results indicate a difficultly in maintaining accurate
600 continuation tapping for supra-second rates (Allman et al. 2014). However, this was not
601 necessarily linked to individual participants' SMT/PPT. Inspection of performance across
602 individual participants demonstrates that most participants maintained highly accurate
603 continuation tapping for fast rhythms, even when far from their their SMT/PPT. Similar

flexibility to sychronize to faster, but not to slower rhythms, has been previously reported even in young infants (Bobin-Bègue et al. 2006), suggeting it is linked to the more general scalar property of timing, predicting underestimation of supra-second intervals, rathar than specific rhythmic preferences per se (Allman et al. 2014; Gámez et al. 2019). Supporting this, when continuation-tapping was inaccurate – primarily for supra-second intervals - this was not systematically linked to how far the rhythm was from individual SMT/PPT. Some participants even showed inaccurate tapping for rate within the range of their own personal SMT/PPT. This pattern is consistent with another recent study who failed to find a correspondance between SMT and performance on motor syncronization-continuation task (McPherson et al. 2018). In that study, synchronization-continuation accuracy was negatively correalted with the overall isochrony of spontaenous tapping, however not to participants' personal SMT rate.

Taken together, these findings raise questions regarding the broader functional relevance of perferred/default motor and perceptual rhythms. At least in the specific context of the synchronization-continuation task tested here, we do not find evidence that rhythmic behavior is facilitated by so-called 'default preferences'. It is possible that SMTs do benefit performance on more complex tasks, such as synchronization to complex rhythms (Phillips-Silver et al. 2011) or perception of threshold-level stimuli (Schurger et al. 2017). However, together with the broader concern disccussed above questioning how consistent and replicable individual rhythmic preferences really are, the lack of specific advantages for SMT/PPTs in the current study brings us to conclude that unequivolcal empirical indications for behavior benefits of "presonal rhythmic preferences" in adults, are still lacking.

5. Conclusions

This study highlights two main points regarding rhythmic motor tapping behavior, in ADHD adults and controls. *The first* refers to the theoretical and empirical distinction between self-generate and synchronized rhythmic tapping. Synchronized tapping is highly accurate and flexible across a large range of sub-second to supra-second rhythms. However, maintaining an isochronous rhythm without an external pacer, guided either by temporal working memory or internal counting, is substantially more difficult, particularly for individuals in the ADHD group. *The second* refers to the existence and functional utility of default personal rhythms, that generalize across production and perception. While the current results indicate that many participants do exhibit reproducible and correlated SMTs and PPTs, they also highlight the existence of vast intra-subject variability and sensitivity to task-specific context and

instructions. Moreover, at least in the specific context tested here, it is difficult to gauge the functional relevance of default rhythms, since synchronization-continuations performance was not biased by personal preferences. Rather, our results suggest that rhythmic motor behavior is highly adaptable to a wide range of rhythms, a trait which is arguably extremely important for many real-world aspects of behavior, including attention, communication skills and social interactions (Nobre and Coull 2010; Tierney and Kraus 2014; Haegens and Zion Golumbic 2018; Jones 2019b; Lagrois et al. 2019).

Acknowledgements

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Data Availability

The data and code for statistical analysis will be made available on request from the corresponding author

652 **Supplementary Material**

653 A preliminary study conducted in our lab aimed to replicate previously reported findings
654 regarding the correspondence between SMT and PPT (McAuley et al. 2006). We followed
655 common procedures, asking participants to either tap at their most 'comfortable' rate, or give
656 ratings as to how 'comfortable' rhythmic stimuli were to them. However, in contrast to
657 previous studies, the range of rhythms used to assess perceptual preferences was not centered
658 around participants' SMTs, rather a fixed set of 10 rhythms were presented to all subjects.

659 Procedure

660 The overall procedure was similar to that reported in the main experiment. N=20 participants
661 were tested, after giving written informed consent. None of the participants were diagnosed
662 with ADHD, or reported any other neurological or psychiatric clinical condition.

