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2 authors, including:

Laura R Marusich

Army Research Laboratory

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Assessing Temporal Integration Spans in ADHD Through Apparent Motion

Laura R. Marusich and David L. Gilden
The University of Texas at Austin

Objective: We use psychophysical methods to examine the maximum time intervals over which discrete events can be temporally integrated into the percept known as apparent motion. We hypothesized that the maximum time interval would be *shorter* in participants with attention deficit hyperactivity disorder (ADHD) than it would be in a control group. ***Method:*** Thirty-five adults with ADHD and 40 adult controls without ADHD participated in an apparent motion task, in which they viewed a stimulus flashing in 2 different locations and were asked to complete the trajectory of motion that they perceived. The stimulus flashes were separated by varied temporal intervals ranging from 200 to 2300 ms. Clear trajectory perception in this task indicates successful temporal integration. ***Results:*** At short intervals, we found evidence of clear trajectory perception in both groups, indicated by low variability in path estimations. At the longest intervals, neither group demonstrated path perception, evidenced by high variability in estimations. However, at intermediate intervals (1.7 s), the control group demonstrated path perception while the group with ADHD did not, indicating a difference between the 2 groups in the maximum interval over which apparent motion could be perceived. ***Conclusions:*** We suggest that ADHD is generally characterized by a contraction in the time scale governing the rate at which association strength decays. In contrast to theories that postulate general time-processing deficits, this work provides a precise sense in which temporality is disturbed in ADHD.

Keywords: apparent motion, attention deficit hyperactivity disorder, dopamine, temporal integration

Attention deficit hyperactivity disorder (ADHD) is one of the most commonly diagnosed disorders among children in the United States, and it is now recognized that it persists into adulthood in many cases (Barkley, Fischer, Smallish, & Fletcher, 2002; Biederman, Mick, & Faraone, 2000). The behavioral symptoms of inattention, hyperactivity, and impulsivity that characterize ADHD are well documented; however, the cognitive deficits underlying the disorder and leading to these behavioral symptoms are still the subject of much debate. Many constructs have been proposed to account for the behaviors associated with ADHD, including impaired behavioral inhibition and executive function (Barkley, 1997), delay aversion (Sonuga-Barke, 2002), impairment in the regulation of arousal/activation (Sergeant, 2000), temporal processing deficits (Smith, Taylor, Rogers, Newman, & Rubia, 2002; Sonuga-Barke, Bitsakou, & Thompson, 2010), and altered reinforcement mechanisms (Johansen, Aase, Meyer, & Sagvolden, 2002; Sagvolden, Johansen, Aase, & Russell, 2005; Scheres, Tontsch, Thoeny, & Kaczkurkin, 2010). Gilden and Marusich (2009) described a new perspective of ADHD as a shortening of the maximum intervals over which temporal integration can occur, providing preliminary evidence in support of this perspective using a study of rhythmic tapping in adults with and without ADHD. In the current work, we describe the results of an experiment using an apparent motion task to demonstrate further evidence of shortened windows of temporal integration in ADHD. We begin with a brief explanation of the theoretical perspective that motivates this work.

Scaled Delay-of-Reinforcement Gradients in ADHD

Recent work in ADHD emphasizes the bridging of neurobiological accounts with symptom-level descriptions of the disorder through intermediate constructs, known as endophenotypes (Castellanos & Tannock, 2002). One promising candidate endophenotype is the notion of altered delay gradients (Sagvolden et al., 2005), which provides a compelling integration of the widespread neurobiological evidence of impaired dopamine systems (for a review, see Swanson et al., 2007) in ADHD and the well-studied connection between dopamine and reinforcement learning.

The dopamine system, particularly the mesolimbic and nigrostriatal pathways, is known to be involved in reinforcement learning (Beninger & Freedman, 1982; Beninger & Miller, 1998; Robbins & Everitt, 1996). Specifically, dopamine is released in the striatum in response to an unpredicted reinforcer, which allows for long-term potentiation (LTP), the strengthening of synaptic connections. Studies show that with repeated experience with reinforcement, the phasic release of dopamine transfers from the onset of reinforcement itself to the response or to earlier cues that predict the delivery of reinforcement. This process of transfer is the biological evidence of a learned association. Lowered levels of extracellular dopamine in ADHD are hypothesized to cause this transfer process to occur more slowly in ADHD (Sagvolden et al., 2005; Tripp & Wickens, 2008). In other words, each exposure to

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Laura R. Marusich and David L. Gilden, Department of Psychology, The University of Texas at Austin.

Laura R. Marusich is now a postdoctoral fellow at the Human Research and Engineering Directorate, U.S. Army Research Laboratory.

