Schizophrenia

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Automated analysis of clinical interviews indicates altered head movements during social interactions in youth at clinical high-risk for psychosis

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Alterations in social functioning are commonly observed in youth at clinical high risk (CHR) for psychosis. Previous research has focused on perception and interpretation of social stimuli. Assessments of social behavior have been limited and have typically been conducted using time-consuming, manual, and not always reliable methods. The current study aimed to characterize patterns of head movements, a critical feature of nonverbal social behavior, to determine alterations among CHR individuals, using novel automated tools. A total of 87 CHR and 90 healthy control youth completed video-recorded clinical interviews. Segments when participants were responding to questions were processed using an open-access machine learning-based head tracking program. This program extracted target variables such as total head movement, amplitude, and speed in each direction (x, y, and z). Relationships between head movement patterns and symptoms were then examined. Findings indicated that the CHR group exhibited the same amount of head movements as the control group, establishing that results did not reflect a more global deficit. Notably, the CHR group executed spontaneous head turns in side-to-side movements (such as the "no" gesture) at a significantly slower speed when compared to controls ($U = 2860$, $p = 0019$, $d = -0.41$). Slower side-to-side head movement was also associated with elevated clinician-rated scores of "disorganized communication" ($r = -0.23$), but not with other symptoms in the positive domain nor negative or depressive phenomenology. These findings provide new insights into alterations in social processes in individuals at CHR and highlight the promise of using automated tools to capture spontaneous head movements, thereby expanding the assessment of social behavior, communication, and applied social cognition.

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INTRODUCTION

Social deficits are associated with increased loneliness, reduced quality of life, and diminished psychological well-being and are particularly severe for people with schizophrenia spectrum disorders, where they contribute to significant functional disability[1]. Individuals at clinical high risk (CHR) for psychosis, representing youth in the prodromal phase, also exhibit marked social deficits[2]. Indeed, a defining feature of CHR syndrome includes attenuated positive symptoms, brief full psychotic symptoms, and decline in functioning coupled with schizotypal personality disorder or a family history of psychosis[3]. These social and functioning deficits likely contribute to characteristic impairments in social skills prevalent across stages of psychosis[4–6]. However, to date, research on social skills has largely focused on perception and interpretation[7]. Studies of performed social behavior have been relatively rare. This is surprising as nonverbal social behaviors, such as hand gestures and facial expressions, have strong clinical potential for improving psychosis risk assessment and serve as viable treatment targets as well[8,9]. To date, there have been no studies examining head movements in a CHR sample, a frequent and important component of every-day conversation. Recent advances in technology and methodology now provide an ideal opportunity to enhance the assessment and analysis of these complex nonverbal behaviors in a social context. The present study aims to advance our understanding of CHR head movement performance during social interaction utilizing new automated methods to assess social skills alterations and examine relationships to clinical symptoms.

Impaired social cognition, common to both individuals at CHR and people with schizophrenia, can result in reduced participation in social activities, difficulty in communication, and limited social support[10,11]. Individuals at CHR can exhibit impaired social skills that alter their social interactions, including altered speech fluency, verbal expressions, and gaze[12], as well as blunted emotional facial expressions[13]. In addition, youth at CHR may struggle to perceive gestures accompanying speech[7], interpret their communicative functions[14], and perform hand gestures, often producing more mismatched and retrieval gestures than healthy controls[15]. For example, they may use more gestures that are semantically incongruent with their speech content (i.e., mismatch) and more gestures during pauses in speech while searching for a word or idea (i.e., retrieval). In more naturalistic settings, during clinical interviews, individuals at CHR produce fewer spontaneous hand gestures than healthy controls[16]. Using precise body movement analysis, studies have identified greater speed and lower variability in CHR individuals' movements[17]. Moreover, alterations in these social behaviors, notably gesture performance, have been associated with negative symptoms[18,19], emphasizing the importance of assessing these

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behaviors to identify CHR individuals and their symptom profile. Despite these insights, little is known about other nonverbal behaviors beyond hand gestures, such as head movements, in individuals at CHR.

During social interactions, head movements are (often) unconsciously performed by both speaker and listeners to convey semantic concepts, emotions, involvement in the conversation, or to signal turn-taking[20,21], all of which provide valuable social information across interactive roles. The communicative functions of head movements were investigated in a 1931 experiment by Dobrogaev and reported in Kendon (1980). Participants were asked to suppress all head movements while speaking. No participants were completely successful, and the resultant speech lacked pitch variation and fluency, with lexical selection itself becoming difficult. Although crucial to everyday social interactions, we lack extensive knowledge about head movement behavior in individuals on the schizophrenia spectrum. In first episode psychosis, reduced frequency of head movements during speech has been reported[22], along with decreased amplitude and velocity in people with schizophrenia[23]. For individuals at CHR, the limited research on spontaneous head movements during speech has yielded mixed results, showing either no difference from healthy controls[17] or lower amplitude and higher variability[24], without detailed analyses of specific movement direction or their significance. Moreover, psychosis is not the only medical condition in which patients exhibit altered head movements during social interactions. Depressed patients, for example, display less nodding[25] and adopt more downward head poses than healthy controls[26], along with decreased amplitude and velocity of vertical and horizontal head movement in cases of high severity[27]. Given that individuals at CHR often present with depressive symptoms, with over 40% reaching criteria for a depressive disorder[28], it is crucial to distinguish head movement alteration caused by the CHR state from those attributable to depressive symptoms.

