Towards Diagnostic Support of Hyperactivity in Adults with ADHD Using a Virtual Reality Based Continuous Performance Test and Motion Sensor Data

Tobias Delcour Jensen, Weronika Katarzyna Korbutt, Georgi Petrov Nedelev, and Brian Bemman(✉)

Department of Architecture, Design and Media Technology, Aalborg University, Rendsburggade 14, 9000 Aalborg, Denmark
bb@create.aau.dk

Abstract. Attention Deficit Hyperactivity Disorder (ADHD) is a neurodevelopmental condition that affects up to 5% of adults worldwide. Recent research has suggested that diagnostic support technologies for ADHD may be less effective for adults while many focus on identifying attention deficits, leaving assessments of hyperactivity largely to subjective criteria and observations by clinicians. In this paper, we present a virtual reality (VR) based continuous performance test (CPT) intended to provide users with an attention task, during which their physical movements are measured by the system's sensors, within an environment designed to resemble a real-world situation in which symptoms of ADHD would typically manifest. The design of this virtual environment was informed through a series of interviews and collaborative design sessions with clinicians. The VR-CPT system was tested using 20 adult participants with and without ADHD in order to determine which of any single or combined measures of motion by sensor (head-mounted display, arm controller, leg controller) and inertial variable (acceleration, velocity, angular acceleration, angular velocity) can be used to distinguish the two groups. Our results indicate that of our single measures, angular velocity across all sensors, angular acceleration of the leg controller, and velocity of the arm controller proved significant. Additionally, isolating high levels of mean motion activity, as measured by our combined inertial variables measure for a single sensor, proved insufficient at distinguishing between motion activity events corresponding to observations of physical movements considered indicative of hyperactivity and events considered non-indicative by a clinician.

Keywords: ADHD · Hyperactivity · Diagnostic support · Virtual reality · Continuous performance test · Motion sensor data

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1 Introduction

Attention Deficit Hyperactivity Disorder (ADHD) is an often debilitating chronic neurodevelopmental and behavioral disorder often identified in childhood and which frequently persists into adulthood [5]. The world-wide prevalence of ADHD is estimated to be approximately 5.3% in children and adolescents and anywhere between 3–5% in adults depending on reported demographics [8]. The primary clinical signs of ADHD, namely, impulsivity, inattention, and hyperactivity, manifest differently for adults and change with time. In the case of hyperactivity, while children may engage in, for example, uncontrolled running or climbing, adults may experience restlessness [8], excessive talking, an unorganized lifestyle, or the need to be constantly busy [22]. Due to the varied nature of how adult hyperactivity may manifest, doctors risk misdiagnosis [5].

Diagnosing ADHD typically involves lengthy assessments by psychologists and doctors through various clinical assessments (e.g., observations), self-reported rating scales, interviews, and computerized assessment tools, such as continuous performance tests [14]), with recommended diagnoses frequently supported by criteria specified in e.g., the Diagnostic and Statistical Manual of Mental Disorders (DSM-5) or the International Statistical Classification of Diseases and Related Health Problems (ICD-10) for ADHD [5]. Unfortunately, many of these assessments remain subjective in nature and their use differs from clinic to clinic, making rigorous and consistent diagnosis challenging. Moreover, many of the existing assessment tools based on computerized CPTs used in practice assess attention deficits and not hyperactivity while further having varying success with adults [3,14]. In recent years, however, widely available virtual reality (VR) and motion sensing technologies have shown promising results for use in diagnosis support for ADHD due, in particular, to their ability to provide more immersive experiences [1,9] and collect more sensitive measurements of bodily movement [12,18,19], respectively. A systematic integration of both a VR-based CPT and analysis of relevant bodily movements captured by various sensor measurements of a VR system for distinguishing adult ADHD hyperactivity, however, remains a problem worth continued exploration.

