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Impairments of interpersonal synchrony evident in attention deficit hyperactivity disorder (ADHD)

Hila Z. Gvirts Problovski[a,*], David Lavi[a], Roi Yozevitch[c], Mor Sherman[a], Yael Hagay[a], Anat Dahan[b]

[a] Department of Behavioral Sciences and Psychology, Ariel University, Israel
[b] Braude College of Engineering, Israel
[c] Department of Computer Science Holon Institue of Technology, Israel

A R T I C L E I N F O

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A B S T R A C T

In addition to well-known attention deficiencies, attention deficit hyperactivity disorder (ADHD) is accompanied by deficiencies in social cognition. Both intentional and spontaneous interpersonal synchrony have been found to be an essential part of successful human interaction. Here, we used a novel paradigm to assess intentional and spontaneous interpersonal synchrony in adults with and without ADHD. Our data indicate that intentional interpersonal synchrony is reduced in ADHD, whereas spontaneous interpersonal synchrony remains intact. These results suggest that a dysfunctional pattern of interpersonal synchrony may account for interpersonal difficulties in ADHD.

1. Introduction

It has been demonstrated that children with ADHD display inadequate social behavior (Nijmeijer et al., 2008) and suffer from social problems in reciprocal relationships (Rokeach & Wiener, 2017). Notably, these symptoms tend to persist over the lifespan of the disorder, as adults with ADHD display friendship problems, poorer social interactions (Kooij et al., 2010), loneliness (Philipsen et al., 2009), poorer intimate relationships, and marital adjustments (Eakin et al., 2004), collectively reflecting their difficulties in social interaction. Previous studies on social cognition in ADHD have been conducted mostly with children with ADHD. Studies have shown impairments in empathy and Theory of Mind (ToM) functioning in children with ADHD (Maoz, Gvirts, Sheffer, & Bloch, 2017; Pineda-Alhucema, Aristizabal, Escudero-Cabarcas, Acosta-López, & Vélez, 2018). Children with ADHD showed significantly lower levels of self-reported empathy than children in a control group on the interpersonal reactivity index (IRI), a self-reported empathy questionnaire. In addition, they showed impairments in ToM as measured by the “faux-pas” recognition task (Maoz, Gvirts, Sheffer, & Bloch, 2019). Although some of these social impairments persist over time (Abdel-Hamid et al., 2019; Bora & Pantelis, 2016), the specific social cognition deficits in adults with ADHD are yet to be determined.

One fundamental aspect of social behavior that may be dysfunctional in ADHD is Interpersonal Synchrony (IS). IS refers to two or more individuals performing time-coordinated actions (e.g., drumming at the same time or two people walking at a coordinated rate) (Delaherche et al., 2012). Given that IS requires the ability to anticipate the other’s movement and understand their intention, so that the movement can be coordinated in time, it is not surprising that IS was found to be positively associated with Theory of Mind (Baimel, Severson, Baron, & Birch, 2015) and empathy (Novembre, Mitsopoulos, & Keller, 2019). Synchrony plays a pivotal role in parent-child interaction, starting from consolidation of biological rhythms during pregnancy and continuing to symbolic exchange between parent and child (Feldman, 2007b). Importantly, IS continues to play a role in interactions throughout development (Semin & Cacioppo, 2008).

IS can emerge spontaneously and unconsciously during everyday social interactions such as when our footsteps unconsciously synchronize with our partner while walking together (Sylos-Labini, d’Avella, Lacquaniti, & Ivanenko, 2018) and during tasks performed in pairs (Varlet, Marin, Lagarde, & Bardy, 2011). Even when participants who saw each others’ movement were specifically instructed not to coordinate their movements, the movemens were unintentionally synchronized in the frequency domain (Issartel, Marin, & Cadopi, 2007). Spontaneous synchronization scores during conversation of body movement synchrony were shown to be associated with the degree of information

* Corresponding author at: Ramat HaGolan St 65, Ariel, Israel.
E-mail address: hilag@ariel.ac.il (H.Z. Gvirts Problovski).

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exchange (Tsuchiya et al., 2020). A time series analysis during joke-telling revealed that speaker and listener movements contained rhythms which were correlated in time and exhibited phase synchronization (Schmidt, Nie, Franco, & Richardson, 2014). Spontaneous synchronization also occurs when audience hand-clapping naturally synchronizes into a steady rhythm (Neda, Ravasz, Brechet, Vicsek, & Barabasi, 2000).

However, IS can also emerge intentionally as part of goal directed movement aimed at achieving the explicit social goal of synchronizing our movements with those of others. Dancing is an example of such an intentional IS. Dancers intentionally modify the timing of their rhythmic movements to accomplish the goal of synchronizing with other dancers. Notably, they acknowledge that their partners are sharing the same goal and that this shared intentionality is necessary for creating the cooperative effects of collective music and dance (Reddish, Fischer, & Bulbulia, 2013). It can be concluded that while both spontaneous and intentional IS involve joint actions, intentional IS requires greater allocation of attention to the interactive partner in order to achieve the synchronization.