Although social cognitive deficits are well-documented in the CHR syndrome, little attention has been given to the performance of subtle nonverbal behaviors such as head movement in a social context. Traditionally, assessing nonverbal behaviors in psychopathology has relied on manual coding methods, such as the Ethological Coding System for Interviews[29]. However, advances in motion analysis technology have enabled more efficient and precise assessment of social behavior. Motion Energy Analysis (MEA), for example, has been widely used to quantify nonverbal behavior in clinical interviews without requiring special equipment[30] but lack precision in capturing movement direction, speed and amplitude. Recent machine learning-based tools require minimal technical expertise and only a low-resolution video from basic devices like webcams or smartphones. They can extract 3D trajectories of bodily keypoints, allowing for the calculation of specific motor variables and enhancing the precision and scalability of social behavior evaluation[31,32]. Leveraging these advancements, we investigated movement in a sample of CHR and young healthy control (HC) participants. Each participant was recorded during a structured clinical interview, and the first 5 minutes of footage were processed using an open-access machine learning-based head tracking program to extract target variables such as total movement, amplitude, and speed in each direction (x, y, and z). We hypothesized, based on previous findings of reduced communicative nonverbal hand gestures in this population[16], that head movements would be fewer and altered (in terms of speed and amplitude) in the CHR group. Further, exploratory analyses were conducted to examine relationships with disorganized domain as well as subdomain symptoms across each domain. Furthermore, given prior findings suggesting links between alterations in social behavior and clinical symptoms[15,33,34], we posited that these deficits would correlate with increased positive symptoms such as disorganized communication as well as elevations in negative symptoms. Recognizing the significant influence of depression on social motor behavior[35], particularly head movements, we also conducted an exploratory analysis to examine its effects.

RESULTS

Demographic characteristics

Among sociodemographic characteristics, age and race did not differ between CHR and healthy control (HC) groups (Table 1). As gender significantly differed between groups, we included it in all models to investigates its influence. Regression analysis including our motor variables as dependent variables and the interaction between gender and group as a predictor were not statistically significant, demonstrating no influence of gender on our findings about CHR's head movements.

Between group comparisons on head movements

Concerning our first hypothesis, there was no significant difference in the total amount of head movement in the three axes combined between the CHR group and the control group ($U = 3924$, $p = 980$, $d = 0.04$).

For the mean amplitude of movement peaks, there were no significant differences between groups on the x-axis (head raise; $U = 3723$, $p = 574$, $d = -0.08$), y-axis (head turn; $U = 3344$, $p = 094$, $d = -0.20$), and z-axis (head tilt; $U = 4160$, $p = 473$, $d = 0.01$).

For the median speed of rotation, values were significantly lower in the CHR group compared to the control group in the

Table 1. Sociodemographic characteristics and SIPS symptoms of CHR and healthy control groups.

Characteristic	CHR ($n = 87$)	HC ($n = 90$)	Statistical
Age	19.8 (2.4)	19.5 (3.17)	$U = 4248$, $p = 0.323$
Gender, % female	46%	67.8%	**$X^2(1) = 7.71$, $p = 0.005$**
Race,			$X^2(5)–7.20$, $p = 0.206$
American Indian	1 (1.15%)	1 (1.11%)	
Asian	3 (3.45%)	12 (13.34%)	
African American	10 (11.5%)	9 (10%)	
Pacific Islander	0 (0%)	0 (0%)	
Hispanic-Latino	11 (12.6%)	15 (16.7%)	
Caucasian	55 (63.2%)	47 (52.2%)	
Multiracial	5 (5.75%)	4 (4.44%)	
SIPS			
P1 - unusual thought content	3.29 (1.12)		
P2 - suspiciousness	2.55 (1.37)		
P3 - grandiose ideas	1.72 (1.47)		
P4 - perceptual abnormalities	2.70 (1.31)		
P5 - disorganized communication	1.80 (1.39)		
Positive symptom subscale	11.9 (1.46)		
Negative symptom subscale	8.55 (6.18)		
BDI	16.9 (11.8)	4.99 (5.04)	**$U = 6077$, $p < 0.0001$**