In this paper, we present a VR-based continuous performance test (VR-CPT) intended to provide users with an attention task, through which their physical arm, leg, and head movements are measured by the system's sensors, within an immersive environment designed to resemble a real-world situation in which symptoms of ADHD would typically manifest. Importantly, the design of this virtual environment was informed by consultations with expert clinicians having experience in the diagnosis of ADHD in adults. In our evaluation with the VR-CPT system, we carried out two tests in order to determine: (1) which of any single or combined measures of motion by sensor (head-mounted display (HMD), arm controller, leg controller) and inertial variable (acceleration, velocity, angular acceleration, angular velocity) can be used to distinguish between participants with and without ADHD, and (2) the extent to which significant motion activity events, as measured by our combined inertial variables measure for a single sensor, align with observations of physical movements indicative of

hyperactivity by clinicians. In Sect. 2, we describe the current process of clinically diagnosing ADHD and provide an overview of different technological approaches that have previously been employed in the screening and diagnosis of ADHD. Section 3 details the findings from our semi-structured interviews with expert clinicians that informed the design of our VR-CPT system environment and evaluation criteria. Section 4 explains the design of the virtual environment of our VR-CPT system based on these interviews and a series of collaborative design sessions with the same clinicians. In Sect. 5, we present the two aforementioned experiments carried out with participants with and without ADHD, and discuss our results. Section 6 concludes our findings and provides a brief discussion of possible future work.

2 Related Work

In this section, we provide an overview of ADHD clinical diagnosis and how various technologies, such as CPTs, sensors, and VR, have been used in the screening and diagnosis of ADHD.

2.1 ADHD and Clinical Diagnosis

Diagnoses of ADHD can be made along three dimensions – predominantly inattentive, predominantly hyperactive-impulsive, or combined – each of which characterizing a distinct set of symptoms [5]. Predominantly inattentive individuals have difficulty in maintaining focus, planning, and executing tasks while predominantly hyperactive-impulsive individuals are impulsive and exhibit excessive motor activity. Children diagnosed with the latter tend to run, jump, and climb constantly while adults exhibit restlessness, fidget with their hands and legs, or speak at inappropriate times in conversation. Other individuals who may not be one or the other, regularly exhibit symptoms of both inattentive and hyperactive-impulsive types. The process of diagnosing ADHD is often lengthy, subjective in nature, and varies from clinic to clinic [2,5]. Recommended diagnoses are made by clinicians following a variety of methods, including observations, self-reported rating scales (e.g., D.I.V.A. [15]), interviews, and various digital assessment technologies—the most common of these latter methods perhaps are computerized continuous performance tests (CPTs) [14]. In Europe, eventual diagnoses are supported by assessment criteria specified in the International Statistical Classification of Diseases and Related Health Problems (ICD-10) for ADHD [5] which identifies, among others, criteria such as an individual fidgeting with their hands or feet and persistent and excessive motor activity not consistent with the demands or context of society.

2.2 Relevant Diagnostic Support Technologies for ADHD

Digital technologies are increasingly being used as measures for assessment of ADHD and its symptoms [1], particularly those that relate to the motor system

[7]. Some technologies, such as computerized CPTs [14], are routinely used in practice by clinicians while others, such as various sensors and VR, have been proposed for diagnostic support for ADHD [6,11,13,16,18–21].

Computerized Continuous Performance Tests. Continuous performance tests (CPTs) are neuropsychological assessments for measuring sustained and selective attention typically by presenting an individual with a repetitive and lengthy task [14]. CPTs are commonly employed by clinicians for providing supplemental and quantifiable measurements of ADHD attention deficits, however, they are generally not applicable for diagnostic support of hyperactivity and have been shown to not be particularly effective with adults [3]. One popular commercialized example is the Conners' CPT3^{TM} [14] which uses various neuropsychological measures (e.g., omission/co-mission errors and reaction time) to aid in the identification of certain attention deficits and impulsivities. During the test, letters from A–Z are presented on a computer to users for a fixed duration of 250 ms each in six blocks each consisting of a distinct ordering of three sets of 20 letters which appear at varying inter-stimuli intervals of time (i.e., 1, 2, and 4 s) and where 'X' has a 10% probability of appearing and the remaining alphabet has a combined probability of 90%. The user is tasked with pushing the space-key on the keyboard whenever any letter except 'X' appears [1,10,14].