663 ***Spontaneous Tapping Task:*** Participants tapped with their preferred index finger at a constant
664 rhythm for 30 taps, following the instruction "Tap at your most comfortable rate, not too slow
665 and not too fast, but at a rhythm that feels just right". Participants repeated the spontaneous
666 tapping task in three separate sessions throughout the experiment, with each session containing
667 three consecutive tapping trials. These repetitions were used to test for tapping consistencies
668 at different time-scales.

669 ***Perceptual Preference Task****:* Participants listened to sequences of tones at 10 different tempi
670 (250, 350, 450, 550, 650, 800, 1000, 1400, 1800, 2200 ms ISI; 10-second long trials), presented
671 in random order. They were asked to grade each tempo on a scale between "-5" being "very
672 slow" to "+5" being "very fast", when the grade "0" means "comfortable". Participants
673 repeated the PPT task in two separate sessions throughout the experiment, with each session
674 containing two consecutive trials in which tempi were presented in a randomized order.

675 Results

676 ***Spontaneous Motor Tapping:*** For each participant, the SMT was evaluated as the median rate
677 tapped across all sessions. We observed a broad range of SMT values, between 0.4 - 1.5
678 seconds ITIs (median = 0.73; Figure S1A, upper panel). Tapping consistency within trial and
679 within session was relatively high (Figure S1B, upper and middle panels). However, we
680 observed a large within-subject variabiliy in spontaenous tapping across the three sessions.
681 Using a threshold of CV > 0.25, used previously to classify "inconsistent" tappers, **half** of the
682 participants (10/20) demonstrated generate inconsistant spontaenous rhythms in difference
683 sessions (gray line, Figure S1B lower panel).

684

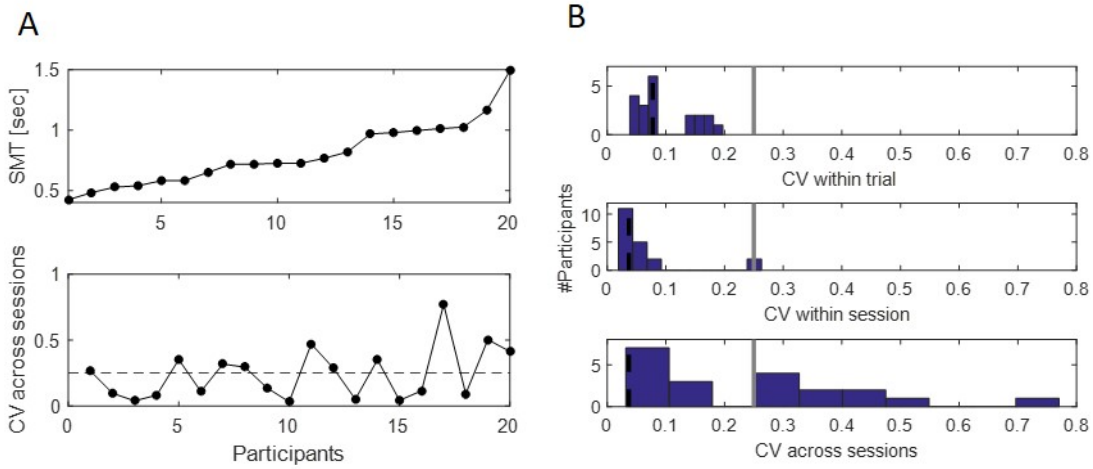

Figure S1. SMT distribution A) SMT values (top) and SMT consistency (CV, bottom) for all participants, in ascending order of mean SMT. B) Distribution of within-trial CV (top), within session CV (middle) and across sessions CV (bottom), across all participants. The dashed black line represents the group median and the gray line indicates the cutoff of CV>0.25 used previously to classify participants with inconsistent SMT across sessions.

Preferred Perceptual Tempo: For each participant, the PPT was calculated as the mean rate that participated indicated as "most comfortable", across all trials. PPT values ranged broadly between 0.49-1.38 (median 0.93) (Figure S2, upper panel). Consistency in participants' perceptual evaluation of how "comfortable" each rhythm was (PPT consistency), was assessed by calculating the CV of the ratings applied to each tempo across four repetitions. PPT consistency was not particularly high, and almost all participants had CV values exceeding the 0.25 threshold (Figure S2, lower panel).