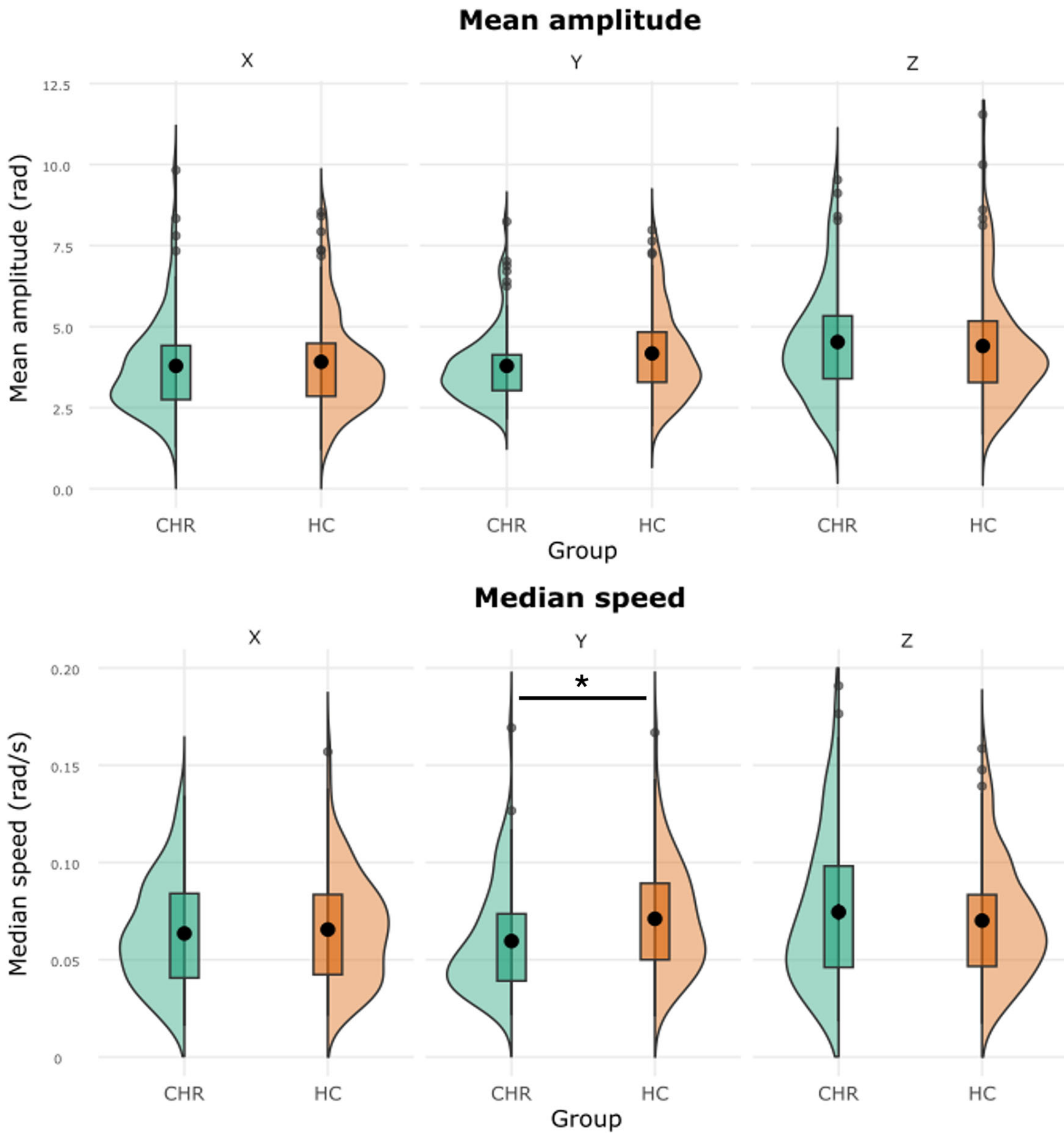

Fig. 1 Mean amplitude and median speed of head rotation for each axes x, y and z for both groups. *$p < 05$: significant using Mann–Whitney U tests.

y-axis only (head turn; U = 2860, $p = 0019$, $d = -0.41$), surviving multiple correction ($p = 015$ with FDR correction). However, no significant group differences were found in the x-axis (head raise; U = 3745, $p = 619$, $d = -0.07$) and the z-axis (head tilt; U = 4008, $p = 786$, $d = 0.13$) (see Fig. 1).

As a supplementary analysis, we further explored whether these findings remained stable throughout the interview by conducting the same analyses on the first and last 2.5 minutes separately. Results showed similar findings across both segments, except for the median speed of head turns (y-axis), where no significant group difference was observed (first 2.5 min: U = 3691, $p = 512$, $d = -0.13$; last 2.5 min: U = 4148, $p = 495$, $d = 0.14$)—unlike in the full 5-min interview. To assess within-subject consistency, we correlated each motor variable between the two segments across the full sample. We found significant correlations for total amount of movement, mean amplitude on the y- and z-axes, and median speed on the y-axis (see Supplementary Analysis for detailed correlation results).

