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Uncoupling Between Multisensory Temporal Function and Non-Verbal Turn-Taking in Autism Spectrum Disorder

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***Abstract* — The integration of information across distinct modalities enhances perceptual abilities. An ecologically important role of multisensory integration is in scaffolding verbal communication, which relies upon the precise temporal integration of auditory and visual cues. However, the role of (multi)sensory function in supporting another important aspect of communication, namely, non-verbal communication, is unknown. Here, individuals with ASD and a group of typically developing (TD) participants performed a simultaneity judgment task to index their audiovisual temporal acuity for speech stimuli. Further, under a naturalistic scenario, non-verbal synchrony between the participant and a naïve experimenter was measured. Automated motion analysis was performed to quantify movements of different body-parts. Results demonstrate a wider window of audiovisual temporal integration for ASD participants in comparison to their TD counterparts. Moreover, ASD individuals performed less complex movements and demonstrated less non-verbal synchrony during the interactive exchange. Lastly, multisensory temporal acuity significantly predicted the synchrony in hand and head movements between TD participants and the experimenter, but not between the ASD participants and the experimenter. Taken together, the results suggest an important role for multisensory perceptual abilities in shaping non-verbal communication between dyads and highlight the important role of perceptual systems in supporting social interactive skills.**

***Index Terms*— Autism, Body, Non-Verbal, Communication, Multisensory, and Interaction**

I. Introduction

THE last several decades have seen the introduction of robotic devices to fields such as industrial production and medicine [1, 2]. Further, these devices, which are becoming increasingly human-like [3], are expected to become an integral part of our social landscape as they permeate our homes and offices [4, 5]. While the automation accompanying the widespread introduction of robots into our daily lives certainly holds great promise, this occurrence will pose a number of significant challenges [6, 7]. For instance, establishing appropriate social exchanges, both in the context of human-human [8, 9] and human-robot [10, 11] interactions, takes place over a protracted developmental timecourse. Hence, the relatively abrupt introduction of robotic devices into an already well-established human-human social landscape may be well served to follow social norms humans have acquired through evolution and an extensive period of development [12, 13]. Consequently, to be good social partners, robots should understand and follow existing human communication structures [14]. It is under this context that the refinement of our understanding of human-human interactions and the mimicking and implementation of these interactions in human-robot systems becomes increasingly important for the seamless integration of machines into our society.

In the current study we focus on further refining our understanding of human-human social interactions, and make the argument that a crucial component to any social interaction is communication [15]. Moreover, we argue that an important yet often overlooked aspect of communication is in the associated non-verbal signals. In particular, non-verbal turn taking [16], motor contagion [17], and resonance [18] have all been shown to impact the quality of social interactions (see equally [19-21]). Despite a growing appreciation for the importance of these non-verbal signals, our knowledge of how successful non-verbal communication emerges between dyads remains elusive. Although we implicitly assume that higher-level cognitive abilities (such as social communication) are scaffolded upon sensory systems [22, 23], we are missing strong and specific links between non-verbal communication and perceptual ability.

A potentially fruitful area of inquiry around this question lies in the clinical arena. Thus, to establish a putative association between perceptual abilities and non-verbal interactive skills one can contrast non-clinical individuals with individuals in whom a known deficit exists in both social interaction and perceptual skills. The study of individuals diagnosed with Autism Spectrum Disorder (ASD) provides such an opportunity, as these individuals typically show deficits in social interaction and communication, as well as repetitive patterns of behaviors and restricted interests [24]. More specifically within the social interactive arena, among other deficits, individuals with ASD show difficulty in forming social relationships [25], understanding gestures and facial expressions [26], and empathizing with others [27], which includes weaknesses in abilities such as understanding other's intentions, feelings and mental states [28]. Additionally, the presence of sensory and multisensory abnormalities in these patients is increasingly recognized [29], as highlighted by the inclusion of sensory features as a core diagnostic element of ASD in the DSM-5 [30]. Indeed, it has been postulated that changes in sensory and multisensory function may play an important and under-recognized role in the behavioral, perceptual and cognitive deficits exhibited by ASD patients [31, 32]. Hence, the study of ASD individuals and the relationship between sensory and social communication measures may represent an important stepping-stone toward a better characterization of the perceptual skills necessary to support successful social interactions in both typical and clinical populations.