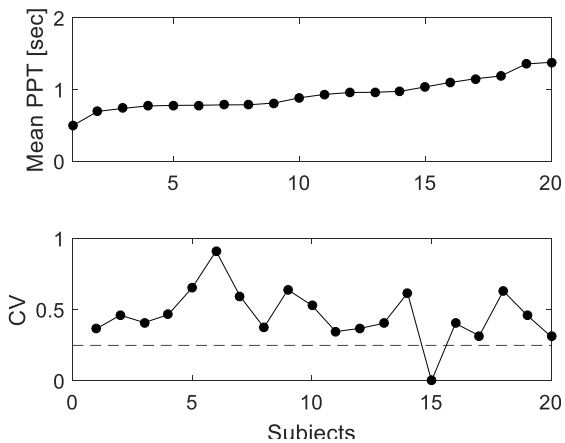

Figure S2. PPT distribution PPT values (top) and PPT consistency (CV, bottom) for all participants, in ascending order of mean PPT. The dashed line in the lower panel represents the cutoff of CV>0.25 used to classify inconsistent PPT across sessions.

SMT-PPT correspondence: Linear regression analysis between the median SMT and PPT values within participants revealed no significant correlation between the two measures ($r=0.18$, $p>0.4$). The lack of correlation stands in contrast to several previous studies, and is inconsistent with the Preferred Period Hypothesis.

We hypothesized that the loose nature of the instructions given in the current task, emphasizing assessing how 'comfortable' a rhythm is, may have contributed to the inconsistencies in both spontaneous and perceptual preferences, and may also drive the lack of a correspondence between them. This served as motivation for replacing the vague 'comfortable' instructions with the more specific 'counting' instructions used in the main experiment.

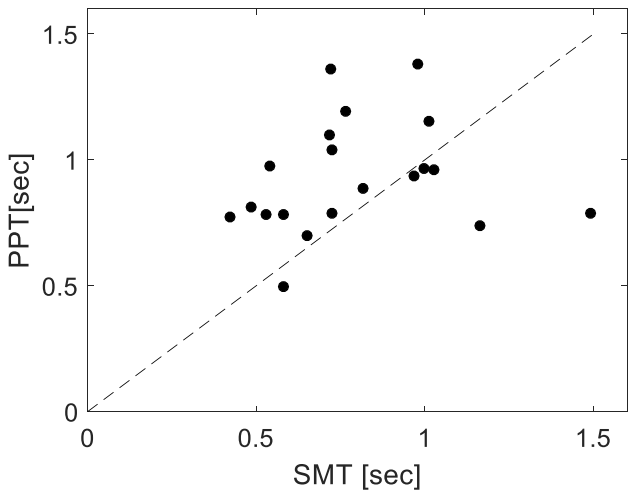

Figure S3. Correspondence between SMT and PPT. Linear Regression between the median SMT and PPT values within individuals revealed no significant correlation between the two measures in the current study. The dashed line represents the diagonal.

References

Ahissar E, Assa E. 2016. Perception as a closed-loop convergence process. Elife. 5.

Allman MJ, Meck WH. 2012. Pathophysiological distortions in time perception and timed performance. Brain. 135:656–677.

Allman MJ, Teki S, Griffiths TD, Meck WH. 2014. Properties of the Internal Clock: First- and Second-Order Principles of Subjective Time. Annu Rev Psychol. 65:743–771.

Baldwin RL, Chelonis JJ, Flake RA, Edwards MC, Feild CR, Meaux JB, Paule MG. 2004. Effect of Methylphenidate on Time Perception in Children With Attention-Deficit/Hyperactivity Disorder. Exp Clin Psychopharmacol. 12:57–64.

Barkley R a, Koplowitz S, Anderson T, McMurray MB. 1997. Sense of time in children with ADHD: effects of duration, distraction, and stimulant medication. J Int Neuropsychol Soc. 3:359–369.

Ben-Pazi H, Gross-Tsur V, Bergman H, Shalev RS. 2003. Abnormal rhythmic motor response in children with attention-deficit-hyperacitvity disorder. Dev Med Child Neurol. 45:743-745.