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Correspondence concerning this article should be addressed to Laura R. Marusich, ATTN: RDRL-HRS-E, 459 Mulberry Point Road, Aberdeen Proving Ground, MD 21005-5425. E-mail: lmarusich@utexas.edu

the response-reinforcement contingency is somewhat less effective at inducing transfer in ADHD, so more exposures to the response-reinforcement contingency are required for the transfer to take place. This attenuation of the transfer process has consequences for the time scales over which reinforcement learning can occur.

The ability to form an association between a reinforcer and the behavior that produced it (the operant response) is subject to the decaying memory trace of that behavior. That is, if the reinforcer is delivered immediately after the operant response, the memory trace of the response will still be quite strong and thus available to be associated with the reinforcement. However, if the reinforcer is delayed substantially, the memory trace of the response will have decayed to a point where it is no longer available. In this case, any intervening behaviors or cues that occur between the operant response and the reinforcement are more likely to be reinforced, and the environmentally relevant association will be frustrated. This concept is illustrated by the delay-of-reinforcement gradient (see Figure 1), which relates the amount of time separating response and reinforcement to the probability of learning an association between the two. This inverse relationship between reinforcement delay and probability of reinforcement has long been recognized in the animal learning literature, and the upper limit on delay for successful reinforcement is known to be on the order of a few seconds (see, e.g., Perin, 1943).

Here, we formalize the probability of learning in terms of a simple product:

$$\textit{Probability} = \textit{memory trace strength}(\Delta t) * \textit{magnitude of dopamine signal}, \quad (1)$$

where Δt is the interval between response and reinforcement. The memory trace strength, as described above, is a function of Δt: the trace strength decays as Δt increases. The impaired dopamine response hypothesized to occur in ADHD would effectively scale the delay-of-reinforcement curve, as shown in Figure 1. To achieve the same probability of association in a scaled gradient compared to a normal gradient, the reinforcer must be delivered more closely in time. Sagvolden et al. (2005) proposed that this shortening in the timescale of reinforcement learning could lead to many of the observed global symptoms of ADHD. For example, the symptom of inattention is explained as follows:

> The potency of a stimulus as a conditioned reinforcer depends on the time between its onset and the subsequent delivery of a reinforcer in its presence, according to the same delay gradients that operate for the relation between responses and subsequent reinforcers . . . if the gradient is short, the reinforcer must follow quickly after stimulus onset. If not, the stimulus does not become a potent reinforcer, and the individual will not attend to it when it appears. (p. 414)

This account of shortened timescales of reinforcement learning in ADHD is compelling; however, dopamine release is known to occur in response not just to rewarding stimuli, but also more generally in response to salient events (Horvitz, 2000; Jensen et al., 2007; Schultz, Dayan, & Montague, 1997). If dopamine function is not limited to reinforcement, it follows that an altered dopamine system can affect not only the timing of reinforcement learning, but also the timing of more general types of association formation. The consequences of this conjecture are expanded below.

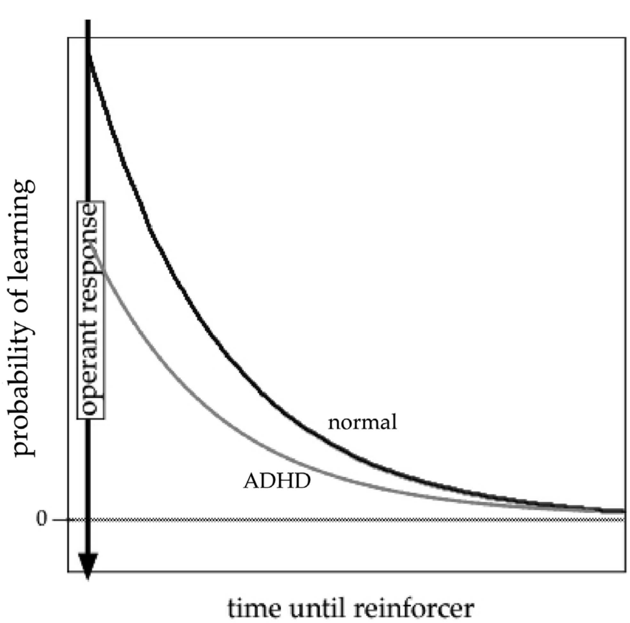

Figure 1. Illustration of normal and scaled delay-of-reinforcement gradients.

Temporal Integration

Every moment of waking life involves the organization of the moment-to-moment flux in action and thought into intelligible behavior, intelligible streams of thought, and a coherent and stable world in which to live. The experience of events in time requires the ability to integrate discrete episodes into unified experiences; in cognitive psychology, all the processes that go into this ability fall under the field of event perception (see, e.g., Zacks, Speer, Swallow, Braver, & Reynolds, 2007; Paine & Gilden, 2013). However, there must also be an upper limit to the size of the window over which this integration can occur, otherwise events would be never-ending, there would be no sense of the present moment, no sense of cause and effect, and the temporal structure of the world would be unintelligible. In this sense, pauses in the temporal stream are important cues about event structure, and it is essential to the understanding of the world that integration not occur over a long pause. Our interest is in the maximum pause length that can be bridged into a single event.

