

**Digital Phenotyping Autism: Investigating Objective Vocal and Movement Quantification
for Characterizing Autism Severity**

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ABSTRACT

Autism Spectrum Disorder is the fastest-growing neurodevelopmental disorder. Despite the prevalence that 1 in 54 children by the age of 8 are diagnosed with autism, there is still a lack of an objective diagnostic. The current gold standard, Autism Diagnostic Observation Schedule (ADOS), suffers from the subjectiveness of clinician evaluations, inability to distinguish symptom severities, and failure to detect autism early because it only evaluates existing conditions of children. COVID-19 halted the administration of autism diagnostics because it prevents the close social interaction necessary to observe children's behavior. As the pandemic disrupts autism diagnoses, there's an exigence for new methods so millions of children don't go undiagnosed.

We used computer vision motion tracking technology to assess mean distances of autistic children from parent and examiner during the ADOS and vocalization recorders to analyze children's language ability. Both predictive measures (movement and vocalization) were analyzed for correlations with the total ADOS score, Restricted and Repetitive Behavior score, and Social Affect score to characterize autism severity.

Using univariate correlations and stepwise multiple regressions, we identified significant models to quantify autism severity. The vocalization hypothesis, which predicted the number of conversational exchanges (CE) initiated by the child would be correlated with the social affect score, was supported and produced the best fit model; a decrease in child initiated CEs correlates to an increase in autism social affect symptoms. This is a significant contribution to autism diagnostics because vocalization is not currently included in the ADOS, yet is strongly correlated with symptom severity and should be further evaluated.

Overall, this study provides a foundation for automating autism diagnosis through digital phenotyping, a technique that can seamlessly be integrated into smartphone apps to provide real time data in natural environments. It revolutionizes autism diagnosis by making mental healthcare accessible and portable, which is vital especially in the midst of the COVID-19 crisis.

I. INTRODUCTION

ASD. Autism Spectrum Disorder (ASD) is a neurodevelopmental disorder with deficits in socialization, communication, and repetitive/ritualistic behaviors (Hadeel, 2010). These social deficiencies greatly impair daily functioning and persist throughout adulthood. Epidemiologically, the prevalence of diagnoses has been rapidly increasing. The CDC reported 1 in 54 American children were diagnosed in 2020 with boys being more susceptible than girls (Autism Speaks, ND). Rates have increased 119.4 % over the course of 10 years and 10% within the past 2 years. This problem is amplified in racial minority populations; black, indigenous, and people of color are more likely to receive lower qualities of care, end services early, and go undiagnosed.

ADOS. A major cause of misdiagnoses is the lack of an objective detection metric. The current gold standard is the Autism Diagnostic Observation Schedule (ADOS) which is a 40-60 minute behavioral exam. Symptoms are categorized into two domains: social affect and restricted and repetitive behaviors (RRB). Social affect measures social activity such as eye contact, initiation of communication, response to name, and joint attention. RRB assesses excessive movement such as hand flapping. Between these two domains, 15 item level scores are evaluated where symptoms are coded from 0-3 scale. 0 means child is exhibiting typical behavior while 3 signifies abnormal behavior that impedes the child's functioning (Akshoomoff et al, 2006).

There are many flaws with this current method: 1) Psychological evaluations are inevitably subjective because psychologists interpret behaviors differently. One psychologist might believe that the patient is smiling regularly while another believes it's abnormal because there's currently no standardized way to assess behaviors like pointing (Ehmke, 2020). 2) The total ADOS score cannot represent the nuances and subtleties amongst ASD symptoms. All symptoms have varying severities that a simple number cannot encompass (Jabr, 2012). 3) The ADOS was not created to account for temporal changes in symptoms. This is problematic due to the dynamic nature of the disease, especially with regards to skills such as communication (Frye, 2018). 4) The ADOS may inaccurately assert ASD as the cause for patients' symptoms. Social communication and interaction related diseases get misdiagnosed with ASD such as learning disorders, depression, or Attention-deficit/hyperactivity disorder. This is because symptoms like irregular facial expression have many underlying causes so it's difficult to pinpoint ASD as the

root cause. This issue is augmented by the fact that several psychiatric disorders (autism, schizophrenia, bipolar disorder, and major depression) have genetic and phenotypic similarities (Cardno et al, 2014). 5) Parental concern can cause parents to over ascribe meaning to certain symptoms which implicitly influences diagnosis. For example, parents may be worried about their child's shyness and push it as an ASD symptom because of their pre-existing tensions (Spectrum, 2017).