Bichsel O, Gassert R, Stieglitz L, Uhl M, Baumann-Vogel H, Waldvogel D, Baumann CR, Imbach LL. 2018. Functionally separated networks for self-paced and externally-cued motor execution in Parkinson's disease: Evidence from deep brain recordings in humans. Neuroimage. 177:20–29.

Bobin-Bègue A, Provasi J, Marks A, Pouthas V. 2006. Influence of auditory tempo on the endogenous rhythm of non-nutritive sucking. Eur Rev Appl Psychol. 56:239–245.

Bohannon RW. 1997. Comfortable and maximum walking speed of adults aged 20-79 years: Reference values and determinants. Age Ageing. 26:15–19.

Chauvigné LAS, Gitau KM, Brown S. 2014. The neural basis of audiomotor entrainment: an ALE meta-analysis. Front Hum Neurosci. 8:776.

Collyer CE, Broadbent HA, Church RM. 1994. Preferred rates of repetitive tapping and categorical time production. Percept Psychophys. 55:443–453.

Corriveau KH, Goswami U. 2009. Rhythmic motor entrainment in children with speech and language impairments: Tapping to the beat. Cortex. 45:119–130.

Curtin K, Fleckenstein AE, Keeshin BR, Yurgelun-Todd DA, Renshaw PF, Smith KR, Hanson GR. 2018. Increased risk of diseases of the basal ganglia and cerebellum in patients with a history of attention-deficit/hyperactivity disorder. Neuropsychopharmacology. 43:2548–2555.

De Pretto M, Deiber M-P, James CE. 2018. Steady-state evoked potentials distinguish brain mechanisms of self-paced versus synchronization finger tapping. Hum Mov Sci. 61:151–166.

Di Martino A, Ghaffari M, Curchack J, Reiss P, Hyde C, Vannucci M, Petkova E, Klein DF, Castellanos FX. 2008. Decomposing Intra-Subject Variability in Children with Attention-Deficit/Hyperactivity Disorder. Biol Psychiatry. 64:607–614.

Fostick L. 2017. The Effect of Attention-Deficit/Hyperactivity Disorder and Methylphenidate Treatment on the Adult Auditory Temporal Order Judgment Threshold. J Speech, Lang Hear Res. 60:2124–2128.

Fraisse P. 1982. Rhythm and Tempo. In: Deutsch D, editor. The Psychology of music. Academic Press. p. 149.

Fujii S, Watanabe H, Oohashi H, Hirashima M, Nozaki D, Taga G. 2014. Precursors of Dancing and Singing to Music in Three- to Four-Months-Old Infants. PLoS One. 9:e97680.

Gámez J, Mendoza G, Prado L, Betancourt A, Merchant H. 2019. The amplitude in periodic neural state trajectories underlies the tempo of rhythmic tapping. PLOS Biol. 17:e3000054.

Ghai S, Ghai I, Schmitz G, Effenberg AO. 2018. Effect of rhythmic auditory cueing on parkinsonian gait: A systematic review and meta-analysis. Sci Rep. 8:506.

Gilden DL, Marusich LR. 2009. Contraction of time in attention-deficit hyperactivity disorder. Neuropsychology. 23:265–269.

Grondin S, Meilleur-Wells G, Lachance R. 1999. When to start explicit counting in a time-intervals discrimination task: A critical point in the timing process of humans. J Exp Psychol Hum Percept Perform. 25:993–1004.

Haegens S, Zion Golumbic EM. 2018. Rhythmic facilitation of sensory processing: A critical review. Neurosci Biobehav Rev. 86.

Halpern AR, Zatorre RJ. 1999. When That Tune Runs Through Your Head: A PET Investigation of Auditory Imagery for Familiar Melodies. Cereb Cortex. 9:697–704.

Harrison EC, Horin AP, Earhart GM. 2018. Internal cueing improves gait more than external cueing in healthy adults and people with Parkinson disease. Sci Rep. 8:15525.

Hinton SC, Rao SM. 2004. “One-thousand one... one-thousand two...”: chronometric counting violates the scalar property in interval timing. Psychon Bull Rev. 11:24–30.

Hove MJ, Gravel N, Spencer RMC, Valera EM. 2017. Finger tapping and pre-attentive sensorimotor timing in adults with ADHD. Exp Brain Res. 235:3663–3672.

