Contraction of Time in Attention-Deficit Hyperactivity Disorder

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Attention-deficit hyperactivity disorder (ADHD) has been associated with anomalies in dopamine systems. Recent advances in the understanding of the core cognitive deficits in ADHD suggest that dopamine dysfunction might be expressed through shortened time scales in reward-based learning. Here this perspective is extended by the conjecture that temporal span in working memory systems might generally be shortened. As a test of this conjecture the authors focus on the implicit memory system involved in rhythmic movement, assessing the minimum tempo at which rhythmic feeling can be sustained in adults with diagnosed ADHD and in a control group of normal adults. The authors found that people with ADHD do in fact have a rhythm cut-off that is faster in tempo than those without ADHD. This finding is consistent with the idea that impaired dopamine dynamics have systemic consequences for cognitive function, essentially recalibrating the clock that sets the time scale for the subjective experience of temporal events.

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Timing behavior is generally assessed in ADHD populations through explicit tests in which the participant must focus attention on the passage of time per se. These tests are quite diverse and include anticipating a future event scheduled some few seconds or minutes in the future (Rubia, Taylor, & Taylor, 1999; Smith, Taylor, Rogers, Newman, & Rubia, 2002; Sonuga-Barke et al., 1998), synchronizing tapping with an external signal (Rubia et al., 1999), discriminating between two given durations (Rubia et al., 1999; Smith et al., 2002; Toplak & Tannock, 2005), or generating a few instances of a given interval (Barkley, Murphy, & Bush, 2001; Kems, McInerney, & Wilde, 2001; Smith et al., 2002). The results of these studies have varied in terms of whether people with ADHD showed timing biases toward shorter intervals, but ADHD timing behavior consistently shows more variability than that of controls. Such a result, however, provides little information about timing mechanisms in ADHD because greater variability is universally found in ADHD cognitive assessment (Castellanos & Tannock, 2002).

What is required here are implicit tests where timing behavior is allowed to emerge as a byproduct of an activity that proceeds without refined judgment and discrimination. There is an implicit aspect of timing behavior that is universally experienced and eminently suitable for psychophysical assessment: the feeling that emerges when we experience rhythm. Such feelings are a prime example of Gestalt; the whole (rhythm) is greater than the sum of the parts (individual time intervals). When we feel rhythm the experience is of the feeling; the actual intervals that create the feeling recede into the background. In this sense the data of interest, the intervals so marked, arise implicitly. We refer to this foreground/background distinction when we inquire if a person is feeling rhythm. Having drawn the distinction, it must be remarked that its relevance to ADHD cognition is not obvious. There are manifestly many musicians who have ADHD; musical or dancing ineptitude is not part of the symptom cluster of ADHD.
That there may be a connection between ADHD and rhythmic expression is suggested by evidence that dopamine pathways are affected in ADHD (Volkow et al., 2007), and that dopamine neurons are tuned to event salience, a key stimulus attribute in the initiation of reward-based learning. Sagvolden et al. (2005) have argued that loss of salience might be functionally expressed by a reward system that is developmentally attuned to shortened delays. At this level of explanation, the symptoms of ADHD (short attention span, hyperactivity, impulsivity) are merely the macroscopic outcomes of steep delay-reinforcement gradients. In this article we conjecture that time scale shortening in conditioned learning may have consequences generally for the organization of behavior, and in particular for the repetitive behavior experienced as rhythmic movement.

The production of rhythm is a human capacity about which quite a bit is already known. Practical musical performance mandates the construction of metronomes that reflect true human capacities in timekeeping, and most metronomes have a limiting largo setting at 40 beats per minute (bpm), an interbeat interval of 1.5 seconds. This is practically the slowest setting at which music can be counted. Our conjecture is that rhythmic feeling may be subject to a shorter limiting interval in ADHD. The suggestion is not that people with ADHD cannot feel rhythm, but that there would be no need to build a metronome that extends to 40 bpm if the intended user has ADHD. A smaller pendulum with a shorter maximum period would suffice.