Digital Diagnostics. Many skills affected in autism are quantifiable so automating collection of behavioral data can create objective metrics for evaluation. This technique, digital phenotyping, is the quantification of behavioral phenotypes through digital devices on a moment-by-moment basis. It overcomes the limitations of the ADOS since it's accurate, quantifiable, and accessible. Since the COVID-19 outbreak, ADOS administration was suspended because social distancing and masks impede the close social interaction necessary to observe behavior. Digital phenotyping ensures millions of children don't go undiagnosed because it can be done virtually, absent close examiner-child interaction. It's also highly accessible to families who struggle with accessing psychiatric healthcare because it can be implemented into a mobile device and easily used. Normalizing the usage of autism diagnostic apps ensures more children are diagnosed and at an earlier age. Lastly, digital diagnosis circumvents the cost and time needed to train clinicians to administer the ADOS.

Vocalization. Children with ASD have difficulty in verbal communication and social practices such as hand gestures and eye contact. Specifically, it is difficult for them to initiate and maintain conversations. Conversational turn counts (CTC), a measure for defining the number of conversations, is when one conversant initiates a discussion and the other responds within 5 seconds (Sng et al, 2018). These child-adult alterations can be measured by Language Environment Analysis (LENA). LENA records adult and child word count, child vocalizations, and CTCs. Currently, professionals merely use parent questionnaires and behavioral observations to understand ASD. LENA is groundbreaking by automating the collection of objective data as opposed to the subjective evaluation in the ADOS. There are many treatments psychologists can offer once aware of irregular conversational skills in ASD patients such as video modeling training or speech therapy. For example, the language "Parentese" encourages language development with simple sentence structure and melodic intonation (Cohen et al, 2013).

Movement. Another metric not assessed in the ADOS is distances children with ASD maintain between themselves and others during social interaction. ASD patients typically engage in behavioral avoidance and are unresponsive to social interaction, which can be observed through expressive control of space (Gessaroli et al, 2013). Self-generated distance is vital in sensorimotor functions such as action regulation and maintenance of gait (Honma et al, 2019). These abilities may be impaired due to cerebellar deficits which are associated with postural control, gait, sensory integration, and reduced connectivity in motor nodes (Kindregan et al, 2015). A novel automated coding technology to objectively record these data is motion-capture systems. Kinect sensors can be installed to the ceiling and note spatiotemporal data of ASD patients and adults' location during the examination (Cohen et al, 2014).

Although the ADOS has been useful for the past 15 years of its use, there are numerous improvements that need to be made. Effective diagnosis is key because it can reduce the cost of lifelong care by $\frac{2}{3}$ with early intervention (Autism Society, 2020). This investigation analyzes the potential in using distances children with ASD maintain from adults during the examination and their conversational abilities as new criteria for digitally phenotyping the severity of ASD symptoms.

II. METHODS

De-identified movement and vocalization data was obtained from the University of Miami's Early Play and Development Laboratory under Dr. Daniel Messinger.

Participants. Trained clinicians administered the ADOS-2 to families who consented to participate in the study. Participants were recruited through a clinic based in the Department of Psychology in the University of Miami, which offered free autism diagnoses. There were 18 males and 7 females with ASD, averaging 38 months in age. 17 children were Latino, 7 were Black, and 1 was white. 6 children were administered the Toddler ADOS module, which is for children under 30 months with nonverbal to one-word speech. 19 children over the age of 30 months with one-word speech were administered the ADOS Module 1.

Vocalization. This study analyzed the total number of conversational turn counts (CTCs), number of conversational exchanges (CE) initiated by the child, average turns in a CE, and duration of each CE. Audio was recorded through video camera eyeglasses worn by examiners.

These recordings were collected during the ADOS-2 and analyzed through LENA SP Hub Version 3.3.0 software.