To examine whether depression, assessed with the BDI-II, accounted for group difference, we conducted a multiple linear regression. Results showed that depression was not a significant predictor ($B = 6.405 \times 10^{-8}$, $SE = 2.385 \times 10^{-7}$, $t(168) = 0.269$, $p = 0.79$), suggesting that depression severity was not associated with median speed rotation in the y-axis.

Concerning our second hypothesis of head movements being linked to positive symptoms among the CHR participants (see Table 2), P5 symptoms (disorganized communication) was significantly correlated with mean amplitude of head movement in the x-axis ($r = -0.311$, $p = 003$) and median speed of head rotation in the y-axis and in the z-axis ($r = -0.231$, $p = 032$ for both axes). Additionally, median speed of head rotation in the z-axis was correlated with the negative symptom subscale ($r = -0.273$, $p = 011$). These correlations showed that the higher the P5 symptoms (i.e., disorganized communication), the lower the head movement amplitude on the x-axis (i.e., head raise) and median speed on the y-axis (i.e., head turn) and z-axis (i.e., head

Table 2. Correlations between head movement variables and symptoms collected during SIPS.

	Axis	P1	P2	P3	P4	P5	N Total
Mean amplitude	X - Pitch	−0.083	0.046	−0.194	−0.051	**−0.311****	−0.049
	Y - Yaw	0.051	0.071	−0.055	0.153	−0.118	−0.027
	Z – Roll	0.092	−0.073	0.053	−0.079	−0.007	0.050
Median speed	X - Pitch	−0.124	0.009	−0.072	−0.113	−0.205	−0.189
	Y - Yaw	−0.193	0.004	−0.041	0.113	**−0.231***	0.006
	Z – Roll	−0.023	−0.073	0.046	−0.157	**−0.231***	**−0.273***

*$p < 05$: significant using Pearson correlations. **$p < 001$: significant using Pearson correlations.

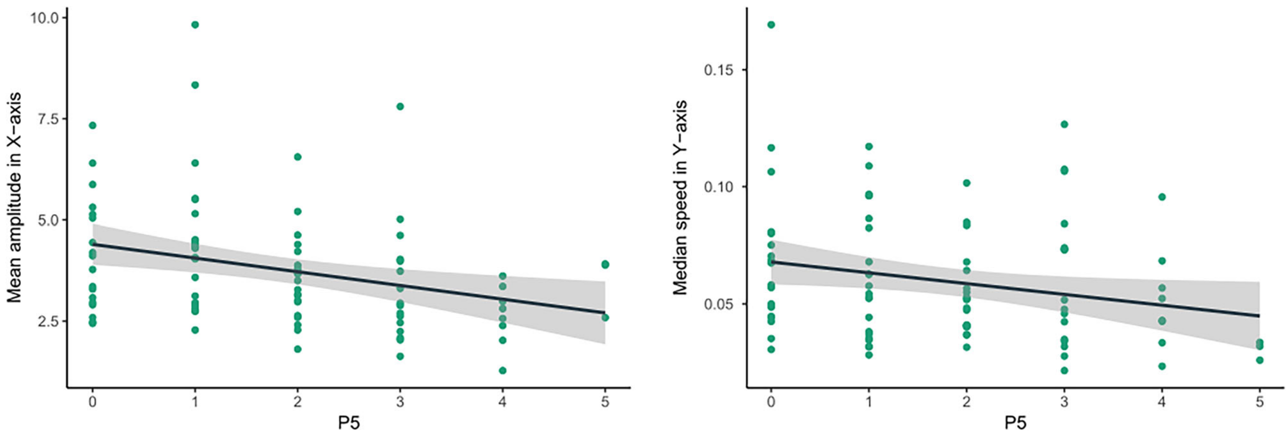

Fig. 2 Significant correlations scatter plots between some head motor variables and P5 symptoms in the CHR group. P5 symptoms correspond to disorganized communication.

tilt). Moreover, the higher negative symptoms, the lower the head rotation median speed on the z-axis. Scatter plots to exemplify the main correlations are represented in Fig. 2. Results did not survive Bonferroni or FDR correction except for the Spearman correlation between P5 symptoms and the mean amplitude on the x-axis (rho = −0.348, $p = 03$). Correlation analyses between head movement variables and other symptom domains and subdomains are presented in the Supplementary Analysis.