Theoretical Issues in the Assessment of Rhythmic Feel

A recorded drumming performance is literally a succession of marked moments in time: beats. The succession of intervals between beats forms a time series that may be used to assess the feeling of rhythm. Examples of drumming performance displayed as interbeat-interval time series are illustrated in Figure 1. These data were produced by a normal adult (one not diagnosed with ADHD) whose task was simply to produce a steady train of drumbeats at various tempi. In each tempo condition the participant drummed with a synchronizing signal for 16 beats and then continued without the signal for another 60 beats. Most of the pertinent facts about rhythm are deducible from simply noting whether the performances appear stable or whether they wander about. At tempi faster than 40 bpm the performances are manifestly stable; their associated time series seem to have a well-defined mean and variance. Performances at tempi slower than 40 bpm lack this apparent stability, showing a pronounced tendency to meander. Meandering is a specific kind of losing one’s way that is characteristic of a random walk process.

Random walks are generated by an imperfect copying mechanism that has the recursive form: \( X(t + 1) = \alpha X(t) + \varepsilon(t) \), where \( \alpha \) determines the rate at which successive copies lose their correlation over generations, and \( \varepsilon \) is the random step that drives the walk to meander. This relation provides an important insight into drumming performances at tempi a little slower than the 40-bpm metronome limit. Consider the options available to a drummer who is asked to perform so slowly that he or she cannot feel the beat. How does such a person know when to strike the drum when the implicit body knowledge, the feel, is missing? One strategy is to use the recollection of the most recent interval as a guide for when it would be judicious to next strike the drum. This strategy naturally generates the recursive pattern observed in the random walk. From the point of view of an observer of drumming performance, inferences about whether somebody else is feeling rhythm comes down to deciding whether the performance indicates the recursive use of explicit memories.

Statistics that are sensitive to recursion are quite different from those that have been typically used to measure timing behavior. Most assessments of the human capacity to produce regular pulses are made at tempi well within the range of rhythmic feel (Allan, 1979; Wearden, 1991), and the sole focus has been on overall accuracy as measured by the coefficient of variation, (standard deviation)/mean. When drumming performance is stable both the mean and standard deviation are well-defined in the sense that they do not themselves change during the performance. In this case, the coefficient of variation is a true measure of relative error. However, in meandering performances the mean drifts, and this makes the interpretation of the coefficient of variation problematic. Assessments made at very slow tempi require statistics that do not assume a stable mean but rather quantify the tendency to drift. Such statistics focus on how well past performance predicts future performance. Meandering performance tends to be less accurate but more predictable than stable performance.

The most common statistic used in psychology to capture predictive accuracy is correlation. In time series analysis the concept of correlation generalizes to the autocorrelation function, the correlation of the series with a copy of itself that has been displaced 1, 2, \ldots, k, trials. The autocorrelation function has demonstrated utility in the assessment of rhythmic tapping (Madison, 2001). Related to the autocorrelation function is its Fourier twin, the power spectrum. The power spectrum is especially useful here because it employs trial wavelength rather than trial separation to partition the correlations, and drumming performance is more easily described in terms of wavelength. In the power spectrum global features such as hills and valleys are resolved at the long wavelengths (low frequencies) while the inevitable beat-to-beat
variation is resolved at the short wavelengths (high frequencies). Spectral representations are commonly used in the analysis of stable timekeeping (Gilden, Thornton, & Mallon, 1995; Lemoine, Torre, & Delignieres, 2006).

Beyond correlation are statistics that measure nonlinear aspects of prediction. The sample entropy (Richman & Moorman, 2000) is one such statistic that has proven worth as a clinical tool in diagnosing cardiomyopathy through wandering heartbeat (Norris, Stein, Cao, & Morris, 2006), and promises to be quite useful in assessing rhythmic feel. The sample entropy measures the tendency for micropatterns in the time series to repeat. Formally, the sample entropy is an average conditional probability; given that X was followed by Y in the past, how likely is it that an event resembling X will be followed by an event resembling Y. Signals that drift generally have lower entropy than signals that fluctuate about a stable mean.

Empirical Assessment of Rhythmic Feel

The following pilot study assessed whether adults with ADHD lose rhythm at faster tempo than do normal controls. The study focused on the range of tempo where people typically lose their sense of rhythm and was designed to provoke both stable and wandering behavior in the two groups.