A simple example of the kind of temporal integration process described above is the perception of melody. A melody is composed of individual notes that are separated by short temporal intervals. If these separating intervals were too long, the perception would be not of music, but rather of the occasional arrival of isolated tones. To perceive melodic contour, the length of the intervals between notes must be relatively small so that the notes are perceived to belong together in a single event. In fact, this limitation is reflected in the construction of metronomes; the slowest tempo built into most metronomes is 40 beats per minute, or one quarter note every 1.5 seconds. The key point here is that all of experience is filled with temporal Gestalts; we do not hear individual notes in music—we hear melody and harmony. We do not see movement sequences—we see gestures and meaningful activity. The whole is greater than the sum of the parts, and the whole is formed by the processes of temporal integration creating bridges across time. Here we propose that scaled gradients in ADHD have consequences not just for reinforcement learning, but for these processes of temporal integration and scene formation, essentially in how time is bridged in making sense of the world.

The conjectures at the heart of the current work are a) that there is a maximum span over which temporal integration can occur, governed by delay gradients and the dopamine system, and b) that dopamine dysfunction in ADHD entails a contraction of the maximum span of temporal integration. The results from a drumming task by Gilden and Marusich (2009) provided preliminary support for these conjectures. Just as in perceiving melodic contour, maintaining a steady tapping rhythm requires integration across the temporal intervals that occur between successive beats. Participants were asked to tap isochronously at several different tempos, meaning that they had to maintain a steady rhythm across intervals of different lengths. When the intervals were short, both participants with ADHD and control participants were able to tap in rhythm. When the intervals were long, both groups displayed arrhythmic drumming. The important finding was that the transition from rhythmic to arrhythmic drumming occurred at a faster tempo (shorter intervals) in the ADHD group than it did in controls. In the current work we extend these findings by demonstrating corresponding/similar results in a task from a very different domain: an assessment of the perceived trajectory of apparent motion.

Apparent Motion

Visual apparent motion is a phenomenon in which discrete flashes of identical stimuli in different locations can elicit the perception of motion (several demonstrations are available at http://www.socsci.uci.edu/~ddhoff/vi6.html). First systematically investigated by the Gestalt psychologists in the early 20th century (Wertheimer, 1912), it is one of the earliest and most well-studied phenomena involving temporal integration.

Wertheimer (1912) demonstrated at the outset the three regimes of simultaneity, motion, and succession, and their dependence on the timing of the stimulus display. When the temporal separation between the flashes of the two stimuli is very short, observers perceive simultaneity of the two stimuli. When the temporal separation is very long, observers perceive succession: the appearance of first one stimulus, then the appearance of the second stimulus. However, at intermediate separations, the perception is of one object moving between two locations.

A critical distinction has been made in this field between long-range and short-range apparent motion (Anstis, 1980; Braddick, 1974; Braddick, Ruddock, Morgan, & Marr, 1980; Pantle & Picciano, 1976; Petersik, 1989). Short-range apparent motion generally occurs over small separations in space and temporal interval, and is attributed to low-level processes of motion detection in the visual system. Long-range apparent motion, on the other hand, often occurs over longer separations in space and time, and is thought to involve higher-level interpretive processes in the visual system.

Many aspects of this long-range process have been discovered and studied—for example Korte's Law (the relationship between the temporal and spatial distance needed to induce the percept of motion), the transition between group and element motion in the Ternus display (demonstration at http://michaelbach.de/ot/mot_Ternus/), bistability http://michaelbach.de/ot/mot-sam/index.html), and transformational apparent motion (http://www.dartmouth.edu/~petertse/tamdemo.htm), to name a few. Apparent motion is a compelling and clear example of temporal integration, and in a very different domain than keeping rhythm, recommending it as a paradigm for the current work.

The experiment we use focuses on path perception in long-range apparent motion, particularly drawing on the work of Proffit, Gilden, Kaiser, and Whelan (1988). There are infinitely many possible paths that can be inferred from the flashing of two stimuli in different locations, but the paths that observers actually perceive in long-range apparent motion are typically those that minimize motion (Wertheimer, 1912). So, for example, a dot flashing in two locations appears to move in a straight line between the two points; it doesn't appear to travel in an arc or some other more circuitous path unless such a path is induced with additions to the stimulus. There are some displays, where the path that minimizes motion is ambiguous. Consider the display shown in Figure 2. The inferred motion could be a simultaneous translation and rotation about the center of the rectangle (shown in Panel B), which would correspond to a minimization of the total distance traveled. Another inferred motion could be a single rotation (shown in Panel C), in which it appears that the rectangle is at the end of a pivoting arm. This perception would correspond to an information minimum, or a minimization of the number of motions.