Sensors and Virtual Reality. Various basic sensing technologies for tracking motion (i.e., inertial sensors), such as accelerometers and gyroscopes, have shown promising potential for diagnostic support for ADHD [6,13,16,18,20]. In [18], for example, general motion sensor data collected from the dominant legs and waists of children during various physical activities was shown to be capable of distinguishing between those with and without ADHD with an accuracy of approx. 95%. Moreover, of these activities, motion data collected while completing a traditional CPT proved most significant. With respect to VR, various systems and their integrated sensors have been employed in research for diagnostic support for ADHD due primarily to their (1) recent widespread availability and low cost, (2) ability to provide immersive experiences that allow for symptoms of ADHD to arise more naturally when compared to clinical settings [1], and (3) ability to measure multiple sensory systems [11,19,21]. In early work by [21], a VR-based CPT placed in a virtual classroom was developed while systematic manipulations to visual and auditory distractions in this environment were evaluated, as these have been shown to be important factors in practice when diagnosing adolescent ADHD through a CPT [4]. In [19], researchers suggested that children with ADHD would show higher levels of hyperactivity while performing cognitive tasks within the virtual classroom [21]. Using data collected from the HMD, the children's physical body displacement in space proved significant in differentiating those with and without ADHD. In more recent work [12], researchers developed the Nesplora Aula, a VR-based CPT similarly set in a classroom environment with several distractions, and evaluated its ability to detect various attention deficits in children between 6 and 16 years old.

In follow-up work [11], the Nesplora Aquarium, based on the virtual environment in [12], was developed with assessments of adult attention and working memory in mind. In [2], the AULA Nesplora was used to discriminate between the sub-types of ADHD in children, showing promising results in discriminating between hyperactivity and impulsivity using the HMD to capture general motion activity. Despite these efforts, the actual physical movements captured by the motion activity of adults measured by such VR systems which prove significant in differentiating those with and without ADHD and whether these align or not with movements that would be indicative of hyperactivity by a clinician, have not been as well studied.

3 Clinical Interviews

In this section, we detail our interviews carried out with clinicians having expertise in the diagnosis of adults with ADHD and provide a brief discussion of our findings. We conclude with a list of subjective assessments and observations used in practice by these clinicians when diagnosing adults with ADHD hyperactivity which we have used to inform the design requirements of our VR-CPT system environment (discussed in Sect. 4) and the criteria for evaluating use of our system with respect to diagnostic support for symptoms of hyperactivity (discussed in Sect. 5).

3.1 Clinicians and Procedure

We carried out five, remote semi-structured interviews across various stages of our design process with two clinicians (Interviewee A: one 1-h long interview; Interviewee B: four 1-h long interviews) where one facilitator and two note-takers participated in each. The facilitator led the conversation using a set of pre-defined questions concerning, for example, how diagnoses of ADHD are made in the clinician's respective practice, what tools and methods are used to aid in this diagnosis, and what observations of an individual's behavior are most indicative of hyperactivity, among others. Additional interview questions and consultations were made in an attempt to increase the clinical validity of the design of our VR-CPT system and environment. Interviewee A has worked in Denmark as a neuropsychology clinician for over five years diagnosing ADHD in both adults and children, while Interviewee B is employed in the same country as a psychologist in a facility focused on diagnosing attention disorders in adults.

3.2 Clinician Criteria For Assessing Hyperactivity in Practice

Responses from both interviewees were analyzed by the two note-takers using qualitative coding and indicated that a variety of approaches to the diagnosis of ADHD in adults, in terms of both methodology and tools, are employed in practice. Both clinicians noted the importance of digital CPTs to their diagnosis process with Interviewee B noting that in their facility, adults with ADHD are

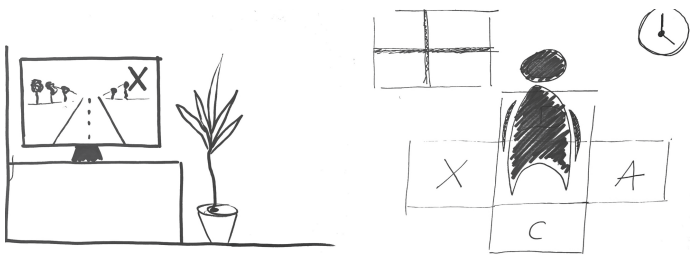
Table 1. Seven subjective assessments and observations of ADHD hyperactivity used in practice by two interviewed clinicians.

Category	Assess./Obs.	Explanation	Source	Code
Motion activity	1. Restless hands or feet	Often fidgets with hands or feet or squirms on seat	ICD-10	I1
	2. General motor activity	Persistent and excessive motor activity not modified by social context or demands	ICD-10	I2
	3. Movement & ticks	How many times they move, have ticks, etc.	Clinical	C3
	4. Excessive energy	So much energy that you always need to do something	Clinical	C4
Verbal patterns	5. Talking loudly	How loud they speak	Clinical	C5
Eye activity	6. Eye activity	How many times they look other places	Clinical	C6
	7. Head movement	How many times they look other places and move their head	Clinical	C7