Multisensory integration, the combination of information from the different senses (e.g., audition and vision), is critical for successful interactions with an external environment that is inherently noisy and dynamic [33-35]. The process of integrating information across distinct senses has been repeatedly demonstrated to result in a host of perceptual gains [36-38]. A critical feature of multisensory integration is the appropriate segregation and binding of sensory information in the temporal domain [39, 40], and it is in this domain that abnormalities in ASD are typically observed [41-43]. Indeed, timing across the different senses is an interesting challenge for the central nervous system, as information from the different senses propagates at very different rates through the environment and is processed at very different rates within the nervous system. Hence, subjective perception of synchrony across the senses is not commonly perceived at true physical simultaneity [44] but rather at stimulus onset asynchronies (SOA) that reflect the statistics of the natural world (i.e., compensating for the difference in propagation times across the senses [45, 46]). Likely as a result of these differences, human subjects typically report perceiving audio and visual stimuli as co-occurring in time even when the individual stimuli are separated by several hundreds of milliseconds. Indeed, this has resulted in the perceptual construct of a Temporal Binding Window (TBW; [47, 48]): the interval of time over which subjects are highly likely to perceive two temporally disparate stimuli from different senses as occurring simultaneously. Interestingly, individuals with ASD possess atypically large TBWs [49, 50], in particular for speech stimuli [51]. More specifically, individuals with ASD judge larger audio-visual asynchronies as co-occuring in time (i.e., being synchronous) than do their typically developing (TD) counterparts. Further, this poor multisensory temporal acuity appears to be strongly related to the communicative challenges frequently observed in these individuals [41, 51, 52].

As stated earlier, however, communication is neither merely verbal nor entirely static. For example, a typical conversation consists of a complex communicative process in which visual and auditory verbal and non-verbal signals are combined in a reciprocal back-and-forth exchange. Such turn-taking is a universal characteristic of social interactions [53], is exquisitely precise in time [54, 55], and reflects a social cooperative coupling that is central to efficient information transfer [56] – particularly in human communication [57]. These properties (e.g., multisensory, cooperative, and relying on precise timing; [58]) raise the question as to whether turn taking, or non-verbal synchrony during conversation, is impaired in ASD (e.g., [59]), and whether such a putative deficit is related to poor multisensory temporal function. The study of non-verbal synchrony in ASD is particularly interesting, as it is a component of communication that has been somewhat neglected in ASD. Furthermore, there appears to be no study to our knowledge investigating the links between sensory processing and non-verbal synchrony in ASD. Amplifying the interest in this question, recent findings in schizophrenia (another condition exhibiting anomalous multisensory temporal function; [60]) have demonstrated that improved coordination of bodily movements between a patient and their interlocutor is associated with positive outcomes including socio-communicative gains [61, 62].

In the current study, we have individuals with ASD and TD controls perform an audio-visual speech simultaneity judgment task to measure multisensory temporal acuity. In addition, in these same subjects we video record neuropsychological evaluation sessions (in a standardized manner and with a naïve experimenter) in order to perform non-verbal synchrony analyses. We index movement in three areas of interest for each participant in the interaction - the head, hand, and trunk – and categorize total number, duration, and complexity of movements, in addition to quantifying the synchrony in the dyadic exchange. By doing so, we provide an account demonstrating the relationship between non-verbal synchrony and multisensory temporal processing in an ecological valid communicative exchange in TD and ASD participants.