Foster (1975) and Proffit et al., 1988 assessed path perception from ambiguous stimuli of this type by asking observers to place a probe rectangle at the halfway point of the path they perceived. The researchers used these placements to infer the type of path perceived. They found that human observers tend to minimize the number of motions, corresponding to the circular path shown in Panel C, although this can be modulated somewhat with very large orientation changes between the two stimuli.

The appeal of this task is its objective nature. In many studies of apparent motion, the data collected is observers' self report of whether they see motion and if so, what type of motion. This methodology can easily lead to stereotyped response; once observers see a specific motion, they can continue to report seeing it

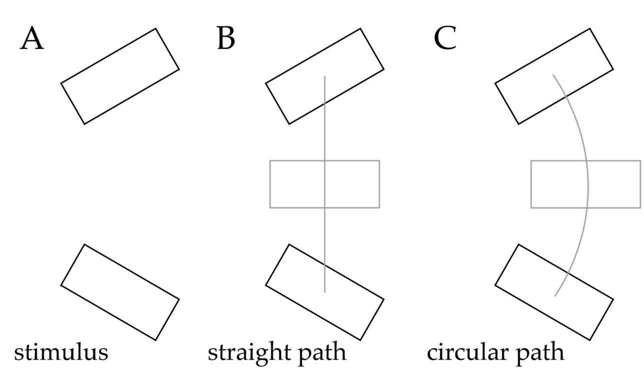

Figure 2. Possible trajectories of apparent motion: A) visible stimulus, B) illustration of the perception of a straight path (translation plus rotation), C) illustration of the perception of a circular path (single rotation).

whether or not the percept is actually there. By contrast, a task that requires observers to complete the trajectory of perceived motion will produce a range of responses which depend on the type and strength of the motion percept. The investigator may deduce the *type* of motion perceived from the average placement of the test rectangle, and may deduce the *strength* of motion perceived from the variability in those placements. In displays where motion is not perceived, observers will have great difficulty completing the path with precision, generating high variability in probe placement. However, when strong apparent motion is perceived, the task is trivial and variability will be quite low. This variability is therefore an excellent metric of the strength of temporal integration across the alternating frames of the display. In this experiment we introduce varying temporal interstimulus intervals (ISIs) as an independent variable. to assess the span of temporal integration in adults with and without ADHD.

The goal of this work is to measure the variability in probe placement across ISIs of varying length, to assess the maximum span of temporal integration in adults with and without ADHD. If dopamine dysfunction in ADHD does, in fact, entail a contraction of this maximum temporal span, this will be evidenced in this task by the following: a) similar high variability in placement in both groups at the longest ISIs, b) similar low variability at the shortest ISIs, and critically c) a region of intermediate ISI in which adults without ADHD demonstrate low variability, but adults with ADHD demonstrate high variability.

Method

Participants

Thirty-five participants with ADHD and 40 control participants completed this study. Participants with ADHD were primarily recruited through the Services for Students with Disabilities (SSD) office at the University of Texas at Austin. To register with this office, students must provide documentation of a *Diagnostic and Statistical Manual of Mental Disorders*, fourth edition (*DSM–IV*) or ICD diagnosis of ADHD from a mental or medical health care professional. If the diagnosis occurred more than three years in the past, students must provide documentation of neuropsychological or psychoeducational evaluation in the past three years demonstrating that the assessment of ADHD is current. A small number of additional participants with ADHD were recruited from a local psychological practice specializing in the diagnosis and treatment of ADHD and related disorders. All participants recruited from this location carried a current diagnosis of ADHD. Control participants were recruited through introductory psychology courses at the university.

Inclusion criteria for participants with ADHD were as follows: a) age 18 to 30 years; b) previous diagnosis of ADHD from a mental or medical health professional; and c) consent from participants taking stimulant medication to undergo a 24-hr washout period before each experimental session. The exclusion criterion was a) uncorrected vision impairment. Inclusion criteria for control participants were as follows: a) age 18 to 30 years; b) no history of diagnosis of ADHD; and c) a t score below 65 (the 94th percentile) on the ADHD Index subscale of the Conners Adult ADHD Rating Scale. Exclusion criteria were as follows: a) the use of psychotropic medications at the time of study; and b) uncorrected vision impairment.

Descriptive Measures

CAARS–S:L. The Conners Adult ADHD Rating Scale (CAARS; Conners, Erhardt, & Sparrow, 1999) is designed to assess current symptoms of ADHD in adults. This scale has demonstrated good reliability and validity (Conners et al., 1999; Erhardt, Epstein, Conners, Parker, & Sitarenios, 1999). The long version of the self-report form (CAARS – S:L) includes 66 questions and yields scores on nine subscales: inattention/memory problems, hyperactivity/restlessness, impulsivity/emotional lability, problems with self concept, *DSM–IV* inattentive symptoms, *DSM–IV* hyperactive-impulsive symptoms, *DSM–IV* total symptoms, ADHD index, and an inconsistency index. The scores on each subscale can be compared with appropriate population norms for age and gender of the respondent. Scores that fall above the 94th percentile are considered clinically relevant elevations, and can indicate that the respondent experiences symptoms of ADHD that meet the *DSM–IV* criteria for diagnosis.