Accumulating evidence indicates that IS encourages social bonding. Synchronized movement promotes feelings of affection and belonging (Hove & Risen, 2009), rapport (Vacharkulksemsuk & Fredrickson, 2012), trust (Launay, Dean, & Bailes, 2013) and empathy (Koehne, Hatri, Cacioppo, & Dziobek, 2016), as well as enhancing capacities for emotion regulation (MacLean et al., 2014). Importantly, even small movement synchrony (e.g., finger tapping) was found to increase feelings of affiliation towards the tapping partner (Valdesolo & DeSteno, 2011) and liking of the tapping partner (Hove & Risen, 2009). A growing body of evidence suggests that IS is linked to prosocial behaviors such as willingness to help a partner with whom someone has synchronized with (Cirelli, 2018a; Shamay-Tsoory, Saporta, Marton-Alper, & Gvirts, 2019) and this tendency is evident even in young infants(Cirelli, 2018b). Moving together was also found to increase collaboration, as measured by success in a joint-action task that required response to a partner's movements (Valdesolo, Ouyang, & DeSteno, 2010).

In light of the beneficial effects of IS, it is not surprising that reduced IS was found to be associated with deficits in social cognition, e.g., in schizophrenia (Lavelle, Healey, & McCabe, 2014) and in autism spectrum disorder (ASD) (Marsh et al., 2013), as it was suggested to be significantly associated with social skills (Brezis et al., 2017; Koehne et al., 2016). As noted above, previous findings showed that individuals diagnosed with ADHD demonstrate deficits in various components of social cognition including Theory Of Mind and perspective taking (Abdel-Hamid et al., 2019; Bora & Pantelis, 2016; Marton, Wiener, Rogers, Moore, & Tannock, 2009), with another distinct line of research showing that these components are positively associated with IS (Baimel, Birch, & Norenzayan, 2018; e.g., Baimel et al., 2015). Collectively, this line of evidence points to the possibility that social synchronization may prove useful in understanding the social problems characteristic of people with social deficits. However, studies focusing on IS in ADHD are currently lacking. It is important to understand whether the deficits of ADHD extend into behavioral synchrony because such a symptom could possibly be useful in ADHD diagnosis and therapy.

Here, we sought to further contribute to the understanding of the social cognition dimension of ADHD by investigating the ability of individuals diagnosed with ADHD to synchronize. In particular, we wanted to evaluate whether disruptions are evident in both intentional and spontaneous coordination.

To this end, we developed a novel computerized task which provides rich sources of data for measuring 3D IS, as it does not require holding a handle or a controller. In the task, the participant and the research assistant sit on two sides of a table (Brezis et al., 2017), with their hands