II. MATERIALS AND METHODS

A. Participants

Twenty-seven participants took part in the study (mean age = 11.39 ± 2.76, range = 7.9 – 16.5, 7 females). Twelve of these participants (mean age = 12.20 ± 3.75, range = 7.9 – 16.5, 4 females) were diagnosed with Autism Spectrum Disorder by a research-reliable clinical practitioner according to the DSM-V [17], using the Autism Diagnosis Observation Schedules [ADOS; 63] and/or the Autism Diagnostic Interview-Revised [ADI-R; 64]. All individuals with ASD were considered to be high functioning, as these individuals are able to perform the battery of psychophysical tasks carried out by our laboratory (for related research see [32], [35], [38], [41], [43], [49], [50], [51]). Individuals in the TD group (n = 15, mean age = 10.94 ± 2.13, range = 8.9 – 14.5, 4 females) had no diagnosis of ASD or any other psychiatric disorder. ASD and TD groups did not differ in age ($t(25) = 1.10$, $p = 0.28$), nor in non-verbal IQ (Test of Nonverbal Intelligence; TONI-4 [65], ASD, M = 106.34, SD = 18.34; TD, M = 111.64, SD = 19.53; $t(25) = 0.71$, $p = 0.47$) and hence our participants were matched for age and IQ at a group level. Participants with ASD on average scored above the population mean for non-verbal behavior (TONI-4 population average = 100 ± 15), thus confirming their high functioning status. Caregivers of all participants gave written informed consent to partake in the study, which was approved by Vanderbilt University Medical Center's ethics board.

B. Multisensory Temporal Acuity: Methods

Multisensory temporal acuity was measured by means of an audio-visual simultaneity judgment task [e.g., 66-68]. Participants were seated inside an unlit and sound-attenuated WhisperRoom, and presented with speech stimuli, a female speaker uttering single instances of the syllable /ba/ or /ga/

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(Figure 1a), in which the audio and visual components were presented at a lag. The visual component of this stimulus was presented in grayscale and had a resolution of 400 x 400 pixels subtending 17.3° of visual angle. Presentations were 2 seconds in duration, and each presentation included the entire articulation of the syllable, including pre-articulatory gestures. The set of audio-visual stimuli onset asynchronies (SOA) utilized were; 0, ±150, ±250, ±300, ±350, ±400, ±500ms (negative values indicating audio-lead and positive values indicating visual-lead). Each condition was repeated 16 times, for a total of 208 trials. Reports of synchrony as a function of SOA were fit for each participant with a Gaussian distribution [66-68] in which the amplitude, mean, and standard deviation of the normal were free parameters. The resulting standard deviation of the best fit Gaussian for each participant was taken as his/her TBW.

C. Quantification of non-verbal behavior; Pre-processing

A total of approximately 20 hours (ASD = 0.81 ± 0.32 hours per subject, total of 9.74 hours; TD = 0.64 ± 0.26 hours per subject, total of 9.64 hours; p = 0.29) of digitized video sequences (10 frames/s; Sony HDR-XR350V, 1920x1080 pixels resolution; Figure 2a) of seated neuropsychological testing and natural conversation (i.e., pauses between tests) between an experimenter and either an individual with ASD or TD were analyzed by means of automated motion energy analysis (MEA; [62]).

Neuropsychological testing were performed using an array of different tasks and tests, and consisted of all or a subsample of the following: Test of Nonverbal Intelligence (TONI-4; [65], the Test of Word Reading Efficiency (TOWRE-2 [69]), The Woodcock-Johnson III [WJ; 70] – an assessment of cognitive ability, achievement and oral language, The Expressive One-Word Picture Vocabulary Test (EOWPVT-4; [71]), and the Clinical Evaluation of Language Fundamentals (CELF; [72]). The videos analyzed were selected solely from the CELF [72] and WJ III [70], as well as during periods between the different tests, in order to maximize the ecological validity of the interaction between the participant and naïve experimenter. The CELF is a flexible system of individually administered tests utilized to diagnose a language disorder and encompasses naturalistic tests of language comprehension, sentence recall, semantic relationships, direction following, etc. The component of the WJ within which videos were analyzed was the General Information assessment, in which subjects respond to questions such as "Where would you find…" or "What would you do with…" Neuropsychological evaluations were not utilized as dependent variables due to the fractioned nature of the data collected (i.e., not all participants completed the same array of tests), and in order to reduce the potential for Type I statistical error.

Video camera placement was fixed and standardized – placed at chest level and approximately 3 meters away from the interacting dyad. Motion energy was quantified as the sum of differences in grey-scale pixels between consecutive video-frames (Figure 2a; see [73] for detail), within a restricted region of interest (ROI). These ROI's (Figure 2a, left-most insert) were centered on the participant's or experimenter's head, hand, or trunk, and extended in space to include the peri-personal space [74] of the mentioned body part. Regions of interest did not overlap. Next, video frames were converted to grey-scale (Figure 2a, middle insert), and a Laplacian filter was applied in order to detect edges (Figure 2a, right-most insert). Change in pixel-values ('1' or '0') over time thus indicate a change in the location of a boundary; i.e., movement.