This scale was used to confirm that participants in the ADHD group were in fact experiencing current symptoms of ADHD, and that participants in the control group did not report clinically elevated symptoms of ADHD.

DASS-21. The Depression Anxiety Stress Scales 21 (DASS-21) is a short version of the longer, 42-item DASS (Lovibond & Lovibond, 1995), which assesses depression, anxiety, and stress. Studies have shown the DASS-21 to have good reliability and construct validity (Antony, Bieling, Cox, Enns, & Swinson, 1998; Henry & Crawford, 2003). Adult ADHD is often comorbid with depression and anxiety (Barkley, Murphy, & Fischer, 2007; Kessler et al., 2006), which can cause a confound in interpreting results of group differences, especially in cognitive measures. The DASS-21 was used to collect information on symptoms of depression and anxiety in both groups, in order to assess potential comorbidity confounds.

WAIS-III – vocabulary and matrix reasoning subtests. Evidence from meta-analyses indicate that ADHD is associated with lower scores on measures of IQ relative to normal controls (Bridgett & Walker, 2006; Frazier, Demaree, & Youngstrom, 2004), although there are many individuals with high IQ that carry a valid diagnosis of ADHD (Antshel et al., 2009). There is considerable debate whether lowered IQ should be considered a confound in studies of ADHD or as a part of the syndrome. Here we collected estimated IQ information using two subtests from the Wechsler Adult Intelligence Scale 3rd edition (WAIS-III; Wechsler, 1993): vocabulary and matrix reasoning. These two subtests were chosen because they have been shown to provide a good estimate of full-scale IQ while producing the smallest gains attributable to practice (Kaufman & Lichtenberger, 2006). Many of the participants with ADHD were likely to have completed an IQ assessment within the previous 1–3 years, as a result of the requirements for registering with the SSD, so it was necessary to use subtests that are relatively less susceptible to practice effects. The estimated IQ scores generated from these subtests were used to generate estimated IQ, in order to assess IQ as a potential confound. Thirty-two participants with ADHD and 37 of the control participants completed the two WAIS-III subtests.

Apparent Motion Task

The stimuli in this experiment consisted of two test rectangles flashing in turn at fixed locations on the screen. After four cycles of this display, a flashing probe rectangle appeared that could be moved by the observer. One side of each rectangle was colored blue, whereas the other was colored red; this was done to make clear the orientation change between the two test rectangles. The dimensions of each rectangle were 4.5 by 1.5 cm, and the distance between the centers of the two test rectangles was 20.5 cm.

An illustration of the system appears in Figure 3. The system had two parameters that varied from trial to trial: a) the angle (theta) of the system axis (a line equidistant at every point to the centers of two test rectangles) relative to the horizontal, and b) the ISI that elapsed after the disappearance of one test rectangle before the appearance of the other. The possible values for theta were 45, 135, 225, and 315 degrees, and the possible ISI values were 200, 300, 500, 1100, 1700, and 2300 ms. This ISI between the test rectangles remained constant before and after the onset of the flashing probe rectangle. The duration of all three stimuli was 100 ms.

The probe rectangle was constrained to move along the system axis, and it flashed in sequence with the test rectangles. The location of the probe rectangle could be manipulated with the mouse, and a mouse click recorded the current position of the probe and ended the trial. On every trial, the flashing probe rectangle first appeared in a randomized location along the system axis, so that the observer could not learn a stereotyped motor pattern for placing the rectangle.

Procedure

Participants viewed a demonstration of the display in which the two test rectangles flashed at a relatively short ISI (200 ms), allowing for strong perception of motion along a path. After 10 cycles, the probe rectangle began to flash in sequence in the display. The experimenter explained the purpose of the probe rectangle, demonstrated how its position on the screen could be manipulated with the mouse, and then gave the participant the opportunity to practice placing it. If the participant placed the probe rectangle in the general vicinity that would indicate either a circular or straight path, the experimenter began the test block. Otherwise, the participant was asked to explain the type of motion he or she was seeing. In the few cases that this occurred, there was an underlying misunderstanding of the task that was easily resolved.

The participants then completed a test block of 24 trials. There were four possible angles of rotation of the system, and six possible ISIs. In total, observers executed one trial at each angle/ISI condition. In analysis, the data were collapsed across the four angle conditions in analysis, yielding 4 observations at every ISI condition. On every trial, the coordinates of the center of the probe rectangle were recorded.