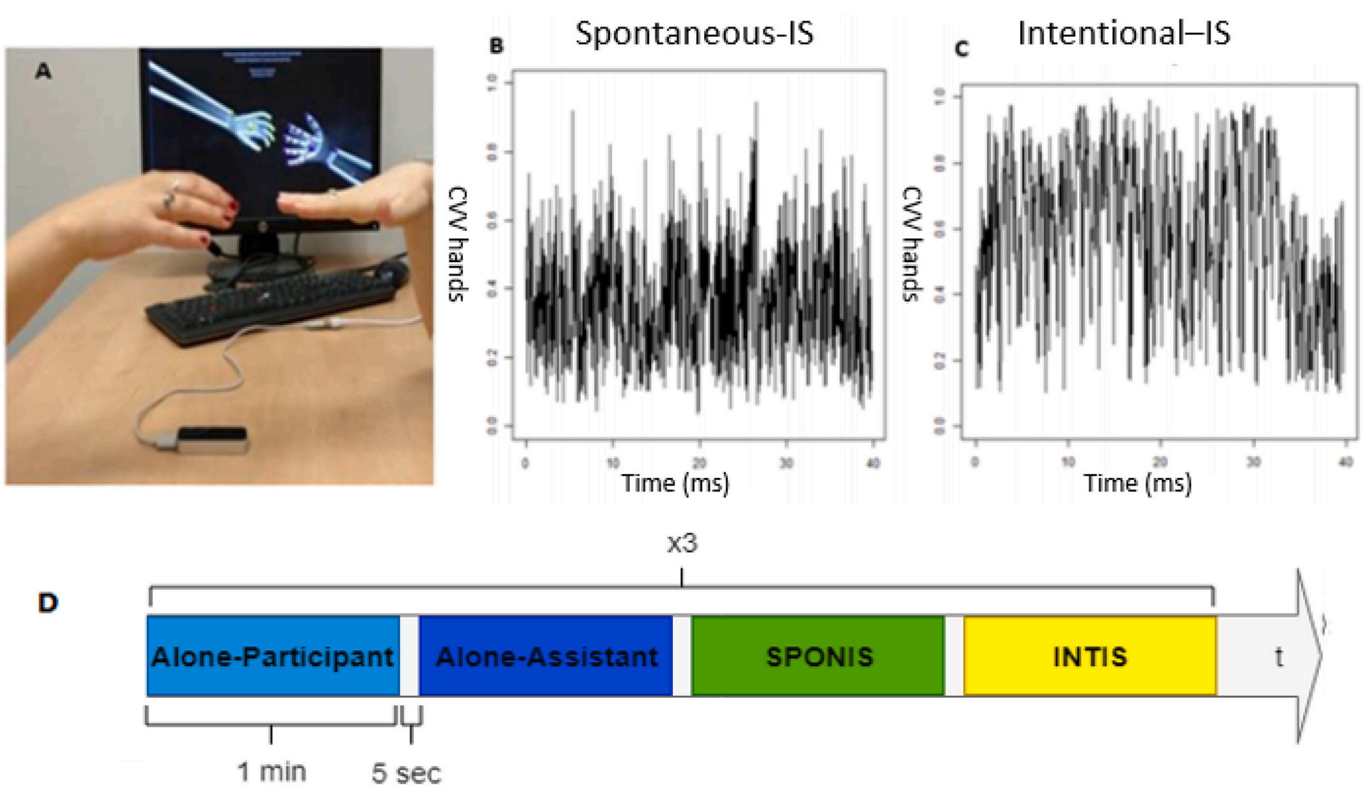

Fig. 1. (A) The task uses a Leap Motion controller depth 3D sensor, explicitly targeted to measure hand gestures. Data is extracted via the official System Development Kit (SDK). A Python logger was implemented, which reports among other parameters, the 3D position and velocity vectors. (B) CVV hand in Spontaneous – IS (SPONIS) trial. (C) CVV hand in Intentional – IS (INTIS). It can be seen that CVV values are higher in the intentional condition (D) The experiment comprised four types of trials that were given in the following order: (1,2) Alone-Participant/Alone-Assistant (3) Spontaneous (4) Intentional– IS (INTIS). Each condition was repeated 3 times. Each trial was repeated 3 times and lasted 1 min with a 5 s pause between conditions.

above a Leap Motion depth sensor. The participant and research assistant are instructed to move the palm of their hand together, as they keep it above the Leap Motion sensor (see Fig. 1A).

It is important to note that this novel task takes a slightly different approach to measure IS than that used in previous articles. More specifically, while existing methodologies to measure IS include a reduction of hand and body movements that naturally occur in three dimensions to one dimension, the novel task measures 3D naturalistic movements. One way by which IS was previously measured in one dimension is by using tasks that restrict the participant's movement to one dimension. For example, in the study by Schmidt and O'Brien (1997), two participants who sat side-by-side were instructed to swing a hand held pendulum. In more recent studies, participant movement was limited to the back and forth movement of a rocking chair (Marsh et al., 2013) or by moving handles across tracks (Noy, Dekel, & Alon, 2011). Another way by which IS was previously measured in one dimension is by using tasks that allow for a naturalistic movement, but reduce the IS measurement to a single dimension. For example, the study by Condon and Ogston (1966) involved human judges who used video recordings to evaluate whether temporal co-occurrence of actions such as body part movement and vocalization occurred. More recent studies have used video to analyze IS between participants that are not restricted to specific movement. However, the methodology that was used to calculate the level of IS did not account for the three dimensions of the movement separately. For example, Schmidt et al. (2012) developed a methodology where a computer algorithm calculated frame-to-frame pixel change information to assess the degree of activity and generate a time series of activity for each participant. The time series of two participants was then evaluated for similarity. Similarly, Motion Energy analysis was used for quantification of movement from recorded video-films (Ramseyer & Tschacher, 2014).

As noted earlier, in the current study we used a novel computerized task, which, as opposed to most previously developed tasks, does not restrict the participant's movement to one dimension. In addition, to calculate the level of IS, we employed a 3D measurement that evaluates the velocity of the three dimensions (Reiss et al., 2019). It is important to note, however, that although the study by Reiss et al. (2019) used the same three dimensions of IS measurement as in the present study, their paradigm requires the participants to hold a handle, whereas our novel task uses a Leap Motion depth sensor, and, thereby, allows measurement of naturalistic movements (without the need to hold a handle or a controller, see Fig. 1A).

Our first goal was to validate the new task; that is, to show that IS occurs in both spontaneous and intentional IS. Next, we compared task performance between a group of participants with ADHD and a group of healthy controls. We hypothesized that participants with ADHD would be less synchronized with the research assistant compared to healthy controls, particularly in intentional synchrony which requires greater allocation of attention. Moreover, we predicted that the level of ADHD symptoms would predict the level of synchrony in the task.

2. Methods

2.1. Participants

The study protocol was approved by the ethics committee of Ariel University. Informed consent was received from all participants. Fifty-five adult subjects (16 men and 39 women) were recruited to the current study. Twenty-five adult subjects diagnosed with ADHD were included in the experimental group and 30 healthy adult subjects were included in the control group (healthy controls).

Participants were recruited through advertisements both within Ariel University and in the community (using digital bulletin boards). We included right-handed participants between the ages of 19–30. Most of the participants were native speakers of Hebrew and all had at least twelve years of education and a high school diploma.