observed while conducting a Conners' CPT. However, they clarified that such tools are unable to adequately assess hyperactivity and therefore diagnoses must rely on observations and subjective assessments, such as those suggested in the ICD-10 and other criteria the clinician feels are important based on their experience and expertise. Additionally, it was clear that the tools used in diagnostic support differ from clinic to clinic and often times those developed for children are used with adults. With respect to making these assessments, the interviewees reaffirmed that adults with hyperactivity may learn to control their symptoms in test environments, often making it difficult to assess. Interviewee B suggested, in particular, that such controlled behavior in test environments could potentially be addressed by testing people in situations that better approximate the real-world and everyday scenarios. The importance of employing a CPT centered on an attention-based task when assessing hyperactivity was clarified by both interviewees through the suggestion that those individuals whose impulsivity was triggered by a certain task or a situation were also more prone to exhibit hyperactive behaviours.

The findings from these interviews suggest the need for improved and reliable digital tools for measuring hyperactivity in particular as well as better clarity regarding the observations that prove useful in practice when assessing such symptoms in individuals when completing CPTs and attention-based tasks. For these reasons, we have compiled a list of the subjective assessments and observations used by the interviewees when diagnosing adults with a hyperactive-impulsivity dominant sub-type of ADHD. Some of these assessments and observations are found in the ICD-10 while others were developed by the clinicians themselves based on their own experiences in practice. Table 1 shows the seven subjective assessments and observations of ADHD hyperactivity used in practice by our two interviewed clinicians – grouped into three categories of motion activity, verbal patterns, and eye activity as well as whether each is found in

the ICD-10 or comes from the clinicians themselves. Note in Table 1 that two of the assessments and observations (i.e., I1 and I2) are found in the ICD-10 questionnaire and the remaining four (i.e., C1, C2, C3, C4) were devised by the clinicians. Collectively, these assessments and observations, combined with our interview findings, are used to inform the design requirements of our VR-CPT system and its environment as well as the criteria used to evaluate use of our system with respect to diagnostic support for symptoms of hyperactivity.



(a) CPT letters appear on the TV in a living room with the user pressing a button.

(b) CPT letters appear on the floor with the user stepping on the tile.

Fig. 1. Initial conceptual designs of the virtual CPT and environment of our VR-CPT system illustrating two different virtual environments, types of CPT, and modes of user interaction.

4 Design of the VR-CPT System and Environment

This section provides an overview of how the virtual CPT and environment of our VR-CPT system was designed in consultation with expert clinicians who provided essential feedback on initial design concepts concerning the requirements of the virtual environment, type of CPT, and mode of user interaction with the CPT.

4.1 Virtual CPT and Environment

The design process for our VR-CPT virtual environment consisted of a design sprint in which a number of basic sketches were generated and narrowed down according to the following four design requirements: (1) a CPT must be integrated tightly into the virtual environment, (2) the virtual environment must be familiar to the user, (3) the CPT and virtual environment must allow for the collection of motion data, such as head, hand, and leg movements, and (4) the type of interaction e.g., stepping, pointing, or pressing a button, must be both explicit to the user and appropriate for the CPT. Figure 1 shows two of the four narrowed down initial design concepts for the virtual CPT and environment of the VR-CPT system. Note in Fig. 1 that each initial design concept illustrates a different virtual environment, type of CPT, and mode of user interaction, with

a living room and the CPT visible on a TV requiring a button press in (a) and an empty room with the CPT visible on the floor requiring stepping in (b). The other two initial design concepts featured an abstract space in which CPT letters float in the immediate field of view and require a pointing motion as well as an outdoor space in which CPT letters appear in the distant night sky as star constellations.

Fig. 2. Final design of the VR-CPT system environment from the point-of-view of the user showing a familiar virtual living room and the letter, 'R', from the virtual Connors' CPT displayed on the black screen visible in the mid-ground.

Collectively, these four initial design concepts were presented to the expert clinicians from Sect. 3 and through a series of consultations and collaborative design sessions, one concept, one type of CPT, and one mode of interaction i.e., the living room with letters appearing at a fixed position in the mid-ground of the user's point-of-view and a button press (shown in Fig. 1(a)), were chosen. The additional following design requirements were devised as a result: (1) the user should be in a seated position, (2) environmental distractions should be present, both in auditory and visual form, and (3) the CPT should be based on a Conners' CPT since this is the test currently employed by the clinicians. With respect to requirement (1), the clinicians noted that such a system would be better aligned with current clinical practice in which CPTs are carried out while sitting and it would be easier to see movement patterns in a position where the user is somewhat restricted in their overall body movement. Regarding requirement (2), visual and auditory distractions for the user can enhance the presence of hyperactivity symptoms during a CPT as distractions are often present in real-life situations where symptoms are more likely to manifest.