DISCUSSION

It is well established that individual at CHR for psychosis experience impairments in social cognition, particularly in perceiving social signals, interpretating their meaning and processing them[36]. However, their social behavior has been relatively underexplored in naturalistic contexts. The present study helps to clarify the specific alterations in CHR head movements during social interactions. Although the overall amount of head movement in CHR individuals was not impacted when compared to controls, the manner in which CHR individuals moved their head was distinct. Specifically, we found that individuals at CHR exhibited slower head movements relative to controls in the horizontal axis (i.e., pitch), representing side-to-side head turns. Motor speed impairments have been consistently demonstrated in individuals at CHR across various body actions, such as finger tapping[37]. Our study highlights that head movements in CHR individuals are similarly affected by reduced speed. What makes these head movements particularly noteworthy is that they occur spontaneously during social interactions. Head turning (right/left) is a nonverbal social behavior commonly used in western cultures and carries significant social meaning[20]. For example, head movements help manage conversational flow[38], indicate listening and agreement[39] and can show conversational engagement[40]. Thus, we showed that this motor slowing also happens in a social situation and may be linked to social cognitive processes, although we did not directly assess social cognitive processes to confirm this association. Notably, only the speed of movement was observed to be affected, while the amplitude and the total amount of movement remained intact. This suggests that other movement alterations commonly observed in the psychosis spectrum[41], or a global paucity of movement, did not account for the group difference, reinforcing the social specificity of this deficit. However, we did not include a non-social comparison condition (e.g., reading a text or memorizing objects) that would help clarify whether this difference is specific to social nonverbal behavior or indicative of broader motor dysfunction. It is therefore important to acknowledge that the head movements difference was observed in a social interaction context, and while they may reflect social and communication dysfunction, this interpretation requires empirical validation. Although previous studies examining head movements in individuals at CHR have been conducted exclusively in a social context[17,24], similar head movement metrics have been evaluated in other clinical populations across both social and non-social conditions (i.e., presentation of video stimuli). For instance, in children with autism spectrum disorder (ASD), higher angular velocity of yaw (y-axis) and roll (z-axis) movements were observed compared to typically developing children—but only during the presentation of social stimuli[42]. This suggests that differences in head movements dynamics between children with and without ASD may be specific to social context. Hence, future studies in CHR for psychosis should incorporate both social and non-social tasks to provide a clearer understanding of the relationship between nonverbal behavior, social processing, and motor dysfunction.

In addition, we found that the speed of CHR individuals' head turns during the interaction was correlated with P5 symptoms (i.e., disorganized communication), but not other positive symptoms. In other words, individuals at CHR who moved more slowly were rated by clinicians as having greater communicative disorganization. Additional specific head movement characteristics were also associated with the disorganized communication symptom (i.e., amplitude of head raise; speed of head tilt) and negative symptoms (i.e., speed of head tilt) subscale. Notably, disorganized communication, which has been shown to affect early adolescent social functioning[43], was rated by the clinician, and reflected a more global impression of how effectively the participant conveyed information and stayed on track when responding to questions during the interview, as well as participant reports of recent outside feedback that they were not communicating effectively. It is therefore interesting and potentially important that a nonverbal behavior may have influenced a rating that is intended to apply more directly to verbal communicative dysfunction. Notably, research has shown that the nonverbal behavior of individuals with schizophrenia (as displayed using point-light displays) was linked to first impressions in the general population[44]. Further experimental research is then needed in the clinical context to tease apart these critical elements. However, we acknowledge that causality cannot be determined from these associations and that it is possible that both nodding behavior and disorganized communication (P5) reflect a broader underlying factor rather than a direct causal relationship. Our findings also raise important considerations regarding the classification of disorganized communication within the positive symptom domain of the SIPS. We observed significant associations between head movement alterations and disorganized communication, whereas correlations with other positive symptoms were absent or less pronounced. This pattern may support the idea that disorganized communication is functionally and mechanistically distinct from other positive symptoms, warranting further investigation into its classification.

Motor systems and perceptual systems are tightly linked[45]. Action influences perception and perception influences action. Over the past decades, research has shown that the interplay between action and perception may contribute to various socio-cognitive and behavioral processes, such as predicting actions, understanding other's mental states and imitating behaviors. This reciprocal relationship provides valuable insights into the idiosyncratic spontaneous head movement patterns observed in CHR participants during social interactions and their association with disorganized communication symptoms. The relationship between motor and social functions has been relatively understudied in the psychosis spectrum compared to other disorders. However, findings have shown that movement alterations are closely associated with deficits in psychosocial functioning in CHR individuals[46] and people with schizophrenia[47]. Similarly, in Parkinson's disease, peoples' ability to express facial emotion has been linked to their ability to recognize facial emotion[48]. In Huntington's disease, the severity of patients' motor symptoms was associated with mental state attribution deficits[49]. These examples from other disorders lend support to our findings, with the specificity of social motor signs impaired in CHR individuals being linked to specific positive symptoms that impact social cognition. Moreover, since motor and socio-cognitive difficulties frequently co-occur, assessing motor abilities may provide insights into underlying socio-cognitive processes. In the present study, evaluating spontaneous head movements in CHR individuals could pave the way for further investigations into patients' social cognition.