Jacoby N, Repp BH. 2012. A general linear framework for the comparison and evaluation of models of sensorimotor synchronization. Biol Cybern. 106:135–154.

Janata P, Tomic ST, Haberman JM. 2012. Sensorimotor coupling in music and the psychology of the groove. J Exp Psychol Gen. 141:54–75.

Jones MR. 2019a. Time Will Tell: A Theory of Dynamic Attending. Oxford University Press.

Jones MR. 2019b. Time will tell: A theory of dynamic attending.

Keller PE, Repp BH. 2005. Staying offbeat: Sensorimotor syncopation with structured and unstructured auditory sequences. Psychol Res Psychol Forsch. 69:292–309.

Kerns K a, McInerney RJ, Wilde NJ. 2001. Time reproduction, working memory, and behavioral inhibition in children with ADHD. Child Neuropsychol. 7:21–31.

Klein C, Wendling K, Huettner P, Ruder H, Peper M. 2006. Intra-Subject Variability in Attention-Deficit Hyperactivity Disorder. Biol Psychiatry. 60:1088–1097.

Kornysheva K, Schubotz RI. 2011. Impairment of Auditory-Motor Timing and Compensatory Reorganization after Ventral Premotor Cortex Stimulation. PLoS One. 6:e21421.

Koshimori Y, Strafella AP, Valli M, Sharma V, Cho S, Houle S, Thaut MH. 2019. Motor Synchronization to Rhythmic Auditory Stimulation (RAS) Attenuates Dopaminergic

Responses in Ventral Striatum in Young Healthy Adults: [11C]-(+)-PHNO PET Study. Front Neurosci. 13:106.

Lagrois M-É, Palmer C, Peretz I. 2019. Poor Synchronization to Musical Beat Generalizes to Speech. Brain Sci. 9:157.

Large EW. 2000. On synchronizing movements to music. Hum Mov Sci. 19:527–566.

Large EW, Fink P, Kelso JAS. 2002. Tracking simple and complex sequences. Psychol Res. 66:3–17.

Large EW, Gray PM. 2015. Spontaneous tempo and rhythmic entrainment in a bonobo (Pan paniscus). J Comp Psychol. 129:317–328.

Larsson M. 2014. Self-generated sounds of locomotion and ventilation and the evolution of human rhythmic abilities. Anim Cogn. 17:1–14.

Lewis PA, Wing AM, Pope PA, Praamstra P, Miall RC. 2004. Brain activity correlates differentially with increasing temporal complexity of rhythms during initialisation, synchronisation, and continuation phases of paced finger tapping. Neuropsychologia. 42:1301–1312.

London J, Thompson M, Burger B, Hildreth M, Toiviainen P. 2019. Tapping doesn't help: Synchronized self-motion and judgments of musical tempo. Atten Percept Psychophys. 81:2461–2472.

Lu L, Zhang L, Tang S, Bu X, Chen Y, Hu X, Hu X, Li H, Guo L, Sweeney JA, Gong Q, Huang X. 2019. Characterization of cortical and subcortical abnormalities in drug-naive boys with attention-deficit/hyperactivity disorder. J Affect Disord. 250:397–403.

Luman M, Papanikolau A, Oosterlaan J. 2015. The Unique and Combined Effects of Reinforcement and Methylphenidate on Temporal Information Processing in Attention-Deficit/Hyperactivity Disorder. J Clin Psychopharmacol. 35:414–421.

Lustig C, Matell MS, Meck WH. 2005. Not "just" a coincidence: Frontal-striatal interactions in working memory and interval timing. Memory. 13:441–448.

MacDougall HG, Moore ST. 2005. Marching to the beat of the same drummer: the spontaneous tempo of human locomotion. J Appl Physiol. 99:1164–1173.

Marvel CL, Morgan OP, Kronemer SI. 2019. How the motor system integrates with working memory. Neurosci Biobehav Rev. 102:184–194.

Matell MS, Meck WH. 2004. Cortico-striatal circuits and interval timing: Coincidence detection of oscillatory processes. Cogn Brain Res. 21:139–170.

McAuley JD. 2010. Tempo and Rhythm. Springer, New York, NY. p. 165–199.