Figure 2 shows the final design and implementation of the VR-CPT system environment based on the chosen initial design concept, type of CPT, mode of interaction (i.e., Fig. 1(a)), and additional design requirements expressed by the clinicians.[1] Note in the final design that the user is seated on a sofa in a familiar living room virtual environment while letters of a virtual Connors'

[1] The complete code for the VR-CPT system can be found in the following repository: https://github.com/GeorgiNedelev/Hyperactivity-screening-tool-for-adults-with-ADHD.

CPT are displayed on the black screen in the mid-ground. While the CPT is being completed, there are two auditory and visual distractions (suggested by Interviewee B) which appear in the virtual environment: a cat and a bus. The cat meows and moves back and forth in the foreground from the right hand side wall to the window every 50 s while the bus drives up and down a street in the background visible from the window every two minutes with a corresponding sound of an engine.

5 Evaluation

In this section, we discuss the two experiments involving participants with and without ADHD when tasked with completing the virtual CPT using our VR-CPT system. Recall that the first experiment was carried out in order to determine which of any single or combined measures of motion by sensor (HMD, arm controller, leg controller) and inertial variable (acceleration, velocity, angular acceleration, angular velocity) can be used to distinguish between these two groups of participants. The second experiment was carried out in order to determine the extent to which significant motion activity events, as measured by our combined inertial variables measure for a single sensor, align with observations of physical movements indicative of hyperactivity by clinicians.

5.1 Sensor Data Collection

The data collected by our VR-CPT system in the two experiments include min-max normalized x, y, z vector value (excluding direction) sums for the inertial variables of acceleration (m/s), velocity (m/s), angular acceleration (deg./s), angular velocity (deg./s)[2] as measured by an Oculus Quest [17] HMD and its two handheld controllers for each of the four subjective assessments and observations of motion activity from Table 1 (i.e., restless hands or feet, general motion activity, movement and ticks, and excessive energy), leaving out the two categories of verbal patterns and eye activity. The data for each of these measurements was recorded at a maximum variable sample rate of approximately 30 samples per second, fluctuating slightly due to various hardware latencies. This means, however, that for two testing sessions with users lasting for equal durations of time, the number of data points collected may be different.

5.2 Experiment 1

Our first experiment was a two sample independent measures design where participants with and without ADHD were asked to complete the virtual CPT using

[2] A given three-dimensional sensor data point, p, is represented as $\langle |x|, |y|, |z| \rangle$ where $|.|$ denotes the absolute value and x, y, z are the coordinate values of the vector along their respective dimension. These non-negative coordinate values for p are summed to provide a single, instantaneous data point for each sensor which forms the basis of the data we use in the sets of combined sensor and variable measurements reported in our evaluation.

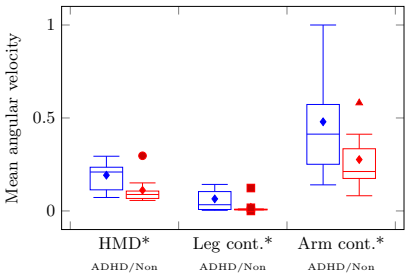


Fig. 3. Motion sensor measurements of mean angular velocity ('single sensor – single variable') from participants with and without ADHD collected by our VR-CPT system for each sensor (HMD, leg controller, and arm controller) during a virtual CPT. Asterisks (i.e., '*') denote statistically significant differences.

our VR-CPT system (discussed in Sect. 4). The purpose of this experiment was to determine whether there was any statistically significant difference between the two participant groups along the collections of data present in the following three combinations: (1) the mean values of a single measurement variable (acceleration, velocity, angular acceleration, or angular velocity) by a single sensor (HMD, arm controller, or leg controller) i.e., $4 \times 3 = 12$ 'single sensor – single variable' measurements, (2) the mean values of the sum of all measurement variables by a single sensor (i.e., three 'single sensor – all variables' measurements), and (3) the mean values of the sums of all mean measurements by all sensors (i.e., one 'all sensors – all variables' measurement). In all, we have tested 16 different measurements.