Method

Participants

Eleven adults with a diagnosis of ADHD and 11 adults without ADHD participated in the study, which was approved by the institutional review board. All participants were students at the University of Texas and were between 18 and 30 years of age. The participants with ADHD were referred by the Office for Students with Disabilities. To register with the Office for Students with Disabilities, students must have a DSM–IV or ICD diagnosis of ADHD from an external clinician, and they must have received a psychological evaluation in the past 3 years to demonstrate that their assessment is current. All of the participants with ADHD had received a clinical diagnosis, and about half received this diagnosis in childhood. Those who were diagnosed as adults all reported childhood-onset symptoms, as required by DSM–IV (C). Counting must be prevented in assessments of rhythm at target tempi slower than 60 bpm, if we wish to ensure that performers do not substitute their own counting beat for the intended target. Covert counting is a problem not often encountered in studies of timing behavior as durations exceeding a second are rarely examined. Madison’s (2001) work is almost unique in this regard, and he dealt with this problem by simply instructing the participants to not count. Such an instruction places conflicting task demands upon the participant as there is always the implicit requirement in any drumming study that performance be as accurate as possible. An alternative strategy is to suppress counting through a secondary task that requires articulation, one that is highly practiced and relatively automatic. Reading elementary text fits this requirement and is the tactic used in this pilot study.

Procedure

Participants each completed three target-tempi conditions of 30, 40, and 60 bpm, corresponding to interbeat intervals of 2, 1.5, and 1 second, respectively. These tempi were chosen to span the critical interval where rhythm breaks down in normal function. In each condition, participants slapped the drum with their dominant hand in time with a synchronizing signal for 16 beats and then continued without the signal for another 3 minutes. To prevent counting, participants drummed while reading aloud from a non-technical book review printed in large clear type.1

Results

Figure 2 displays key statistics at the three target tempi: (A) coefficient of variation, (B) power spectrum in log-log coordinates, (C) serial correlation, and (D) sample entropy.2 We use the coefficient of variation as a measure of overall accuracy, recognizing that its utility is compromised by drifting performance. The power spectrum (see Thornton and Gilden (2005) for computational method), serial correlation, and entropy are used to characterize drift. It is evident from this figure that the statistics are resolving large group differences in drumming performance at the target tempi. The tempo functions are, however, fairly complex, and the data are best understood by considering the conditions in the order of fastest to slowest tempi, progressing from manifest rhythm to its complete breakdown.

At the fastest tempo, 60 bpm (1-s target), the ADHD and normal control groups have similar performance characteristics. They have similar accuracies, nonlinear predictability (entropy), and low frequency power. As the power at low frequencies picks up the large-scale hill-valley structure, equality between the two groups implies that they have comparable stability in the long run. Where the two groups differ in spectral power is at the high frequencies. Here the normal control group actually shows greater fluctuation magnitude, and this is reflected by the marginally larger coefficient of variation in the normal control group. That the high frequency fluctuations are relatively smaller in the ADHD group makes their performances slightly more predictable in the short run as evidenced by the enhanced serial correlation. The finding that ADHD performance is not in any way compromised at 60 bpm is an important benchmark for our method. If the secondary counting suppression task differentially disrupted drumming performance in the ADHD group it might be expected to enter as a main effect across tempo conditions.

Group differences at 40 bpm are quite large and appear in the three measures of sequential correlation that are sensitive to the loss of rhythmic feel and the onset of random walking. Comparing ADHD

1 Interval discrimination studies have demonstrated that counting markedly improves performance when durations exceed about 1.2 seconds (Grondin, Mielleur-Wells, & Lachance, 1999). Counting must be prevented in assessments of rhythm at target tempi slower than 60 bpm, if we wish to ensure that performers do not substitute their own counting beat for the intended target. Covert counting is a problem not often encountered in studies of timing behavior as durations exceeding a second are rarely examined. Madison’s (2001) work is almost unique in this regard, and he dealt with this problem by simply instructing the participants to not count. Such an instruction places conflicting task demands upon the participant as there is always the implicit requirement in any drumming study that performance be as accurate as possible. An alternative strategy is to suppress counting through a secondary task that requires articulation, one that is highly practiced and relatively automatic. Reading elementary text fits this requirement and is the tactic used in this pilot study.