Inclusion criteria for the ADHD group included a clinical diagnosis of ADHD made by a clinician recognized by Ariel University (as in Dahan & Reiner, 2017). Exclusion criteria for both groups were history of neurological or psychiatric illness. For the healthy control group, exclusion criteria included previous ADHD diagnosis.

As shown in Table 1, there was no significant difference between the two groups in age, education or other demographic variables. However, as expected, ADHD symptoms were significantly higher in the ADHD group (see Table 2).

2.2. Materials

2.2.1. The interpersonal synchronization task

The task uses a Leap Motion controller depth 3D sensor, explicitly targeted to measure hand gestures (at 100 Hz). Data is extracted via the official System Development Kit (SDK). A Python logger was implemented, which reports, among other parameters, the 3D position and velocity vectors (see Appendix A).

This task provides rich sources of data for measuring 3D IS, as it does not require holding a handle or a controller (see Fig. 1A and Appendix B). During the task, the participant and the research assistant sit on two sides of a table, with their hands above a Leap Motion depth sensor (see Fig. 1A). Prior to performing the task, participants were instructed that their movements should be limited to an area above the sensor. Hand movement was recorded using the Leap Motion logger for both the participant and the research assistant.

To calculate the level of IS of each dyad, we computed the cosine of velocity vectors (CVV) (Reiss et al., 2019) for: (1) the hands (CVV hand) and (2) the arms (CVV arm). First, the data was pre-processed in each of the three spatial dimensions by spline smoothing. Each of these CVVs was then defined at time t as the cosine of the angle between the velocity vectors. For two individuals with velocity vectors Va [Vxa,Vya,Vza] and Vb [Vxb,Vyb,Vzb] at time t, the CVV is defined as: $CVVab(t) = \frac{\langle Va, Vb \rangle}{\|Va\|\|Vb\|}$ where $\|V\| = \sqrt{Vx^2 + Vy^2 + Vz^2}$ and $\langle V, W \rangle = VxWx + VyWy + VzWz$. Cosine similarity gives a simple measure of how similar two sets of values are, with a value of 1 if the velocity of the two participants are similar in all three dimensions. As the participants sat facing each other

Table 1
Demographic characteristics of subjects in the healthy control group and the ADHD group.

	Total Mean (SD)	Healthy control Mean (SD)	ADHD Mean (SD)	Statistical analysis
Age (years)	23.62 (2.33)	23.83 (2.19)	23.37 (2.51)	T(53) = 0.72, p = 0.47
Gender				
Male	29.1% (16)	33.3% (10)	24% (6)	$\chi^2(1) = 0.57$, p = 0.44
Female	70.9% (39)	66.7% (20)	76% (19)	
Marital status				
Married	12.7% (7)	16.7% (5)	8% (2)	$\chi^2(1) = 0.33$, p = 0.43
Single	87.3% (48)	83.3 (25)	92% (23)	
Native language				
Hebrew	89.1% (49)	90% (27)	88% (22)	$\chi^2(2) = 0.72$, p = 0.69
Russian	5.5% (3)	3.3% (1)	8% (2)	
Other languages	5.5% (3)	6.7% (2)	4% (1)	
Years of education	13.34 (1.56)	13.66 (1.64)	12.96 (1.39)	T(52.97) = 1.72, p = 0.09
Academic studies classification				
Social sciences	67.3%	56.7%	80%	$\chi^2(2) = 3.7$, p = 0.15
Exact sciences	30.9%	40%	20%	
Life sciences	1.8%	3.3%	0%	

Table 2
Clinical characteristics of subjects in the healthy control group and the ADHD group.

	Total	Healthy control	ADHD	Statistical analysis
CAARS score*	86.45 (32.8)	67.82 (17.58)	103.6 (34.47)	$t(53) = -4.58$**, $p < 0.01$
The type of medication				
Methylphenidate			19 (76%)	
Amphetamine			5 (20%)	
Lisdexamfetamine			1 (4%)	

* $p < 0.05$.
** $p < 0.01$.

their movements could be in the same direction in some planes (as up or down) and in opposite directions in others (as left or right). We therefore used the squared values of the CVV (CVV^2).

2.3. Procedure

After the informed consent process and eligibility screening, participants were introduced to the research assistant. Next, the participants and the research assistant performed the IS task. The participants then completed the Connor's Adult ADHD Rating Scale (CAARS) self-reporting of symptoms of attention deficit hyperactivity disorder (similar to Gvirts et al., 2017). Each participant sat at a table facing the research assistant. A Leap Motion controller depth 3D sensor was placed on the table between them (see Fig. 1A).