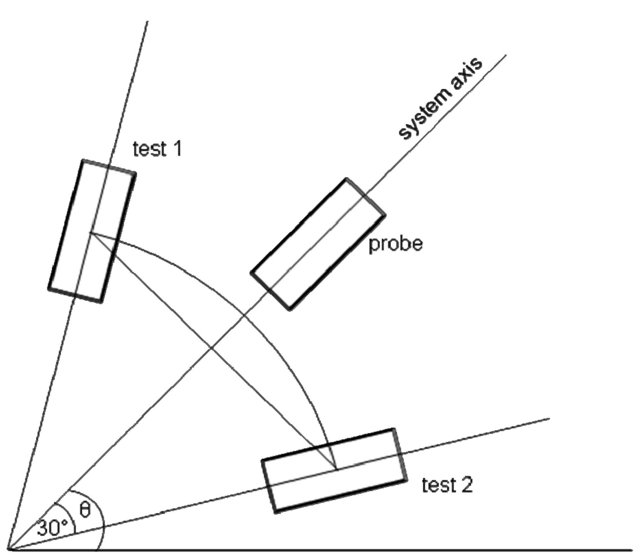

Figure 3. Illustration of the design of the apparent motion task. The only elements visible to the participants were the three rectangles, which flashed in sequence.

Analysis

We used the coordinates of the probe rectangle's placement on each trial to calculate the displacement from the straight path. Positive displacement values indicated displacement in the direction of the circular path, while negative values indicated displacement in the opposite direction of the circular path.

Results

Demographics and Descriptive Measures

Table 1 shows the demographic information and descriptive measures for the two participant groups. As expected, the two groups differed substantially on the CAARS, with the ADHD group scoring higher on all subscales. The groups did not differ significantly on the estimated IQ as measured by the vocabulary and matrix reasoning subtests of the WAIS-III. Neither did they differ on the depression or anxiety scales of the DASS-21. The group with ADHD did score significantly higher than the control subgroup on the stress scale, but the scores for both groups on all three scales of the DASS-21 were in the normal to mild range of severity. Because the measures obtained for IQ, depression and anxiety, which had been anticipated as potential confounds, did not differ between the groups, these variables were not entered as covariates in the analysis of experimental data. On average, the participants with ADHD were two years older than the control participants, and the ratio of males to females was larger in the ADHD group than in the control group. However, there was no relationship between either age or sex with the measures of interest in the apparent motion task, and so these variables were not included in the analysis of the apparent motion data.

Apparent Motion Task

The results of the experiment are shown in Figure 4. The subgroup of control participants who completed the DASS-21 and WAIS-III subtests did not differ significantly on the apparent motion task from those who did not; as a result, the data from all participants were combined. The top panel shows the average displacements (in pixels) from the straight path for both groups. A

Table 1
Participant Characteristics

Characteristic	Control (n = 40) M (SD)	ADHD (n = 35) M (SD)	t
Age	18.9 (1.3)	21.0 (2.2)	5.0***
CAARS			
Inattention	53.3 (9.6)	65.3 (10.5)	5.2***
Hyperactivity	50.0 (9.2)	60.9 (9.5)	5.0***
Impulsivity	48.6 (11.2)	55.6 (12.2)	2.6*
Self-concept	49.6 (11.4)	54.1 (11.2)	1.7
DSM inattentive	55.7 (11.6)	76.7 (9.8)	8.4***
DSM hyperactive	48.8 (11.4)	64.6 (12.0)	5.9***
Total symptoms	53.2 (11.5)	75.1 (10.3)	8.6***
ADHD index	50.7 (8.2)	60.9 (10.2)	4.8***
DASS-21			
Stress	10.7 (7.4)	15.9 (8.1)	2.9**
Anxiety	6.7 (7.1)	8.9 (6.0)	1.4
Depression	7.1 (9.0)	9.7 (8.2)	1.3
			χ^2
Sex	9 M, 31 F	16 M, 19 F	4.5*
	Control (n = 37)	ADHD (n = 32)	t
WAIS-III Estimated IQ	110.7 (9.8)	109.9 (11.6)	0.3

* $p < .05$, ** $p < .01$, *** $p < .001$.

displacement value of 0 indicates placement of the test rectangle at the exact location of the straight path, whereas a value of 107 indicates placement at the exact location of the circular path. In all ISI conditions, both groups tended to place their rectangles at locations that were closer to the circular path. As shown in the figure, ISI length does not greatly influence on the type of path perceived. There is no evidence of a transition from the type of path perceived as temporal intervals increase. As a result, there is no opportunity for a group difference in transition point to emerge.

Although the average location of the test rectangle placement is fairly stable across ISIs, the variability in estimation, shown in the bottom panel of Figure 4, appears to transition from fairly consistent to quite variable as the intervals increase. This measure represents how variable each observer was in his or her placement at a given interval, and unlike the mean displacements, it shows a large effect of ISI.