2 The sample entropy is a function of two parameters, m - the dimension of the embedding space, and r - the neighborhood size. Here m = 2, and r = 2σ, where σ is the interval standard deviation. These values are typical of practical application (Norris et al., 2006).
with normal control participants, their spectra were steeper, \( t(20) = -2.5, p < .01 \), their entropies were lower, \( t(20) = -1.88, p < .04 \), and their serial correlations were larger, \( t(20) = 2.77, p < .01 \). All three of these statistics suggest that 40 bpm defines a new regime of behavior for the ADHD group, a regime where the sense of rhythm has become so diminished that they substitute replicates of their previous estimates for the target interval. The coefficient of variation in the ADHD group is also quite large at 40 bpm compared to 60 bpm, \( t(10) = 2.55, p < .02 \), providing further evidence that the nature of the performances at the two tempi are quite different. It is equally evident that the normal control group performance is rhythmically stable at 40 bpm, justifying the extension of the metronome to this tempo. On every statistical measure of correlation as well as in the coefficient of variation, the differences between 40 bpm and 60 bpm in the normal control group were small and not significant.

Finally we consider performance beyond the metronome limit, at 30 bpm. In this condition neither group produces competent drumming. The coefficient of variation in both groups is some 50% larger than it was at 60 bpm, a sure sign that rhythmic feeling has been compromised (normal control \( t(10) = 4.8 \), ADHD \( t(10) = 3.2 \)). Consistent with previous findings (Madison, 2001), the normal control group meanders at 30 bpm: the serial correlations are almost triple that in the two faster conditions (\( r = .2 \) vs. \( r = .08, t(31) = 2.0, p < .025 \)). As at 60 bpm, the normal control group is slightly less accurate than the ADHD group, as measured by the coefficient of variation. This difference is due, as it was at 60 bpm, to the fact that the normal control group actually fluctuates a little more wildly from beat to beat. Again, the relative suppression of power at the high frequencies in the ADHD group gives them a larger serial correlation. However, the groups are not distinguished by the sample entropy. Both groups are sufficiently erratic in the short run that even in the presence of strong drift, micropatterns in the time series are poor predictors.

The observation that ADHD performance is both slightly more stable and more accurate than that of the normal controls at the two bounding tempi, 60 and 30 bpm, suggests that the secondary task of reading is not differentially diminishing ADHD performance. If the presence of a secondary task is critical in producing group differences at 40 bpm it must be that the ADHD group is more vulnerable at this tempo. If the ADHD group is more vulnerable to the effects of a secondary task only at 40 bpm it must be that their sense of rhythm is compromised differentially at 40 bpm. As this is essentially the conjecture we seek to test, the secondary task is justified as a reasonable measure to prevent counting.

Discussion

This pilot study of ADHD rhythmic behavior resolves three distinct performance regimes that exemplify two different aspects of working
memory. At fast tempo (60 bpm) both ADHD and normal control groups execute accurate and stable performances. The interpretation of this finding is that the system of implicit working memory that produces rhythmic feel has a temporal span that exceeds 1 second in both groups. At rhythmic the metronome limit (40 bpm), this implicit memory system appears to be unavailable to people with ADHD, and their performance reflects a different and more explicit usage of memory, memory of their most recent estimates. As normal controls display rhythmic feel at 40 bpm, this difference implies a difference in the span of rhythmic feel. The effective span of rhythmic feel is apparently contracted in ADHD adults to less than 1.5 seconds. At 30 bpm, both the implicit sense of rhythm and the explicit sense of prior estimates are largely attenuated in both groups. This is presumably why metronomes typically do not offer a setting at 30 bpm. If there is any distinction between the groups at this tempo, it is that the ADHD group has a better sense of what they are doing, as they seem to have a better sense of their most recent estimates. Outside of this observation there is little to distinguish normal control from ADHD performance at 30 bpm.

In this article we have considered one aspect of temporal integration, rhythmic feeling, providing preliminary evidence that this feeling exists over a relatively restricted tempo range in ADHD. Rhythmic feeling is a good place to begin an analysis of the more general issue of temporal integration because it is methodologically simple, it is supported by clear signatures in data, and it involves a system of measurement that does not require sustained vigilance. These preliminary results, however, do not remotely exhaust the range of cognition investigated. Investigators, however, do not remotely exhaust the range of cognition that is involved in the perceptual organization of temporarily based events. Virtually any percept or activity that involves synthesis across time is potentially of interest. In particular, ethological investigation of human actions that imply universal time scales (Schleidt, Eible-Eibesfeldt, & Pöppel, 1987) may be a particularly productive way of investigating ADHD temporality and in understanding what exactly is implied by hyperactivity and inattentiveness.

References