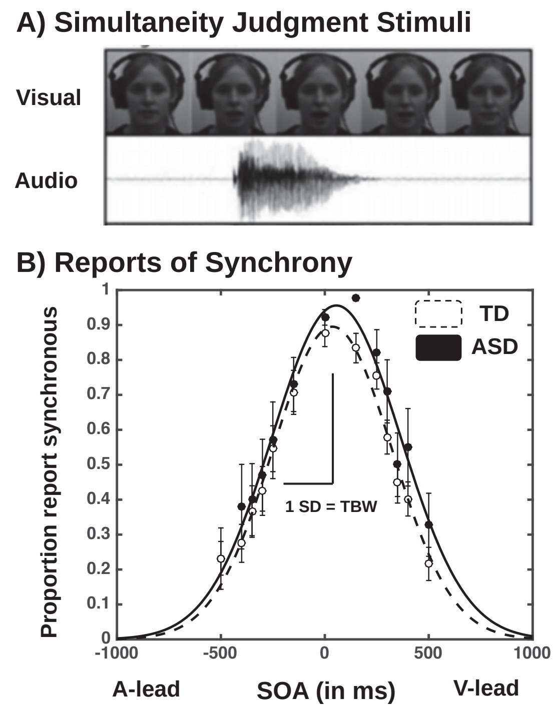

Figure 1. Audiovisual simultaneity judgment stimuli (A) and results (B). Participants viewed a female speaker uttering a single syllable in which the visual (A, top) and audio (A, bottom) tracks were offset in time and they were asked to report on synchrony. Results demonstrate that individuals with ASD (solid lines) report synchrony over larger temporal intervals than did TD participants (dashed lines).

D. Quantification of non-verbal behavior; Analysis

Non-verbal behavior was assessed via the study of movement synchrony between ASD and TD individuals with a naive experimenter. Movement synchrony was measured for various body parts (head, hand, and trunk; Figure 2b). Movement synchrony was operationalized as the co-occurrence of movements in time between the participant and the experimenter, with movement being automatically detected via motion energy detection as a change in the spatial location of body-part boundaries on consecutive video-frames (see Section II. C). In order to quantify non-verbal behavior, thus, as in [62], the motion energy timecourse for each body part was subdivided into epochs of 300 timepoints (30 seconds). For each epoch an R-value (Pearson correlation) was computed representing the synchrony in movement between participant and experimenter. In order to offset the possibility of the results being heavily influenced by epochs of no activity by part of neither the participant nor the experimenter, resulting in spuriously high correlations, epochs with R-values superior to .9 were discarded (~ 12% of epochs, independent sample t-test between ASD and TD, t(25) = 0.84, p = 0.40). Remaining R-values were first averages within and then across subjects.

Next, in order to qualify whether a reduction/enhancement in synchrony between participant and experimenter was due to a difference in the complexity of movements performed by TD and ASD participants, the complexity of the timecourse of movements for the different body parts were quantified via the Lempel-Ziv algorithm [LZ; 75]. LZ complexity is the most popular out of the Kolmogorov class (routinely used to generate TIFF images and ZIP files), and measures the approximate amount of non-redundant information contained within a string by estimating the minimal size of the 'vocabulary' necessary to describe the entirety of the information contained within the string in a lossless manner. LZ can be used to quantify distinct patterns in symbolic sequences, especially binary signals. Thus, before applying the LZ algorithm, as implemented in MATLAB's *calc_lz_complexity.m*, we converted the motion energy analog timecourse to a binary sequence. Separately for every participant and epoch (as defined above) we assigned a value of '1' to a time point if the response was 2 standard deviations above the mean value for that particular epoch and a '0' if it was not. The LZ complexity algorithm then determined the size of the dictionary needed to account for the pattern of binary strings observed in the particular epoch. Epochs were then first averaged within subjects and subsequently across them.