2.4. Design

The experiment comprised four types of trials: (1) Alone-Participant and (2) Alone-Assistant. During these trials, the participant/assistant is asked to move his/her hand freely over the Leap Motion controller, while the other turns his/her back. The data of the two types of Alone trial (Alone-Participant, Alone-Assistant) are analyzed as if they consisted of a face-to-face interaction. In the (3) Spontaneous IS (SPONIS) trials, the participant and assistant were facing each other. They were asked to move as freely as they wish, while in the (4) Intentional–IS (INTIS) trials, they were asked to move in synchronization (see Fig. 1D). Note that participants were invited to interpret synchronization as they understood it. In all trials, participants were not allowed to communicate verbally and the interaction between players was created with their movement.

The data of the two types of Alone trial (Alone-Participant, Alone-Assistant) was analyzed as if they consisted of a face-to-face interaction. The experiment comprised three types of conditions:

1) The control condition, consisting of data of the two types of Alone trial (Alone-Participant, Alone-Assistant).
2) In the SPONIS (Spontaneous IS)
3) In the INTIS (Intentional IS)

2.5. Statistical analysis

We conducted a repeated-measure two-way ANOVA, with condition (control, SPONTIS, INTIS) as the within-subject factor and group (ADHD/control) as the between-subject factor. Note that since the IS task is a novel one, our first goal was to validate that the task measures both spontaneous and intentional IS. Post-Hoc tests with Bonferroni correction were conducted to determine the nature of the main effect for condition. We expected these analyses to show that IS is higher in the INTIS condition and in the SPONIS condition as compared to control. We also expected this analysis to show that IS is higher in the INTIS condition as compared to SPONIS.

As noted above, our second goal was to examine whether ADHD is related to impaired spontaneous synchrony and intentional synchrony. Post-Hoc tests with Bonferroni correction were conducted to determine the nature of the interaction between condition and group.

Pearson correlations were carried out to examine the association between the level of ADHD symptoms (i.e., Conners' Score) and the level of IS in both conditions (INTIS and SPONTIS).

3. Results

3.1. CVV hand

The repeated-measure two-way ANOVA revealed a significant main effect for Condition ($F(2,106) = 25.340$, $p < 0.001$, $\eta_p^2 = 0.323$) and marginally significant main effect for Group ($F(1,53) = 3.813$, $p = 0.056$, $\eta_p^2 = 0.067$). Importantly, a significant Group by Condition interaction was found ($F(2,106) = 8.275$, $p < 0.005$, $\eta_p^2 = 0.135$).

3.2. CVV arms

The repeated-measure two-way ANOVA revealed a significant main effect for Condition ($F(2,106) = 26.834$, $p < 0.001$, $\eta_p^2 = 0.336$) and non-significant main effect for Group ($F(1,53) = 0.579$, $p > 0.05$, $\eta_p^2 = 0.011$). Importantly, a significant Group by Condition interaction was found ($F(2,106) = 9.035$, $p < 0.001$, $\eta_p^2 = 0.146$).

3.3. Task validation

3.3.1. CVV hand

Post-Hoc tests with Bonferroni correction confirmed that CVV hand was higher in INTIS as compared to control ($p < 0.001$) and in the SPONIS as compared to control ($p < 0.01$) and in the INTIS trial as compared to SPONIS ($p < 0.001$). Accordingly, we conclude that IS emerges both in the SPONIS and in the INTIS conditions (see Fig. 2A).

3.3.2. CVV arms

Post-Hoc tests with Bonferroni correction confirmed that CVV arms were higher in INTIS as compared to control ($p < 0.005$) and in the INTIS trial as compared to SPONIS ($p < 0.001$). However, there was no significant difference between the CVV arms in the SPONIS as compared to control ($p > 0.05$). Accordingly, we conclude that IS as measured by CVV arm emerges in the INTIS condition and to some extent in the SPONIS condition (see Fig. 2B).

3.4. Comparison of IS between HC and ADHD group

3.4.1. CVV hand

Post-Hoc tests with Bonferroni correction revealed a significant between-group (ADHD/Control) differences in CVV hand score in the INTIS condition ($p < 0.01$). However, in the SPONTIS condition and in the control condition there was no significant differences in CVV hand score between HCs and ADHD ($p > 0.05$ for both, see Fig. 3A), suggesting that ADHD is associated with deficits in intentional IS but not spontaneous IS.

3.4.2. CVV arm

Post-Hoc tests with Bonferroni correction revealed a significant between-group (ADHD/Control) differences in CVV arm score in the INITIS condition ($p < 0.005$). However, in the SPONIS condition and in the control condition there was no significant differences in CVV arm score between HCs and ADHD ($p > 0.05$ for both, see Fig. 3B), suggesting that ADHD is associated with deficits in intentional IS but not spontaneous IS.