I imported the LENA file to Excel and deleted extraneous columns except vocal ID, segment duration of CTC, and the number of CTCs. Total CTC count, CTC duration, exchange duration, vocal ID of initiator, and number of CTCs within CEs were calculated.

Movement. This study used motion tracking technology to measure distance from child to parent and from child to examiner during the ADOS. Videos recorded from a motion tracking ceiling camera during the ADOS-2 were analyzed using Mask Regional Convolutional Neural Network to detect child, parent, and examiner every 1/100th of a second.

I saved the motion capture data into a workable format, text files, with X and Y coordinates of the child, examiner, and parent present in the diagnostic room. I exported the location data to R to calculate average distances between child and parent and child and examiner. Sample code is attached below to calculate distance between parent and child:

```
names(d)<- c("ParentX", "ParentY", "ChildX", "ChildY", "Ex1X", "Ex1Y")
PaCh<- sqrt((d$ParentX-d$ChildX)^2+(d$ParentY-d$ChildY)^2)
mean(PaCh)
```

Heatmaps were created in R to visualize movement using the following code:

```
names(d)<- c("ParentX", "ParentY", "ChildX", "ChildY", "Ex1X", "Ex1Y")

require(MASS)
dens_child <- kde2d(d$ChildX, d$ChildY, h=75, n=50)
filled.contour(dens_child, xlim =range(0,1000), ylim = range(0,1000))

dens_parent <- kde2d(d$ParentX, d$ParentY, h=75, n=50)
filled.contour(dens_parent, xlim =range(0,1000), ylim = range(0,1000))

dens_ex <- kde2d(d$Ex1X, d$Ex1Y, h=75, n=50)
filled.contour(dens_ex, xlim =range(0,1000), ylim = range(0,1000))
```

Analysis. I conducted Pearson's correlations and stepwise multiple regressions to analyze the correlation between the movement and vocalization variables to the ADOS scores. Each independent variable was tested for correlation to the diagnostic scores individually. They were then jointly tested in a stepwise multiple regression where the least correlated variable (the variable with the highest p-value) was removed. This was repeated until the most significant model remained, with the highest adjusted R square value and lowest p-value.

III. RESULTS

Figure 1: Pearson's Correlation				
		Total ADOS Score	Social Affect Score	Restricted and Repetitive Behavior Score
Child Initiated Conversational Exchanges	Pearson Correlation	-0.356	* -0.442	0.024
	P-value	0.081	* 0.027	0.910
Conversational Turn Counts	Pearson Correlation	-0.363	* -0.414	-0.073
	P-value	0.075	* 0.040	0.727
Distance from Child to Examiner	Pearson Correlation	0.091	0.129	-0.051
	P-value	0.667	0.537	0.809
Distance from Child to Parent	Pearson Correlation	0.234	0.237	0.129
	P-value	0.260	0.255	0.540

Vocalization. Vocalization was analyzed through the number of child CE initiations, duration of CE, total number of CTCs, and average number of CTCs in one CE. The number of child CE initiations was correlated with Social Affect score ($p=0.0269$, $R^2 0.161$), echolalia ($p=0.0103$, $R^2 0.221$), social overture ($p=0.0084$, $R^2 0.234$), and requesting ($p=0.0088$, $R^2 0.231$). Low number of child-initiated CEs correlates with a higher score on the ADOS for coding echolalia. Echolalia, or the repetition of an adult's last statement, is a sign of impaired communication in autism and has a relationship with the child's ability to commence social interaction. Low CEs also correlates with higher social overture scores, indicating the child has weak social interaction skills. Signs of low-quality overture include lack of child's interest in the

examiner's attention, poor integration of verbal and nonverbal communication, and absence of eye contact when attention seeking. ASD children also have low requesting abilities which means either they don't desire an object or don't use proper gesture, eye contact, vocalization, or facial expression when expressing their request. The other vocalization variable statistically significant with social affect score was the total number of CTCs ($p=0.040$).

Movement. Movement was analyzed during the duration of the entire ADOS exam and the freeplay subsection. Pearson's correlations of the distance of child to parent during the free play, child to examiner during the full ADOS, and child to parent during the full ADOS were not correlated with any dependent variable. The only distance relevant during the ADOS exam (structured, free play, and exploration period) is the distance maintained between child and clinician during the free play. Distance between child and examiner during the free play was correlated with echolalia ($p=0.0205$, $R^2=0.178$) and pointing ($p=0.0182$, $R^2=0.186$). These are both item level symptoms with echolalia being categorized in the RRB domain and pointing in the SA domain.