McAuley JD, Jones MR, Holub S, Johnston HM, Miller NS. 2006. The time of our lives: Life span development of timing and event tracking. J Exp Psychol Gen. 135:348–367.

McNab F, Klingberg T. 2008. Prefrontal cortex and basal ganglia control access to working memory. Nat Neurosci. 11:103–107.

McPherson T, Berger D, Alagapan S, Fröhlich F. 2018. Intrinsic Rhythmicity Predicts Synchronization-Continuation Entrainment Performance. Sci Rep. 8:11782.

Meaux JB, Chelonis JJ. 2003. Time perception differences in children with and without ADHD. J Pediatr Health Care. 17:64–71.

Merchant H, Grahn J, Trainor L, Rohrmeier M, Fitch WT. 2015. Finding the beat: a neural

perspective across humans and non-human primates. Philos Trans R Soc B Biol Sci. 370:20140093.

Merchant H, Harrington DL, Meck WH. 2013. Neural Basis of the Perception and Estimation of Time. Annu Rev Neurosci. 36:313–336.

Michaelis K, Wiener M, Thompson JC. 2014. Passive listening to preferred motor tempo modulates corticospinal excitability. Front Hum Neurosci. 8:1–10.

Mioni G, Capodieci A, Biffi V, Porcelli F, Cornoldi C. 2019. Difficulties of children with symptoms of attention-deficit/hyperactivity disorder in processing temporal information concerning everyday life events. J Exp Child Psychol. 182:86–101.

Morillon B, Schroeder CE, Wyart V. 2014. Motor contributions to the temporal precision of auditory attention. Nat Commun. 5.

Nenadic I, Gaser C, Volz H-P, Rammsayer T, Häger F, Sauer H. 2003. Processing of temporal information and the basal ganglia: new evidence from fMRI. Exp Brain Res. 148:238–246.

Nobre AC, Coull JT. 2010. Attention and Time. Oxford, UK: Oxford University Press.

Nombela C, Hughes LE, Owen AM, Grahn J a. 2013. Into the groove: Can rhythm influence Parkinson's disease? Neurosci Biobehav Rev. 37:2564–2570.

Noreika V, Falter CM, Rubia K. 2013. Timing deficits in attention-deficit/hyperactivity disorder (ADHD): Evidence from neurocognitive and neuroimaging studies. Neuropsychologia. 51:235–266.

Nozaradan S, Peretz I, Keller PE. 2016. Individual Differences in Rhythmic Cortical Entrainment Correlate with Predictive Behavior in Sensorimotor Synchronization. Sci Rep. 6:20612.

Nozaradan S, Schönwiesner M, Keller PE, Lenc T, Lehmann A. 2018. Neural bases of rhythmic entrainment in humans: critical transformation between cortical and lower-level representations of auditory rhythm. Eur J Neurosci. 47:321–332.

Palmer C, Lidji P, Peretz I. 2014. Losing the beat: deficits in temporal coordination. Philos Trans R Soc B Biol Sci. 369:20130405.

Pellegrino F, Coupé C, Marsico E. 2011. Across-Language Perspective on Speech Information Rate. Language (Baltim). 87:539–558.

Phillips-Silver J, Toiviainen P, Gosselin N, Piché O, Nozaradan S, Palmer C, Peretz I. 2011. Born to dance but beat deaf: A new form of congenital amusia. Neuropsychologia. 49:961–969.

Pine A, Shiner T, Seymour B, Dolan RJ. 2010. Dopamine, time, and impulsivity in humans. J Neurosci. 30:8888–8896.

Pitcher TM, Piek JP, Barrett NC. 2002. Timing and force control in boys with attention deficit hyperactivity disorder: Subtype differences and the effect of comorbid developmental coordination disorder. Hum Mov Sci. 21:919–945.

Provasi J, Anderson DI, Barbu-Roth M. 2014. Rhythm perception, production, and synchronization during the perinatal period. Front Psychol. 5:1048.

Qi W, Nakajima T, Sakamoto M, Kato K, Kawakami Y, Kanosue K. 2019. Walking and finger tapping can be done with independent rhythms. Sci Rep. 9:7620.