Participants and Procedure. We collected data from 20 adult volunteer participants split equally into two groups consisting of those either having a diagnosis of ADHD or not having a diagnosis of ADHD. All participants in the first group confirmed verbally that they had received a diagnosis of ADHD from a doctor or psychiatrist and all participants in the second group confirmed verbally that they had not received a diagnosis of ADHD nor had any underlying mental disorder. Eight participants with ADHD were recruited on social media groups recommended by clinicians experienced in diagnosing adult ADHD while the remaining two were recruited with the help of our interviewed clinicians (discussed in Sect. 3). The ten participants without ADHD were recruited similarly using general social media platforms. The data collected from all participants was anonymous motion sensor data concerning the movements of their head, one arm, and one leg as well as an indication of their dominant hand and diagnosis status. There was one left handed participant and the remaining 19 were right handed. An additional set of data in the form of anonymous audio-video recordings was collected from some participants who provided consent. No other personal data about the participants (e.g., age, gender, or occupation) was recorded. All data was collected in compliance with both EU GDP regulations and the participating university's protocol for carrying out non-clinical user testing with human participants.

Table 2. Independent two samples t-test results for all 16 motion sensor measurements of participants with and without ADHD collected by our VR-CPT system following the completion of a virtual CPT. Statistically significant results are indicated in boldface and with an asterisk (i.e., '*').

Measurements	*t*-value	*p*-value
Single sensor – single variable		
Acceleration HMD	1.399	0.179
Velocity HMD	1.941	0.068
Angular acceleration HMD	1.860	0.079
Angular velocity HMD	2.537	**0.021***
Acceleration leg controller	1.994	0.061
Velocity leg controller	1.555	0.137
Angular acceleration leg controller	2.263	**0.036***
Angular velocity leg controller	2.172	**0.043***
Acceleration arm controller	1.959	0.066
Velocity arm controller	2.595	**0.018***
Angular acceleration arm controller	1.737	0.099
Angular velocity arm controller	2.465	**0.024***

Measurements	*t*-value	*p*-value
Single sensor – all variables		
HMD motion activity	2.028	0.058
Leg controller motion activity	1.980	0.063
Arm controller motion activity	2.231	**0.039***
All sensors – all variables		
Overall motion activity	2.326	**0.032***

The experiment was carried out in a controlled and isolated environment over the course of seven days under the same conditions for each participant. Participants took part in the experiment individually and were asked to sign a consent form before they were permitted to begin. There were two types of consent forms allowing for either collection of anonymous audio-video recording and sensor data or only collection of anonymous motion sensor data. The participant was seated in the center of the room facing the direction of the virtual CPT, while a facilitator was located to the left of the participant and was responsible for introducing the participants to the test. Prior to the start of the test, the right controller button of the system was shown to the participants by the facilitator to ensure that they knew how to interact with the CPT, and then this controller was placed in their dominant hand. The facilitator ensured a proper fit of the HMD on the participant and the left controller was attached firmly to the leg opposite of their dominant hand. The placement of the controller positioned on the leg was due to limitations of the devices, as in some cases, if one controller hovers above the other the tracking of the controllers is lost. No irregular tracking behaviors (e.g., dropped controller or lost connection) were observed. Before each test, the point of view of the participant was reset to make sure all of the participants began with the same view. Participants were given one minute to look around in order to get familiar with their virtual surroundings and then informed of the environment by the facilitator and instructed on how to carry out the CPT. When participants felt ready, they were told to start the test by pressing the right controller button and afterwards whenever they see a letter other than 'X' on the screen. The number of stimuli presented in the CPT was reduced by half when compared to the number found in the original Connors' CPT (i.e., three blocks of 60 stimuli each) in order to minimize risk of VR sickness. Thus, the duration of each test was seven minutes, covering

the time beginning from the first button press and ending with the moment the participant pressed the button on the controller for the final stimulus of the test.