There are three clear epochs in the data displayed here. The first is a region of low variability probe placement for both groups, occurring at ISIs of .2, .3, .5, and 1.1 s. At these ISIs, the path is very clear and easy to see. The second is a regime of extremely high variability of probe placement for both groups that occurs at large ISI (2.3 s). Here, none of the observers, ADHD or control, could consistently indicate the location of a motion path. This is a regime of succession, described by Wertheimer, where no path is perceived. The third and most interesting epoch is the single interval in between, where the two groups differ. At ISIs of 1.7 seconds, the control group demonstrates low variability in probe placement, whereas the group with ADHD demonstrates high variability. The inference here is that the control group can see a path at 1.7 s ISIs, whereas the group with ADHD does not. This is precisely the result that is predicted by steepened delay-of-reinforcement gradients attenuating the span of temporal integration. The *maximum window* over which integration can occur is smaller in ADHD. As a result, the only intervals where performance would be expected to differ are those just larger than this ADHD maximum but still within the control window's span. At all other intervals, sameness in probe placement variability between the groups is predicted.

Note that an omnibus ANOVA, which tests for any significant difference among the condition means, is an inappropriate test of the significance of these results. Our hypotheses involve prediction of sameness at every interval condition but one. It is a much more specific prediction than that tested by the ANOVA: that there exists some difference between any of the condition means. In order to test the significance of the specific result of only one regime of group differences out of six, we used a bootstrapping procedure. We resampled the data 10,000 times, randomly assigning group membership and recording the percentage of resamples that met the following criteria:

1. Of the six intervals, there is only one in which the difference in group means is large enough to generate a p value less than 0.05 in a two-sample t test.

2. The interval at which this difference occurs is 1.7 s.

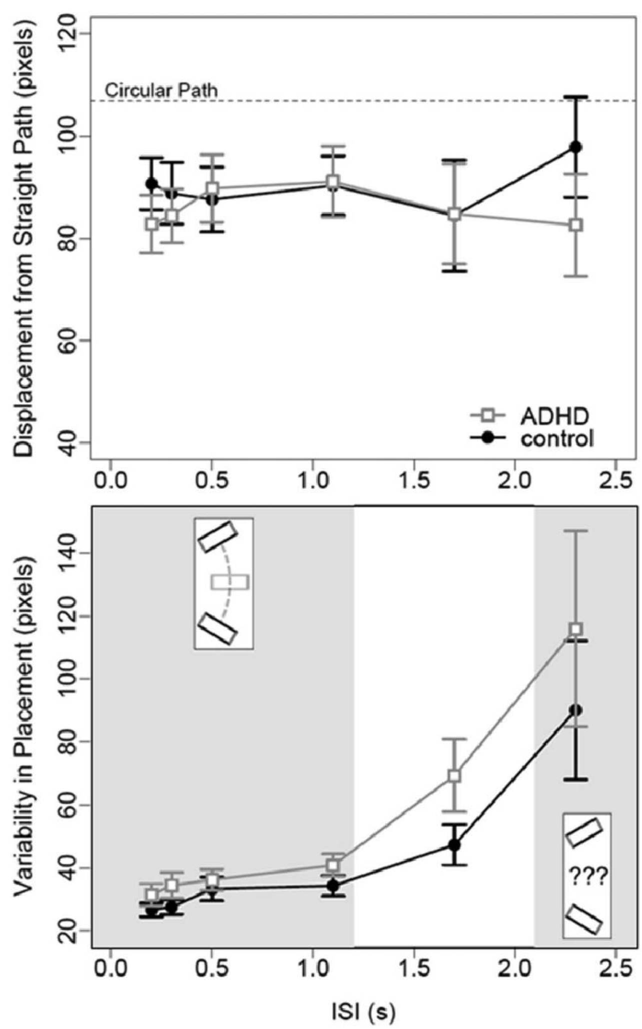

Figure 4. Means and standard deviations of displacement in the apparent motion task.

3. At this interval, the ADHD mean is larger than the control mean (higher variability in the ADHD group).

The percentage of resamples in which these are criteria are met is the effective *p* value—the probability that we obtain this specific result due to chance alone. The value we obtained from this resampling procedure was 0.039. This indicates that random chance would produce these results, higher variability in the group with ADHD only at 1.7 s and no group difference at the other five intervals, less than 4% of the time.

Notably, the interval of difference between the two groups in this experiment (1.7 seconds) is almost the same as the interval of difference found in Gilden and Marusich (2009), where the two groups showed differences in drumming performance only at intervals of 1.5 seconds.

Discussion

Using an apparent motion task in which we varied ISI to manipulate percept strength, we found that the ADHD and control groups performed similarly at the fastest and slowest ISIs. Only at the intermediate ISI of 1.7 seconds did the two groups differ; the ADHD group no longer experienced a consistent trajectory of motion, whereas the control group still did.