Repp BH, Moseley GP. 2012. Anticipatory phase correction in sensorimotor synchronization. Hum Mov Sci. 31:1118–1136.

Repp BH, Su Y-H. 2013. Sensorimotor synchronization: A review of recent research (2006–2012). Psychon Bull Rev. 20:403–452.

Rimmele JM, Morillon B, Poeppel D, Arnal LH. 2018. Proactive Sensing of Periodic and Aperiodic Auditory Patterns. Trends Cogn Sci. 22:870–882.

Rimoldi HJA. 1951. Personal tempo. J Abnorm Soc Psychol. 46:283–303.

Rubia K, Halari R, Christakou A, Taylor E. 2009. Impulsiveness as a tinning disturbance: Neurocognitive abnormalities in attention-deficit hyperactivity disorder during temporal processes and normalization with methylphenidate. Philos Trans R Soc B Biol Sci. 364:1919–1931.

Rubia K, Noorloos J, Smith A, Gunning B, Sergeant J. 2003. Motor timing deficits in community and clinical boys with hyperactive behavior: The effect of methylphenidate on motor timing. J Abnorm Child Psychol. 31:301–313.

Schaefer RS. 2014. Auditory rhythmic cueing in movement rehabilitation: findings and possible mechanisms. Philos Trans R Soc B Biol Sci. 369:20130402.

Schaefer RS, Morcom AM, Roberts N, Overy K. 2014. Moving to Music: Effects of Heard and Imagined Musical Cues on Movement-Related Brain Activity. Front Hum Neurosci. 8:774.

Schmidt R, Herrojo Ruiz M, Kilavik BE, Lundqvist M, Starr PA, Aron AR. 2019. Beta Oscillations in Working Memory, Executive Control of Movement and Thought, and Sensorimotor Function. J Neurosci. 39:8231–8238.

Schroeder CE, Lakatos P. 2009. Low-frequency neuronal oscillations as instruments of sensory selection. Trends Neurosci. 32:9–18.

Schurger A, Faivre N, Cammoun L, Trovó B, Blanke O. 2017. Entrainment of Voluntary Movement to Undetected Auditory Regularities. Sci Rep. 7:14867.

Schwartze M, Keller PE, Kotz SA. 2016. Spontaneous, synchronized, and corrective timing behavior in cerebellar lesion patients. Behav Brain Res. 312:285–293.

Schwartze M, Keller PE, Patel AD, Kotz SA. 2011. The impact of basal ganglia lesions on sensorimotor synchronization , spontaneous motor tempo , and the detection of tempo changes. Behav Brain Res. 216:685–691.

Schwartze M, Kotz SA. 2015. The Timing of Regular Sequences: Production, Perception, and Covariation. J Cogn Neurosci. 27:1697–1707.

Shalev L, Ben-Simon A, Mevorach C, Cohen Y, Tsal Y. 2011. Conjunctive Continuous Performance Task (CCPT)-A pure measure of sustained attention. Neuropsychologia. 49:2584–2591.

Smith A, Taylor E, Rogers JW, Newman S, Rubia K. 2002. Evidence for a pure time perception deficit in children with ADHD. J Child Psychol Psychiatry Allied Discip. 43:529–542.

Snyder J, Krumhansl CL. 2001. Tapping to Ragtime: Cues to Pulse Finding. Music Percept An Interdiscip J. 18:455–489.

Sowiński J, Dalla Bella S. 2013. Poor synchronization to the beat may result from deficient auditory-motor mapping. Neuropsychologia. 51:1952–1963.

Styns F, Leman M. 2007. Walking on music. Hum Mov Sci. 26:769–785.

Tal I, Large EW, Rabinovitch E, Wei Y, Schroeder CE, Poeppel D, Golumbic EZ. 2017. Neural entrainment to the beat: The “missing-pulse” phenomenon. J Neurosci. 37:6331–6341.

Teki S, Gu B-M, Meck WH. 2017. The Persistence of Memory: How the Brain Encodes Time in Memory. Curr Opin Behav Sci. 17:178–185.

Ten Oever S, Schroeder CE, Poeppel D, Van Atteveldt N, Mehta AD, Mégevand P, Groppe DM, Zion-Golumbic E. 2017. Low-frequency cortical oscillations entrain to subthreshold rhythmic auditory stimuli. J Neurosci. 37.