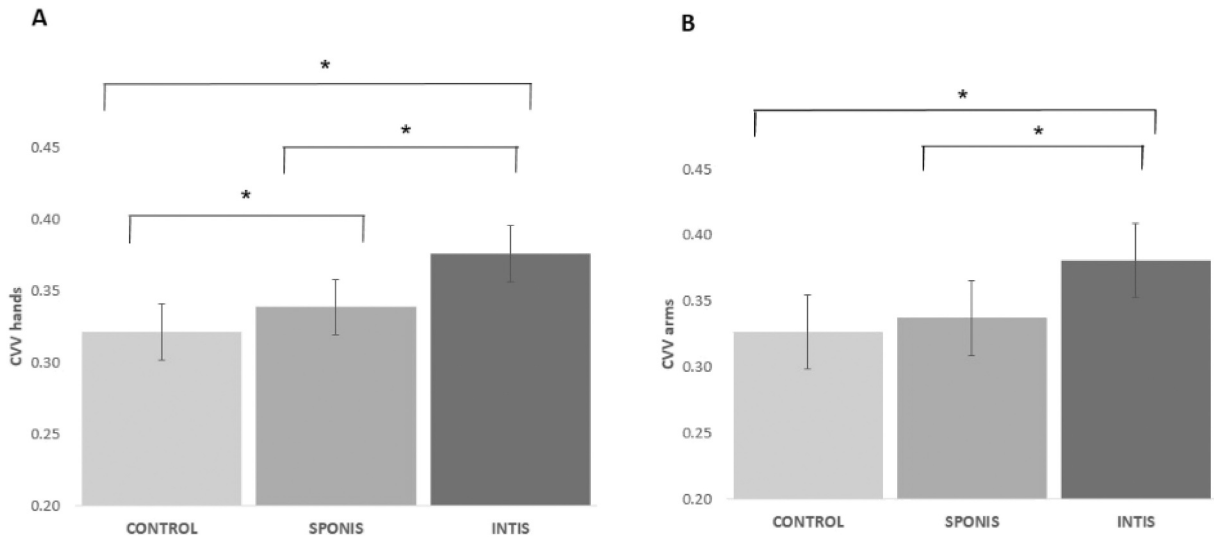

Fig. 2. Task validation – mean and standard error for each condition (control, SPONSIS, INTIS). Task performance is measured by (A) CVV hand and (B) CVV arm.

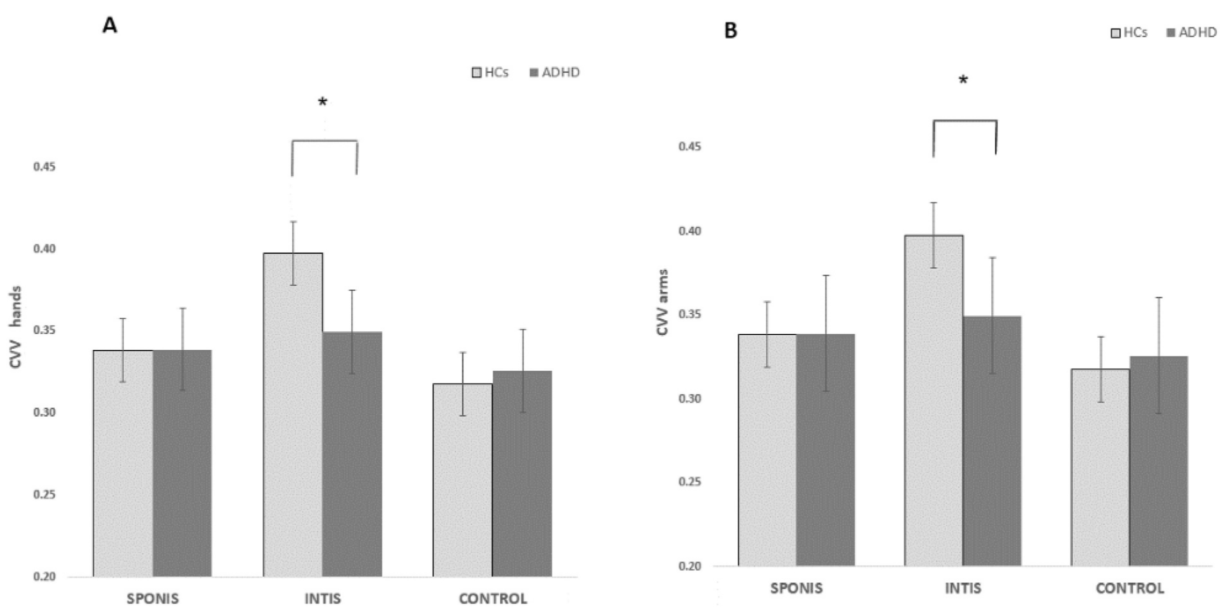

Fig. 3. Intentional IS (INTIS) is reduced in ADHD as indicated by (A) reduced CVV hand and reduced (B) CVV arm in comparison to control in INTIS condition.

3.5. *Association between IS and symptoms of ADHD*

Pearson correlations revealed a marginally significant negative association between ADHD symptoms and level of synchrony during INITIS condition ($r = -0.276$, $p = 0.057$) but not during SPONIS condition ($r = -0.107$, $p = 0.470$).