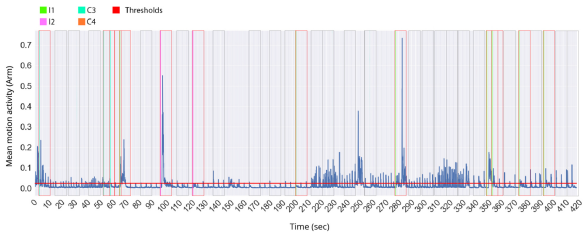
Results and Discussion. All 16 mean participant motion sensor measurements were approximately normally distributed and met the additional underlying assumptions of an independent samples Student's t-test. Table 2 shows the t-test results from Experiment 1 for all 16 motion sensor measurements divided into the three measurement types (i.e., 'single sensor – single variable', 'single sensor – all variables', and 'all sensors – all variables'). Note in Table 2 that in the 'single sensor – single variable' collections of data, the mean motion sensor measurements of angular velocity for all sensors, velocity of the arm controller, and angular acceleration of the leg controller proved to be significantly different between the groups (i.e., $p < 0.05$). Moreover, the difference in mean motion activity measurements for the arm controller under the 'single sensor – all variables' collections of data also proved significant (i.e., $p < 0.04$). In contrast to previous work [19], the differences in the mean overall motion activity measurement proved to be statistically significant ($p < 0.04$). Figure 3 shows boxplots illustrating the statistically significant motion sensor measurements of mean angular velocity ('single sensor – single variable') from participants with and without ADHD collected by our VR-CPT system for each sensor (HMD, leg controller, and arm controller). For all sensors, we can see that the mean and median of mean angular velocities of participants with ADHD were higher and the spread of values was greater when compared to participants without ADHD – indicating that the participants with ADHD exhibited more varied physical movements that were generally either more active or 'sharper' in their rotations in space. What exactly these physical movements may have been will be looked at in greater detail in the following experiment.

5.3 Experiment 2

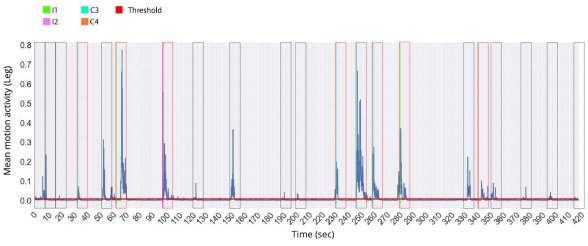
In our second exploratory experiment, we established a threshold in the motion activity ('single sensor – all variables') of participants with ADHD in order to isolate significant events and used precision and recall as measures to assess the extent to which these significant motion activity events align with observations of physical movements indicative of hyperactivity by clinicians. In our analysis, significant events are those which have motion activity above this threshold – an assumption that movements indicative of hyperactivity in individuals with ADHD have generally higher mean levels of motion activity than both movements which are not indicative of hyperactivity in these same individuals and movements that are made by individuals without ADHD.

Participants and Procedure. We collected anonymous audio-video recordings from eight of the participants with ADHD who participated in Experiment 1 and who provided consent for both the collection of anonymous motion sensor data and anonymous audio-video recording. Each recording was 7 min long,

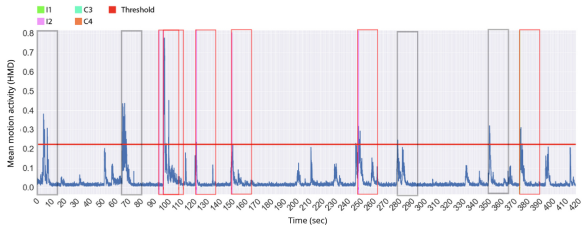
corresponding to the duration of the virtual CPT, and contained the seated profile view of the entire participant's body with the face obscured by the HMD. Recordings were provided to one of the interviewed clinicians (from Sect. 3) who agreed to participate and was asked to identify any moments in the recordings when participants exhibited signs which would indicate potential symptoms of hyperactivity, just as they would normally do in their daily practice when making a diagnosis in person. Both the types of observations (e.g., 'restless arm', 'scratches neck', or 'speaking aloud') and times at which they occurred in the recording were noted by the clinician and provided to the experimenters.



(a) Arm controller.



(b) Leg controller.



(c) HMD sensor.

Fig. 4. Mean motion activity ('single sensor – all variables') of a participant with ADHD as measured by all sensors (HMD, arm controller, leg controller) of our VR-CPT system while completing a virtual CPT. Clinician annotations of four motion activity subjective assessments and observations of ADHD hyperactivity (i.e., I1, I2, C3, and C4) are indicated with vertical colored lines and the vertical threshold is indicated with the horizontal red line. (Color figure online)