Heatmaps. The white areas represent areas where the children did not move to. The darker the color gets, from yellow to red, the longer the child spends in that location.

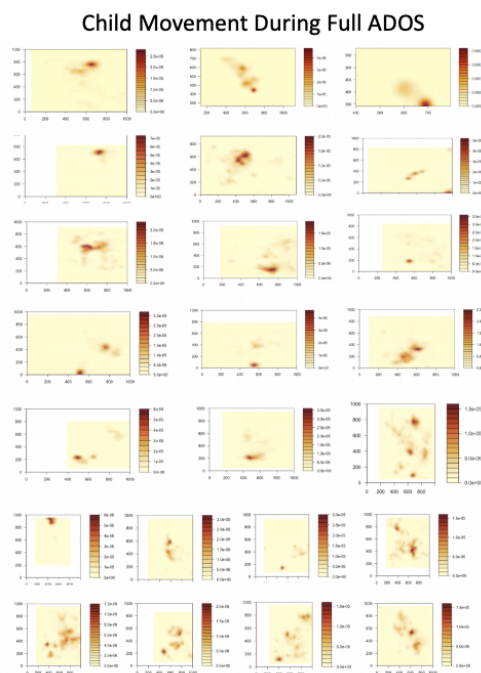


Figure 2: Heatmaps for children movement during the structured ADOS.

Structured ADOS. This heatmap was generated from child movement during the structured part of the ADOS where the examiner leads activities to assess child behavior. Although there is some general movement, the children are fixated in one region for the majority of the exam.

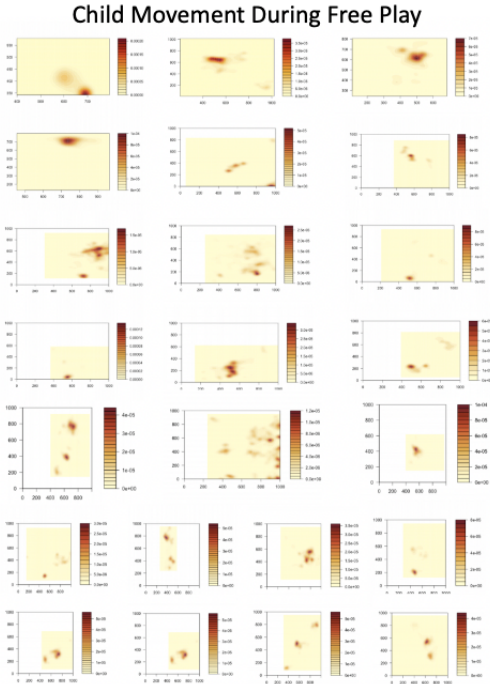


Figure 3: Heatmaps for children movement during the free play.

Free Play. The children are not moving much during the free play as indicated by the large white areas and strong localization in one to three areas. Most children are in the periphery of the room where they stay fixated for the majority of the diagnostic period.

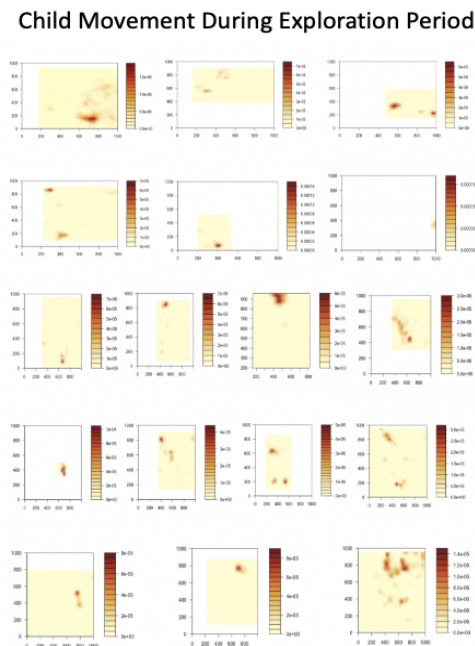


Figure 4: Heatmaps for children movement during the exploration period.