Moreover, results revealed that the patients' depression level did not influence the observed speed difference in head movements. Individuals with depression have been shown to exhibit less nodding[25] and a specific kinematic pattern of head movements, such as less horizontal (i.e., pitch) and vertical (i.e., yaw) amplitude and angular velocity[27]. Although CHR individuals often display depressive symptoms[28], we demonstrated that the decreased speed of head turn found here is unlikely to be a byproduct of depression and may instead be more specific to the psychosis spectrum. These findings hold significant relevance for psychosis risk detection and for distinguishing psychotic disorders from other psychiatric conditions.

The novelty of this study also lies in the methodological approach to assessing spontaneous head movements. While nonverbal behaviors are typically estimated through manual annotation using specific coding systems[16,50], one major advantage of this automatic methodology is the reduction in the need for extensive training and the time and labor intensity associated with manual coding. Furthermore, a unique feature of this motion capture tool is the granularity of analysis it provides. Only this automatic method could assess the kinematic profile of head movements and detect the speed alterations in CHR individuals—details that manual methods would likely miss. The automatic measurement of spontaneous head movements has multiple implications and has already been applied to other clinical populations, demonstrating its relevance. Studies have utilized this method with depressed individuals[51] and children with autism spectrum disorder[42,52]. For example, head movements patterns collected automatically from a three-minute conversation were able to distinguish between autistic and neurotypical individuals[53]. Since these tools only require videos from standard cameras, they have the potential to be easily adopted in the future by mental health professionals. Videos captured in an ecological context or online footage could be used to improve psychosis risk detection and enable automatic assessment in the community.

While this study has several strengths, such as the large sample size and the objective, scalable, and precise methodological approach to automatically assessing spontaneous head movements, there are also some limitations to consider. First, the reliance on videos of clinical interviews is a limitation. While this provides a standardized and emotionally neutral context, this setting may not elicit as many head movements compared to a fully natural interaction. Additional research should investigate head movements in contexts beyond clinical interviews to better understand the generalizability of the findings, as well as across multiple interview segments to determine the reliability of the results. Second, as is common in studies investigating dyadic interactions, we cannot be entirely certain whether the impaired head movement patterns observed in the CHR participants are inherent to the patients themselves or are influenced by impairments in their ability to synchronize with the interviewer's movements or some other aspect of their dyadic interaction. Human social interactions are inherently bidirectional and both interactors influence one another[54]. To date, no studies have examined interpersonal synchrony or mimicry abilities in CHR individuals. Existing research on schizophrenia has reported mixed results regarding patients' ability to mimic their conversation partner, with most studies only focusing on emotional facial expressions[55]. Therefore, future studies should assess both conversation partners' head movements to clarify the role of social entrainment in shaping CHR individual behaviors. In addition, we further explored whether these movement patterns remained stable throughout the clinical interview. While no significant group differences were observed when analyzing shorter segments of the interview (first or last 2.5 min), correlations between early and later head movement variables—particularly for the speed of head turns—suggested individual stability in head movement dynamics. These results support the utility of analyzing at least 5 min of interaction to detect subtle, yet meaningful, group-level differences. They also underscore the importance of considering temporal variability and the dynamic interpersonal exchange in nonverbal behavior during social interactions[56,57]. Future studies will be need to determine optimal time frames, as slicing shorter windows has been found to be effective for detecting aberrant facial expressions in CHR[13], but not for head movement patterns. Similarly, since we recorded clinical interview where speech was exchanged, linguistic variables such as the amount of speech or its emotional content could have influenced head movements[58]. A key limitation of this study is the lack of detailed speech annotations. Extracting speech transcription, defining turn-taking, counting the number of questions answered or words spoken, and identifying positive and negative emotional content could provide valuable insights into the functional role of head movements. Future research should incorporate automatic motion analysis and speech-event annotation to better contextualize head movement findings in relation to conversational dynamics.

To conclude, analyzing short excerpts of clinical interview using automated approaches to extract head movement patterns revealed that CHR individuals exhibit an idiosyncratic kinematic profile, specifically a decreased speed of side-to-side head turn behavior relative to healthy individuals. This study serves as a proof of concept for the use of automated method to support and enhance traditional manual coding. This also provides new insights into alterations in social functioning—specifically alterations in a nonverbal social behavior with important links to social communication and social cognition—in this population. Our results also indicate that this specific alteration is linked to the positive symptom of "disorganized communication," a symptom with significant implications for individuals' social lives and everyday functioning. These findings further support the relationship between motor and social domains and hold promise not only for research but also for screening, psychosis risk detection, and social functioning assessment in this population. Longitudinal studies are now needed to track head movement patterns across different stages of illness, which could help determine whether these changes correspond with symptom progression or treatment response.