4. Discussion

The aim of the current study was to assess the ability of individuals diagnosed with ADHD to synchronize. To this end, we developed a novel task that measures both spontaneous and instructed IS in a face-to-face interaction. Our findings confirmed that the novel task measures both spontaneous and intentional IS. Importantly, comparison between a group of ADHD and a group of healthy controls revealed for the first time that social synchronization successfully differentiates adults with and without ADHD. In accordance with our hypothesis, participants with ADHD demonstrated a disruption in intentional synchronization, but not in spontaneous synchronization. Furthermore, while the association between the level of ADHD symptoms and the level of synchrony in the INTIS condition was marginally significant, no association was found between ADHD symptoms and level of spontaneous synchrony. These findings suggest that ADHD symptoms may partially reduce intentional synchronization but not spontaneous synchronization.

As discussed, synchronizing one's movements with another person is a crucial component in facilitating social connection. Notably, social synchronization deficit appears to be associated with other disorders that are also characterized by problems with social interactions, e.g., in schizophrenia (Lavelle et al., 2014) and in autism spectrum disorder (ASD) (Marsh et al., 2013), where IS was suggested to be significantly associated with social skills (Brezis et al., 2017; Koehne et al., 2016). From this perspective, our findings may be interpreted as further supporting the association between disruptions in IS and disorders that are characterized by deficits in social cognition. Given that many social interactions involve IS, and in light of the fact that IS was found to be associated with additional pro-social benefits including social bonding

(Cirelli, 2018a; Kokal, Engel, Kirschner, & Keysers, 2011; Ramseyer & Tschacher, 2014), it may be reasonable to suggest that difficulties in IS may underlie aberrant social behavior in ADHD.

From a developmental perspective, IS is thought to play a key role in the acquisition of social cognition skills during the early years of life (Feldman, 2007a, 2015). As noted earlier, we are not aware of previous studies that have directly assessed IS in ADHD. However, one finding relevant to the current study is that the extent of IS between mother and child is associated with the degree of functioning of the child with ADHD at preschool age (Healey, Gopin, Grossman, Campbell, & Halperin, 2010). Combined with our findings, this line of evidence suggests the possibility that dysfunction in the ability to synchronize with a caregiver persists into adulthood and may contribute to social cognition deficits in ADHD. Future research is required in order to determine if dysfunction in the ability to synchronize with a caregiver could increase the risk of developing ADHD in adulthood.

As mentioned above, while both spontaneous synchrony and intentional synchrony involve joint action, intentional synchrony seems to require greater allocation of social attention than spontaneous IS (Fitzpatrick et al., 2016). This idea is reinforced by a recent model which postulates that greater allocation of attention to interactive partners and social interaction may promote interpersonal synchrony (see: Gvirts & Perlmutter, 2019). Accordingly, we hypothesized that ADHD will be associated with aberrant performance in intentional IS. The results of the current study confirmed the hypothesis that individuals with ADHD showed impaired performance in the intentional synchrony condition, whereas spontaneous IS was found to be intact among these individuals. Interestingly, individuals with schizophrenia were also shown to have an IS deficit during intentional synchronization, but not during spontaneous IS (Varlet et al., 2012). By contrast, individuals with ASD show both spontaneous synchronization and intentional synchronization (Fitzpatrick et al., 2016). The results of these studies combined with the current research point to a dissociation between intentional and spontaneous IS and suggest the possibility that these two types of IS function independently and have distinct underlying mechanisms.

In this context, it is important to mention that the possibility that intentional IS and spontaneous IS may dissociate in psychopathological populations has been raised before (Fitzpatrick et al., 2016). These authors proposed that earlier onset of a disorder can be accounted for by more robust disruptions in IS. They further suggested that the fact that onset of ASD is much earlier (mostly within the first 36 months after birth) than onset of schizophrenia explains why individuals with ASD are associated with more robust disruptions. Given that onset of ADHD is similar to that of schizophrenia (that is, both are much later than onset of ASD), our findings may be interpreted as further supporting the link between age of onset of the disorder and development of the specific disruption in IS (intentional or spontaneous). Future research is warranted to explore these hypotheses by comparing performance during both types of IS between different diagnostic groups (defined by different age onset).

It is, therefore, possible that while impaired intentional IS may account for the ADHD and schizophrenic tendency for interpersonal dysfunction, spontaneous IS may account for the more substantial social cognition deficits observed in ASD.

This study should be interpreted in the context of several limitations. First, the diagnosis of ADHD was not confirmed by a standardized interview and we did not screen for comorbid disorders. Second, our results are correlative in nature and lack causal interpretation. Hence, the role interpersonal synchrony plays in the etiology of ADHD remains unresolved. Third, the sample size of each group (ADHD and control) is moderate and, therefore, larger studies are needed to further substantiate our findings. Fourth, although the research assistant was not blind to the diagnosis, the impact of this possible bias is lessened by the fact that the research assistant was blind to the research question. Finally, although the novel task allows measuring similarity of velocity without restricting the movement to one dimension, the limitation of using this novel measure is that it is hard to perform a direct comparison of the results with previous studies. Moreover, as we used the CVV^2 measure, it is not possible to analyze the pattern and direction of synchronization in each separate plane. Further research with more couples would lead to a more detailed analysis of the synchronization patterns in the different planes and directions.