Exploration Period. After the structured portion of the ADOS, children are allowed to explore the room without adult instruction. There is little to no movement for most children during this exploration period. White areas are significantly larger than in the other two periods and children spend most of their time in fewer spots.

Combining Predictive Variables. After analyzing Pearson's correlations, multiple regressions were performed to develop models that could account for a greater amount of sample

variance. Three categories of models (two movement variables, three vocalization variables, and the 5 movement and vocalization variables) predicted the social affect score. None of the combinations of variables were significantly correlated ($p < 0.05$) with the total ADOS score. Redundancies, which existed because of the stepwise regression method, were eliminated by narrowing models through their adjusted R^2 values.

Figure 5. Multiple Regression Predicting the Social Affect Score			
Model	F-Stat	Adjusted R^2	P-value
Distance from child to parent, Distance from child to examiner, Number of CE initiated by child, Number of CTC in series, Segment Duration of CE	1.763	0.136	0.169
Distance from child to parent, Number of CE initiated by child, Number of CTC in series, Segment Duration of CE	2.261	0.173	0.099
Distance from child to parent, Number of CE initiated by child, Number of CTC in series,	3.087	0.261	*0.049
Distance from child to parent, Number of CE initiated by child	3.524	0.174	*0.047
Number of CE initiated by child	5.591	0.161	*0.027
* $p < 0.05$. CE = Conversational Exchanges, CTC = Conversation Turn Count			

The multiple regression models in Figure 5 predicting the social affect score contained five independent variables: distance from child to parent during the ADOS, distance from child to examiner during the ADOS, number of child initiated CEs, segment duration of child CTCs, and number of CTCs in a series. The weakest correlated variable was removed in a stepwise manner. Both distance variables, child to parent and child to examiner distance during the ADOS, were not able to predict the social affect score neither independently nor in conjunction with the vocalization variables. The only significant independent variable in this series of models was the number of CEs initiated by Child, accounting for 16.1% of variance in the social affect score.