Thaut MH, McIntosh GC, Hoemberg V. 2015. Neurobiological foundations of neurologic music therapy: rhythmic entrainment and the motor system. Front Psychol. 5:1185.

Thaut MH, McIntosh KW, McIntosh GC, Hoemberg V. 2001. Auditory rhythmicity enhances movement and speech motor control in patients with Parkinson’s disease. Funct Neurol. 16:163–172.

Tierney A, Kraus N. 2013. The ability to move to a beat is linked to the consistency of neural responses to sound. J Neurosci. 33:14981–14988.

Tierney A, Kraus N. 2014. Auditory-motor entrainment and phonological skills: precise auditory timing hypothesis (PATH). Front Hum Neurosci. 8:1–9.

Tiffin-Richards MC, Hasselhorn M, Richards ML, Banaschewski T, Rothenberger A. 2004. Time reproduction in finger tapping tasks by children with attention-deficit hyperactivity disorder and/or dyslexia. Dyslexia. 10:299–315.

Todd NPM, Cousins R, Lee CS. 2006. The Contribution of Anthropometric Factors to Individual Differences in the Perception of Rhythm. Empir Musicol Rev. 10:104–110.

Toplak ME, Dockstader C, Tannock R. 2006. Temporal information processing in ADHD: Findings to date and new methods. J Neurosci Methods. 151:15–29.

Toplak ME, Tannock R. 2005a. Time perception: Modality and duration effects in attention-deficit/ hyperactivity disorder (ADHD). J Abnorm Child Psychol. 33:639–654.

Toplak ME, Tannock R. 2005b. Tapping and Anticipation Performance in Attention Deficit Hyperactivity Disorder. Percept Mot Skills. 100:659–675.

Toyomura A, Shibata M, Kuriki S. 2012. Self-paced and externally triggered rhythmical lower limb movements: A functional MRI study. Neurosci Lett. 516:39–44.

Valera EM, Spencer RMC, Zeffiro T a., Makris N, Spencer TJ, Faraone S V., Biederman J, Seidman LJ. 2010. Neural substrates of impaired sensorimotor timing in adult attention-deficit/hyperactivity disorder. Biol Psychiatry. 68:359–367.

van der Wel RPRD, Sternad D, Rosenbaum DA. 2009. Moving the Arm at Different Rates: Slow Movements are Avoided. J Mot Behav. 42:29–36.

Van Dyck E, Moens B, Buhmann J, Demey M, Coorevits E, Dalla Bella S, Leman M. 2015. Spontaneous Entrainment of Running Cadence to Music Tempo. Sport Med - Open. 1:15.

Vaughan RA, Foster JD. 2013. Mechanisms of dopamine transporter regulation in normal and disease states. Trends Pharmacol Sci. 34:489–496.

Wiener M, Turkeltaub P, Coslett HB. 2010. The image of time: A voxel-wise meta-analysis.

Neuroimage. 49:1728–1740.

Williams AM, Grant A. 1999. Training perceptual skill in sport. Int J Sport Psychol. 30:194–220.

Witt ST, Laird AR, Meyerand ME. 2008. Functional neuroimaging correlates of finger-tapping task variations: An ALE meta-analysis. Neuroimage. 42:343–356.

Woodruff Carr K, White-Schwoch T, Tierney AT, Strait DL, Kraus N. 2014. Beat synchronization predicts neural speech encoding and reading readiness in preschoolers. Proc Natl Acad Sci U S A. 111:14559–14564.

Yoles-Frenkel M, Avron M, Prut Y. 2016. Impact of Auditory Context on Executed Motor Actions. Front Integr Neurosci. 10:1.

Zamm A, Pfordresher PQ, Palmer C. 2015. Temporal coordination in joint music performance: effects of endogenous rhythms and auditory feedback. Exp Brain Res. 233:607–615.

Zelaznik HN, Vaughn AJ, Green JT, Smith AL, Hoza B, Linnea K. 2012. Motor timing deficits in children with Attention-Deficit/Hyperactivity disorder. Hum Mov Sci. 31:255–265.