Since, to our knowledge, the current study is the first to suggest dissociation of spontaneous and intentional facets of IS in ADHD, these findings should be regarded cautiously pending replication in a larger sample. In addition, future research should include comparisons with other clinical groups. Nonetheless, the current study provides evidence that, compared with controls, individuals with ADHD exhibit a dysfunctional pattern of IS, with decreased intentional IS and intact spontaneous IS.

CRediT authorship contribution statement

Dr. Hila Gvirts designed the study, managed the statistical analysis and wrote the first draft of the manuscript. Dr. Dahan helped analyzing the data and revised the manuscript and developed the task. Mr., Lavi, Miss Sherman and Miss Hagay helped in gathering the data and reviewing the literature. Dr. Yozevitch developed the task and measurements (together with Dr. Dahan).

Acknowledgements

We thank Roman Koifman for implementing and sharing the software for assessing interpersonal synchronization according to the leap motion data.

Appendix A. The Leap Motion logger

The Leap Motion controller

The Leap Motion controller is a unique 3D depth camera device which can track and record exact human hand postures. Different from the Microsoft Kinect, the Leap Motion is explicitly targeted to hand gesture recognition and directly computes the position vector of the fingertips and hand orientation. While the amount of information is limited compared to other depth cameras (e.g., Kinect), the extracted data is much more accurate (an average accuracy of 7 mm). The official rate is 100 Hz for 2-hands tracking and the field-of-view is 150° wide and 120° deep (an average of 135°). Information that can be obtained from the device includes wrist and elbow position, hand position, velocity and attitude vectors (all in 3D), grabbing strength indicator (degree of closed/open palm), etc.

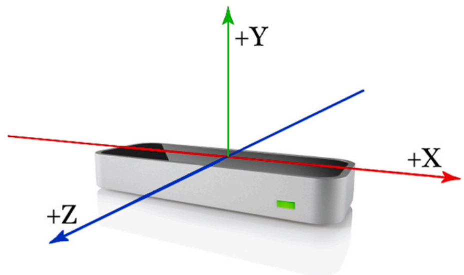

Fig. 1. The Leap Motion controller, from: https://www.leapmotion.com.

Appendix B. The SyncMeasure software

The SyncMeasure software was developed to analyze level of interpersonal synchronization. The input for the system is a CSV file representing movement of two hands. The mandatory columns that must be in the CSV file are frame ID and timestamp, number of hands in frame, hand position, elbow position, arm position, grab and pinch strength. Given these parameters, the software analyzes the synchrony using the CVV package (available at http://works.bepress.com/phil_reiss/45/; Reiss et al., 2019).

The software is managed at the GitHub page: https://github.com/Romansko/SyncMeasure and SyncMeasure versions are available at: https://github.com/Romansko/SyncMeasure/releases.

Data processing

Data for each experimental trail is analyzed using the SyncMeasure software that uses the CVV package. Data frames in which the number of hands detected in the frame were not equal to two are ignored by the software and are not included in the synchronization calculation.

Within the CVV package, data along each dimension is smoothed using spline smoothing. Spline smoothing assumes that a smooth function f(t) can be represented, with small error, as a linear combination of cubic B-spline basis functions defined on the time range of interest, with coefficients β_1, $\beta_2 \ldots \beta_k$ such that

$$f(t) = \sum_{k=1}^{K} \beta_k b_k(t) \tag{1}$$

The spline representation (1) allows for data compression as the number of spline functions (or coefficients) K may be much smaller than the number of observations M. In addition, the spline representation of a function f gives us an estimate of the function value f(t) at any point t for which we do not have an observation.

Unlike many usages of spline smoothing for noise reduction, for the motion time series achieved with the Leap-Motion sensor, fine details may be either signal or noise. This creates a delicate tradeoff when selecting the number of coefficients.

To define the number of coefficients, the SyncMeasure software allows for the definition of the nBasis parameter. In the results described in this study, we used nBasis = 200.

Further, the CVV package calculates the CVV grade as the cosine of two velocity vectors (defined by f′(t) the derivative of the evaluated f(t)).

For the velocity vectors of recordings from participants a and b, the CVV is defined as:

$$CVV_{ab}(t) = \frac{\langle f_a'(t), f_b'(t) \rangle}{\| f_a'(t) \| \| f_b'(t) \|} \tag{2}$$

where $\langle u, v \rangle = u_1 v_1 + u_2 v_2 + u_3 v_3$ and $\|v\| = \sqrt{\langle v, v \rangle} = \sqrt{{v_1}^2 + {v_2}^2 + {v_3}^2}$.

Measure

There are three different measures that may be considered CVV, |CVV|, CVV^2. As the participants in this study are facing each other, movement may be mirrored. We therefore chose the CVV^2 measure.

Combining alone CSV files with single hand in frames

The software can combine two CSV files that represent single hand movement into one combined CSV file that merges hand movement and updates the hands in frame to be two. We used this methodology to combine the files of the Alone-Assistant and Alone-Participant and calculate the score for this condition.

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