Results and Discussion. Of the eight participant recordings, our single participating clinician provided complete annotations for one participant with ADHD (due simply to time and resource constraints), so we will provide an analysis consisting of only the motion activity for this single participant. Figure 4 shows the mean motion activity of this participant as measured by the combined inertial variables measure for each of the sensors ('single sensor – all variables') from our VR-CPT system while completing the virtual CPT. In Fig. 4, we have established a vertical threshold (shown by the horizontal red line) above which indicates significant events of high mean motion activity. The vertical threshold was defined by the lowest occurring peak in the mean motion activity for each sensor that corresponds to a movement which the clinician annotated as being indicative of hyperactivity and differs from sensor to sensor. Additional horizontal thresholds were set to four second windows within which only a single motion event would be considered to occur and was defined according to the longest duration movement indicative of hyperactivity according to the clinician. Ideally, only mean motion activity events that appear both above the vertical threshold and within the horizontal thresholds would be movements identified by the clinician, however, this turns out not to be the case. Colored boxes (excluding grey) indicate significant motion activity events that align with annotations made by the clinician while grey boxes indicate significant motion activity events that do not. Some significant motion activity events which do not have any boxes (e.g., at 40 and 150 s in Fig. 4(a)) are due to sympathetic movements from other parts of the body and not due to the part of the body in which the given sensor was attached. For assessing the extent to which these movements align with significant events in motion activity, we consider the clinicians' time-stamped annotations (i.e., I1, I2, C3, and C4) as a ground truth and all events in mean motion activity above the vertical threshold and within the horizontal thresholds (i.e., the colored and grey boxes) as examples which require classification as either being 'indicative' or 'not indicative'.

Of all 35 significant arm motion activity events identified according to our thresholds, there were 12 annotated instances of indicative arm movements, resulting in a precision of $pr = 0.3428$ and recall of $r = 1$. There were 21 significant leg motion activity events and 8 annotated instances of indicative leg movements, resulting in a precision of $pr = 0.3809$ and recall of $r = 1$. There were only 10 significant HMD motion activity events and 6 annotated instances of indicative head movements, resulting in a precision of $pr = 0.6$ and recall of $r = 1$. Our relatively low levels of precision indicate that there are relatively many significant motion activity events (i.e., those having high levels of mean motion activity) but only a rather small number of these are actually physical movements indicative of hyperactivity according to our method for setting thresholds. This indicates that there are nuances to indicative physical movements that are not necessarily captured by considering only high levels of mean motion activity (as measured by our 'single sensor – all variables' measure) or motion activity within four second windows. One will further note that we have achieved perfect recall for the significant motion activity events in each sensor

due to the way in which we have chosen our vertical threshold based on the clinician's annotations such that no false negatives are present. While this threshold served well in our analysis for a single participant, such thresholds would likely vary from participant to participant and need to be learned from the data in order to remain reliable. Regardless, the overall low precision indicates that hard thresholds will be unlikely to capture the nuances, either in time or level of motion activity, of indicative physical movements. Some other method, perhaps, relying on machine learning, may be better able to differentiate those significant motion activity events that are indicative from those that are not.

6 Conclusion and Future Work

This paper presented the VR-CPT system—a virtual continuous performance test and environment—designed in consultation with expert clinicians that uses motion sensor data to aid in diagnosis support for adult ADHD. In our evaluation with this system, angular velocity of all single sensor measurements (HMD, arm controller, and leg controller), velocity of the arm controller, and angular acceleration of the leg controller proved most promising in distinguishing between participants with and without ADHD. Moreover, the mean motion activity ('single sensor – all variables') of the arm controller and the overall mean motion activity ('all sensors – all variables') from participants proved significant. In our exploratory follow-up experiment, relatively low precision and perfect recall in classification indicated that setting vertical thresholds based on high levels of mean motion activity ('single sensor – all variables') may be an effective method for helping to isolate events indicative of hyperactivity from non-indicative events having low levels of mean motion activity but that such thresholds alone are insufficient in distinguishing between indicative events and non-indicative events all having high levels of mean motion activity. Collectively, these results provide further promising potential for the use of motion sensor data to support clinical diagnoses of ADHD but that distinguishing relevant physical movements from non-relevant ones remains challenging. In future work, it would be worthwhile to experiment with different virtual environments and existing distractions that might better arouse symptoms of hyperactivity. It would also be interesting to explore eye-tracking technologies and various audio analysis methods as means for investigating the non-motion activity categories of subjective clinician assessments and observations not studied here. Finally, given the amount of data collected by the VR-CPT system, it would be useful to explore different machine learning methods for providing possibly better diagnostic support of individuals with ADHD based on their physical movements, possibly through further consultation with multiple experts to provide inter-coder agreed annotations necessary for training such algorithms and making more reliable conclusions.

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