Figure 6. Child CE Initiated Predicting Social Affect

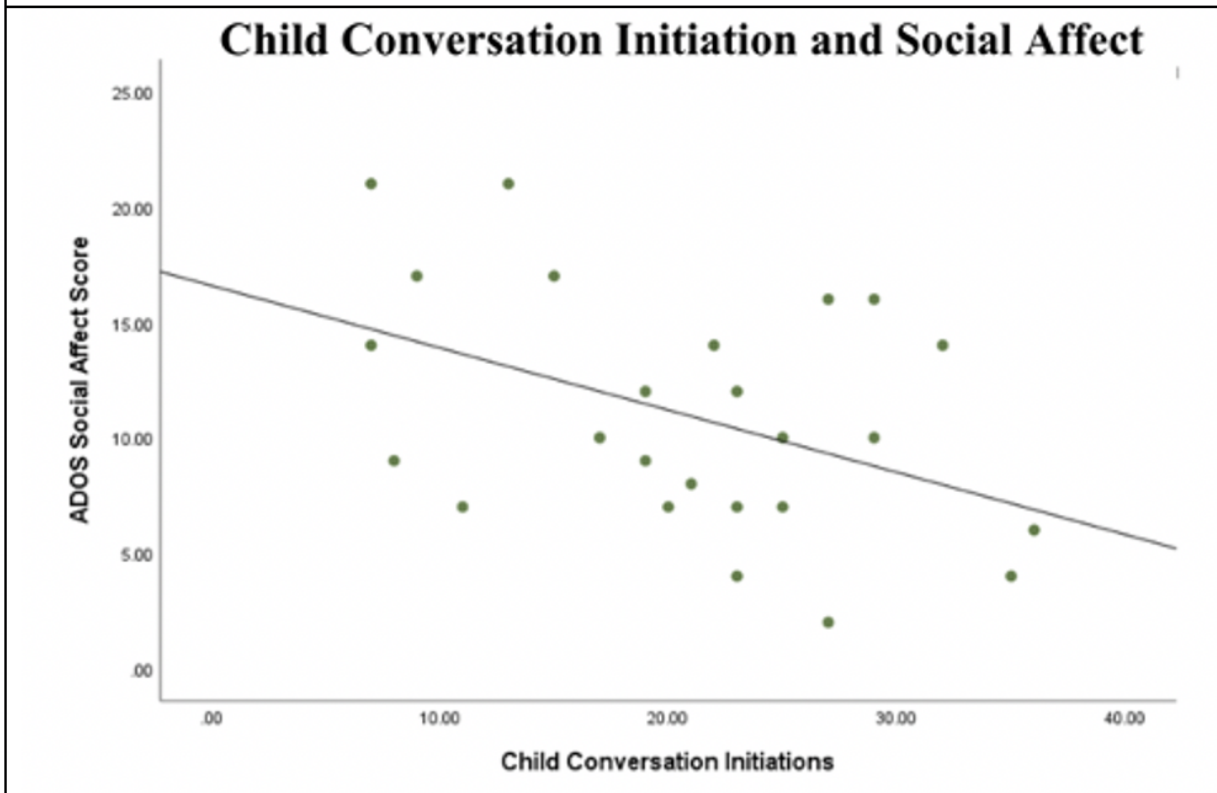


Figure 7. Best Fit Model to Predict the Social Affect Score

	Unstandardized Coefficients	Standard Error	t	P-value
Intercept	16.593	2.563	6.474	0.000
Number of CE Initiated by child	-0.2698	0.1141	-2.364	*0.0269
*p <0.05. CE = Conversational Exchanges. Adjusted R ² = 0.161				

Figures 6 and 7 display the strong negative correlation between the number of child initiated conversations and the social affect score. A decrease in child initiated CE correlated to an increase in the social affect score. The linear regression equation for the best fit model is $y = -0.2698x + 16.593$ where y is the social affect score and x is the predictor variable, child CEs.

IV. DISCUSSION

Current Gold Standard. Autism is an increasingly prevalent disorder and the lack of objectivity in autism diagnostics results in inaccurate diagnoses and interferes with prescribing

appropriate medications. The current leading diagnostic evaluation, the ADOS, is a semi-structured exam that is subjective by requiring a clinician to analyze symptoms. This prevents standardization because each examiner code symptoms differently on the scale the ADOS provides. It also cannot distinguish nuances in symptoms shared with other psychiatric conditions. Similar symptoms of autism are found in anxiety, bipolar, and depressed patients and the inability of the ADOS to decisively characterize symptoms to autism results in misdiagnoses. False positives bring stigma and unnecessary medication to patients while false negatives prevent a chance at treatment of the condition. Furthermore, the ADOS is not an ideal diagnostic for at-risk populations due to inequities in access for psychiatric healthcare. Families must proactively book an appointment after identifying atypicalities in their children, both of which are difficult due to the lack of normalized screening. Early detection is necessary to administer therapeutic interventions to manage the disorder.

Experimental Design. Distances were obtained from ceiling motion tracking cameras which measured the movements of child, parent, and examiner during the ADOS. The mean distances of individuals in the room were calculated via coding in RStudio. Adult and child vocalization was collected by LENA during the ADOS. Pearson's correlations were conducted with movement and vocalization variables independently and then jointly evaluated through multiple regressions to predict ADOS scores and the domain subsections.

Vocalization Analysis. To the best of our knowledge, this is the first study to quantify and correlate child initiated CEs to social affect skills. Child initiated CEs produced the best fit model, accounting for 16.1% of the total variance of the social affect score and therefore serves as a useful tool in predicting ASD. It was also correlated with various item level scores including echolalia, social overture, and requesting which demonstrates how communication deficits are related to social development. Low CE initiations reflect how children with ASD have difficulty in/lower interest in social interaction.

CTC count is a good measure of reciprocal social interaction since it evaluates whether children can sustain a conversation. We found the number of CTCs were also correlated with less developed social affect skills which corroborates the findings of other studies (Warren et al, 2009 & Chen et al, 2020). Overall, vocalization deficits are important to analyze since they are indicators of autism symptom severity as early as 18 months (Lord and Paul, 1997).