METHODS

Participants

A total of 177 participants (87 CHR and 90 young healthy controls), aged 12–30 ($M = 19.64$, $SD = 2.81$), were recruited through the Adolescent Development and Preventive Treatment (ADAPT) Program using Craigslist, e-mail announcement, flyers and community health referrals. Exclusion criteria consisted of head injury, the presence of neurological disorder, and lifetime substance dependance. The presence of a psychotic disorder (e.g., schizophrenia, schizoaffective disorder schizophreniform) was an exclusion criterion for CHR participants, as determined by the SCID-IV[59]. The presence of any psychotic disorder for control participant and their first-degree relative was an exclusion criterion. All participants were informed and signed the consent form before entering the study, approved by the university Institutional Review Board (protocol #10-0398).

Symptom assessment

To identify a CHR syndrome, participants were given the Structured Interview for Psychosis-Risk Syndromes (SIPS)[60], defined by a moderate-to-severe but not psychotic levels of positive symptoms (rated from 3 to 5 on a 6-point scale) or a decline in global functioning accompanying the presence of schizotypal personality disorder or a family history of psychosis. The SIPS was also used to assess symptoms in CHR participants. The interviewers were trained master level, doctoral, and postdoctoral students.

The Beck Depression Inventory-II (BDI-II) was used to assess depression severity of all participants[61]. The BDI-II is a self-rating scale with 21 items (0 to 3-point scale). Out of the 177 participants included in this study, 171 had BDI-II scores (85 CHR and 86 healthy controls).

Head movement analysis

Segments of the first five-minutes of video-recorded clinical interviews from the SIPS were used to analyze participants' head movements. The interviews always took place in the same room, and the participants were seated on a couch in front of the camera, always at the same distance to prevent inter-individual differences in the setup. The camera model was a Canon HD Camcorder VIXIA HF R800. The content included obtaining information regarding demographic and was neutral and uniform across participants. Thin slices of behavior (1–5 min) have been shown to be sufficient for identifying alterations in social behavior, such as facial expressions, in individuals at CHR, as assessed both automatically and manually[13].

Footage was processed using Google's MediaPipe Face Mesh program. MediaPipe Face Mesh is an open-access tool that estimates 468 3D face landmarks from a 2D video[62] (see Fig. 3A). We utilized the Python notebook from the *envisionBOX*, which integrated head rotation into the MediaPipe tracking pipeline[63] (see Fig. 3B). This implementation used specific face landmarks (indices 1, 33, 263, 61, 261, and 199, which are evenly distributed across the face) for generating rotation vectors, obtaining a rotation matrix, and decomposing it into Euler angles in the three axes: x, y and z[64]. For the face landmarks, x and y represent the position of keypoints in the image pixel space, while z denotes the depth, with the center of the head as the origin. Smaller z values indicate closer proximity to the camera.

The adapted MediaPipe pipeline outputted three timeseries representing the Euler angles in radian of head movement along the x, y and z axes. The x-axis rotation corresponds to pitch (i.e, head raise), the y-axis rotation to yaw (i.e., head turn) and the z-axis rotation to roll (i.e., head tilt) (see Fig. 3C). The videos were generally sampled at 29.97 Hz, with some at 59.94 Hz. We downsampled the 59.94 Hz videos by selecting every other time point to ensure uniform analysis at 29.97 Hz. Each timeseries contained exactly 9000 time points. We then applied a 3rd-order zero-phase Butterworth filter with a frequency cutoff of 5 Hz to the timeseries. To normalize the data between participants, we performed centering (subtracting the mean) and rescaling (dividing by the standard deviation) (see Fig. 3D).

Based on previous studies on head movement in CHR individuals[17,24], we computed three motor variables for each participant:

Total amount of head movement was calculated by summing the Euler angle values at every timepoint across the three axes.
Mean amplitude of movement peaks in each axis was calculated by identifying peaks in the timeseries, measuring the amplitude for each peak relative to the preceding local minimum, and averaging these amplitudes.
Median speed of rotation in each axis was calculated as the median of the ratio of peak amplitude to the duration of each peak.

Statistical analysis

Shapiro-Wilk tests were used to evaluate the normality of the distribution of the three motor variables described above (total head movement, mean amplitude in x, y and z, and median speed in x, y and z). Since the distributions were not normal, we performed the non-parametric test Mann–Whitney U on all motor variables. Correction for multiple comparisons was applied across the full set of motor variables (total amount of movement, amplitude and speed in the x-, y- and z-axes) using both Bonferroni and FDR tests. To examine whether depression severity, provided by the BDI-II, accounts for the significant relationship between group and head motor variables, we conducted a multiple regression analysis.