This finding provides strong support for the notion of contracted spans of temporal integration in ADHD. However, our study is limited, particularly in the participants sample, which was made up entirely of adult college students. Although the group scores on the CAARS:S-L were significantly different, the ADHD scores were not uniformly above 65, the score reflecting the 94th percentile and a commonly used criterion for ADHD in diagnostic settings. It may be that this sample does not reflect the most severe expressions of ADHD in the general population. In that case, our results may be seen as a conservative estimate of a possibly larger effect. Nevertheless, it would be beneficial to replicate these findings using a sample of more diverse ADHD participants in terms of symptom expression. By the same token, although sex and age were not associated with performance on this task, it may be useful to replicate this study with groups that are more closely matched on these variables.

Our results show remarkable consistency with the results of the rhythmic tapping study in Gilden and Marusich (2009). These two experiments provide convergent evidence that the span of temporal integration is foreshortened in ADHD cognition. This perspective of ADHD fundamentally as an impairment in time bears a surface similarity to a large body of work in the ADHD literature involving temporal processing. However, these two lines of work have different motivations and make substantially different predictions. For the most part in the extant literature, timing differences are viewed as a secondary consequence of another primary deficit in ADHD. For example, Barkley's (1997) theory of deficient behavioral inhibition predicts impaired working memory, which in turn predicts difficulties with tasks involving time. One aspect of the dual-pathway model (Sonuga-Barke, 2002) is delay aversion, the notion that individuals with ADHD make choices that decrease their experience of delay. It is argued that behavior resembling timing impairment can alternatively be interpreted as a preference for shorter intervals or for ending trials and experimental sessions early. In addition, recent work has proposed that ADHD may involve a pure timing deficit, separate from working memory or other impairments (Smith et al., 2002; Sonuga-Barke et al., 2010). All of these theories predict impairment in ADHD at all temporal intervals, and that the magnitude of the impairment will increase with increasing interval length. In contrast, our perspective predicts that ADHD and control behavior will be similar at both short and very long intervals, and that differences will only emerge at interval lengths that are too long for integration in ADHD but still within the maximum window of integration for controls.

The theories described above have led to a large body of work on timing and ADHD (see Toplak, Dockstader, & Tannock, 2006, for a review). Although many studies found group differences in timing process, the findings as a whole are quite inconsistent. Toplak et al. speculate that the inconsistencies across studies may be explained by the wide array of tasks, modalities, and time intervals assessed. Although these differences are certainly likely to contribute to the lack of consistency, a better explanation may be the explicit conception of time that is universal in these studies. Examples of the timing tasks typically used are duration discrimination, verbal estimation of time intervals, and the reproduction of single time intervals. These tasks require not just the perception of time, but also the explicit judgment of time. Explicit judgments can be made about any property—length, color, sweetness, pitch, and so forth. A task that uses explicit judgments may provide some information about the processing of the property to be judged, but it will be conflated with the processing involved in performing comparisons and making decisions based on these comparisons. There is abundant evidence that on any task at which individuals with ADHD make judgments about stimuli, they will generate data with increased variability relative to controls (see, e.g., Epstein et al., 2011; Klein, Wendling, Huettner, Ruder, & Peper, 2006). In light of this fact, it is unsurprising that previous studies of temporal processing in ADHD that use explicit judgments do not show consistent results, and that when they do find a group difference, it is often one of increased response variability in groups with ADHD (Toplak et al., 2006).

Our work is concerned with how time is used, not how it is judged. To summarize, the idea of altered delay gradients predicts ADHD impairment relative to normal controls only at a narrow range of temporal interval. The method by which this impairment can be assessed is through tasks that include time as a medium over which processes of integration occur, not as an explicit property to be judged and/or compared. This is a novel approach in the ADHD literature.

Our primary goal was to measure the maximum span of temporal bridges in normal adults and in adults with ADHD. To accomplish this goal, we designed an apparent motion experiment to measure the strength of temporal bridges across intervals of varying length. It was expected that integration strength would decay with increasing temporal interval in both groups, and that the adults with ADHD would demonstrate faster rates of decay than the control groups.

The current work benefits from two literatures: one on the consequences of delay of reinforcement upon learning, the other on the effects of dopamine upon learning. These two literatures lead to specific predictions about how dopamine dysfunction shrinks the maximum window for temporal integration across discrete events. By focusing the experimental work precisely on these windows, it was possible to design an experiment that spotlights the critical durations where ADHD and control behavior are distinguished. Given the reports that the sole consistent finding in experiments designed to show differences in ADHD executive function, attention, or inhibition is an increase in response variability across experimental conditions (Castellanos & Tannock, 2002; Toplak et al., 2006), our results here and in Gilden and Marusich (2009) suggest that ADHD might be more productively studied not as a disorder of attention or behavioral inhibition, but rather as a disorder that expresses itself by shortening the intervals over which temporal bridges may be built.

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