Movement Analysis. Budman and colleagues introduced the use of motion tracking technology to quantify social symptoms of autism. They measured child movement during a 5 minute free play period of the ADOS and found correlations to the social affect score (Budman et al, 2019). Our study expanded on their research by 1) analyzing child to parent distance in addition to child to clinician distance and 2) measuring movement during the entire 60 minute exam and an additional exploration period. Contrary to their results, we did not find the distance between child and examiner during the free play to be correlated with the total ADOS score or the two domains, but it was significantly associated with echolalia and pointing. However, when analyzing these distances during the entire duration of the exam, no combination of the variables were able to predict any domain or item level scores. This could be because only small periods of the ADOS are unstructured, so children are restricted in movement when an examiner is leading activities to evaluate their behavior. Further research is needed to determine whether the difference in our results with Budman's team means that either there is no correlation between distances children maintain from parent and examiner over extended periods of time or that there is only correlation during unstructured social interactions.

The heatmaps provide further insight into the different movement behaviors of children during different portions of the exam. In the structured period of the exam, children explore most of the room but largely remain in the center. This is expected since the child is being actively evaluated by the examiner so there is less opportunity for free movement. On the other hand, the free play period is unstructured so there's more flexibility. Therefore, child localization in one area is more indicative of ASD behavioral abnormalities in the free play because the child is able to move around and play. The examiner lays out toys for the children to play with and observes child behavior from a distance. Our heatmaps suggest that children with ASD would rather stay excluded in the periphery than interact with toys and adults in the diagnostic room. This pattern was also seen in the exploration period, another unstructured interval where children can freely explore the room. The majority of children stayed in the periphery of the room, indicating low affinity for social interaction. Social skill deficits are common symptoms for autism and using motion tracking technology allows for objective evaluation of symptom severity.

Digital Phenotyping. Digital Phenotyping is a convenient and portable diagnostic method that can revolutionize autism care. Mobile app based diagnosis circumvents the costly

process of training clinicians because only algorithms to calculate distance and process language data are required. It is also accessible to underserved communities because they can use a digital tool to identify symptoms of autism and then consult a psychologist for more rigorous diagnostic testing.

Further Research. Our study can be expanded by separating the vocalization data collected during the full ADOS into subsections of the exam i.e., have vocal data recorded from only the free play and exploration period. This would allow more precise data analysis and avoid covariance when comparing the movement data collected from different subsections. Although we only used recordings from the 60-minute ADOS, the programs used for data collection can be used for a longer duration of time to have a more holistic understanding of patient movement and language. Analyzing data from a longer period of time will provide a more holistic understanding of patient movement and language.

Another limitation is the setting (clinic) in which data was collected. Children behave differently in unaccustomed environments which can skew their diagnosis. Diversifying the setting to daycare centers or more natural environments will allow for data that reflects the reality of child movement and vocalization. Therefore, collecting data in alternative settings and longer periods will be more productive and accurate.

In our study, children approximated 38 months in age with nonverbal or single word phrase speech. Future research should analyze older children with phrase speech to determine if the linguistic variables can still predict the social affect score when children have more developed speech.

V. CONCLUSION

This study provides necessary insight into predicting autism by analyzing motor and linguistic skills. We analyzed the number of child CE initiations, average duration of CEs, CTC count, and average number of CTCs in one CE, distance between child and parent, and distance between child and examiner. These criteria are significant because they provide a new framework for conducting autism diagnoses. Unlike previous subjective diagnostics which require costly and time-intensive training for clinicians, our computational method creates new avenues for objectively assessing autism symptoms using automated technology. When

comparing the two categories of independent variables, movement and language, vocalization was more correlated with ADOS scores; the number of CEs initiated by the child and CTC count have been identified as new predictive determiners for the social affect score.

The benefits in using LENA and motion capture technology is three-fold. They can be utilized in natural settings such as classrooms which allow patients to act freely in supportive, non-critical environments. This can assist in early diagnosis because it can be integrated seamlessly into spaces inhabited by young children (such as daycares) and be analyzed for at-risk populations. Both measures are objective and automated, deriving precise measurements with high temporal accuracy which eliminates the subjectivity of the ADOS. Vocalization and movement can also be assessed longitudinally to observe changes in symptoms over time. Conversely, the ADOS assigns an incomplete number score as a diagnosis without accounting for fluctuations in symptoms as children age.

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