To test our second hypothesis regarding the association between symptoms and motor variables, we performed Pearson and Spearman correlation analyses on individuals with CHR, primarily focusing on social symptoms represented by disorganized communication (SIPS item P5) and the total score on the SIPS negative subscale. We also explored correlations with (1)

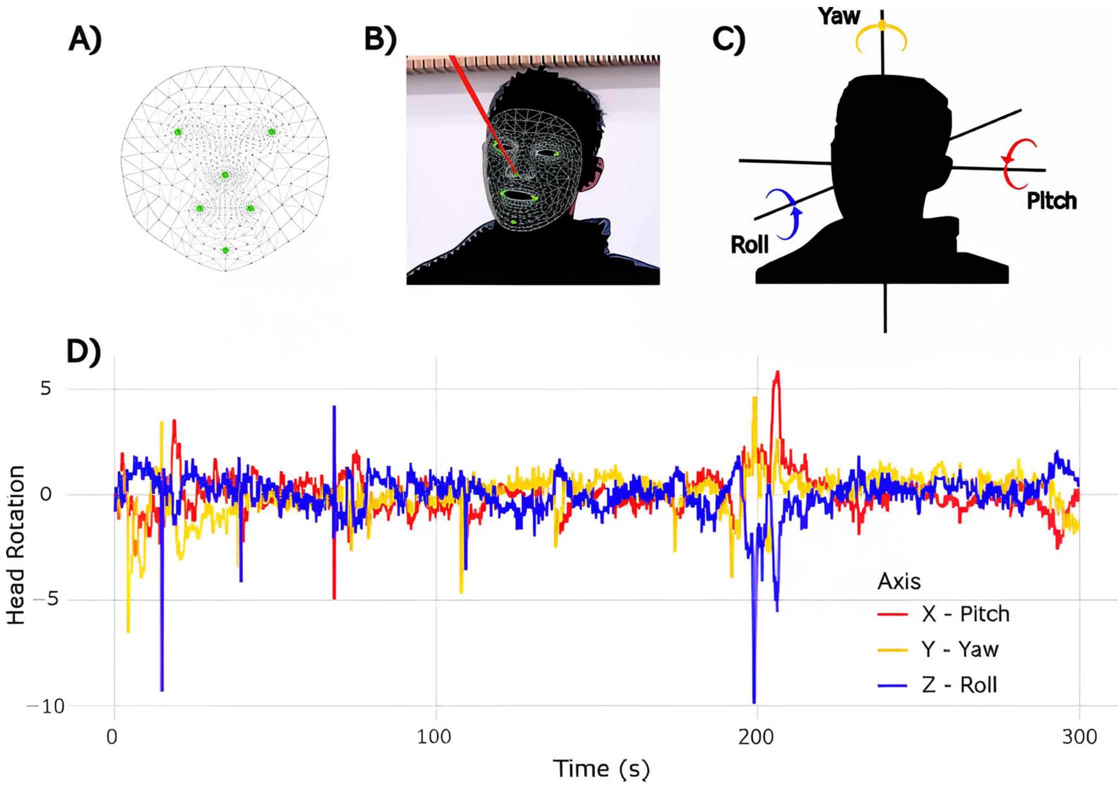

Fig. 3 Methodological procedure for obtaining head rotation timeseries. **A** MediaPipe Face Mesh model, with green landmarks used for head tracking[64]. **B** Screenshot of the head tracking of a participant, with the Face Mesh model and landmarks. The red line indicates the direction of the head. **C** Representation of the three rotations axes to calculate roll, pitch and yaw angles for head tracking. **D** Example timeseries of head rotation in each axis of a participant, filtered and normalized.

unusual thought content (SIPS item P1), (2) suspiciousness (SIPS item P2), grandiose ideas (SIPS item P3), and perceptual abnormalities (SIPS item P4). All p-values are two-sided. Correction for multiple comparisons was applied using both Bonferroni and FDR tests. When Pearson and Spearman correlation analyses produced similar results, we reported only the Pearson coefficient and p-values. We applied the same methodology for an exploratory correlation analysis with the other clinical symptoms (see Supplementary analysis).

DATA AVAILABILITY

The data that support the findings of this study are available upon request from the corresponding author JLG. The data are not publicly available due to them containing information that could compromise research participant consent.

CODE AVAILABILITY

The code used to extract the 3D head trajectories and angular positions from the videos is freely available via the software *EnvisionBOX*[63]. The code used to compute the head motor variables is available upon request from the corresponding author JLG. Head tracking was conducted using Python 3.12.3, and movement analysis and statistical tests were performed in RStudio 2024.12.1.

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AUTHOR CONTRIBUTIONS

T.G. and V.A.M. conceived the concept and designed the study. T.G Collected the data. J.L.G analyzed the data and wrote the manuscript. V.A.M., T.G., T.F.W., A.P., C.H. and S.S. reviewed and commented on the manuscript and results explanation.

COMPETING INTERESTS

The authors declare no competing interests.

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