Lastly, as control analyses, we quantified the first-order characteristics of the movements executed by both ASD and TD participants. This analysis was done in order to insure that the quantification of dyadic movement synchrony was unaffected by intra-personal (as opposed to inter-personal) motoric characteristics, and was carried out by quantifying the duration and total number of movements executed by each participant. For measurement of movement duration, a continuous binary sequence was generated for the entire timecourse of movement, and was divided based on whether movement surpassed a 2 standard deviation threshold or not. Duration of movement (i.e., temporal interval between onset and offset) was quantified by means of MATLAB's (MathWorks, Natick, MA) *findpeaks.m* function. A similar approach was undertaken for the quantification of the total number of movements executed. However, as the total duration of the measured neuropsychological evaluations varied from individual to individual, movement time-courses were first parceled into epochs of 300 timepoints (see Section II.B). Total number of movements were quantified within each epoch, and then averaged first within subjects and then across subjects.

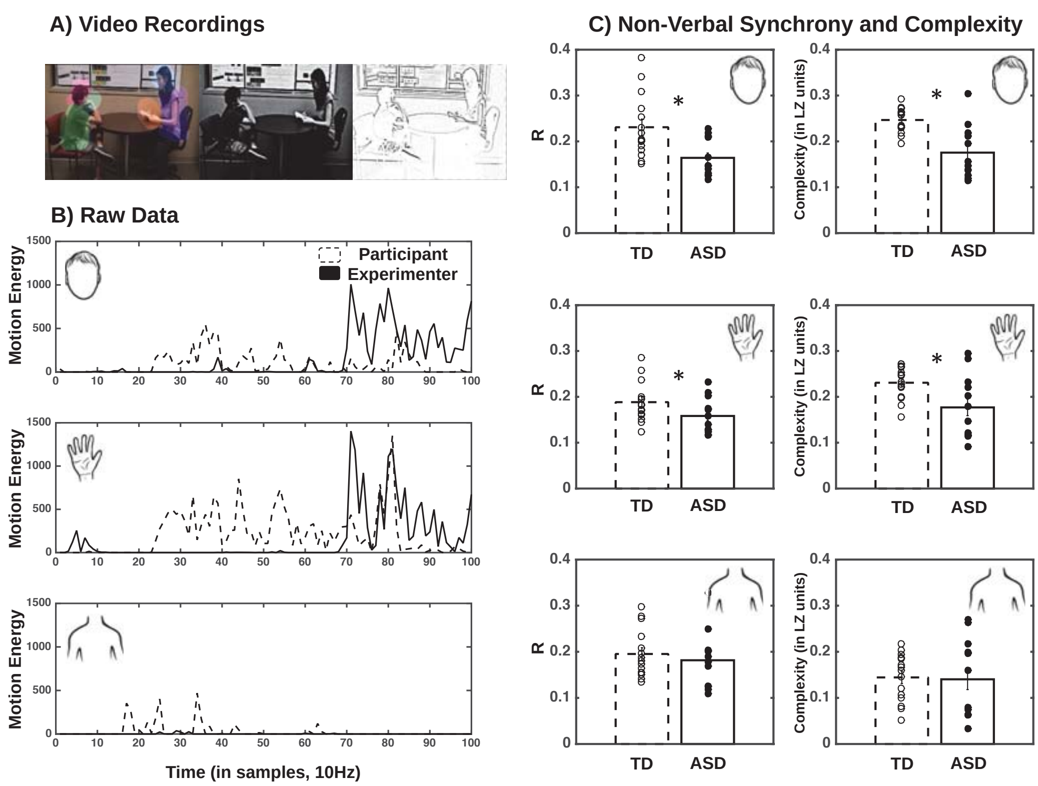

Figure 2. Video motion analyses and quantification of non-verbal behavior. A) Illustration of the pre-processing pipeline in which regions of interest are defined (left), videos are converted to grayscale (center), and Laplacian filtering is used in order to detect edges (right). Motion energy analysis quantifies change in the location of the edges frame-to-frame (i.e., movement (see [53] for more detail). B) Raw motion energy time-course plots for each body part (top: head, middle: hand, bottom: trunk) charted for both the participant (dashed lines) and the experimenter (solid lines). C) Results of non-verbal synchrony and complexity analyses. TD participants (dashed lines) demonstrate both increased synchrony (left column) with their interlocutor and increased complexity (right column) for head and hand movements (top and middle row) when compared with ASD participants (solid lines). There is no difference in complexity or synchrony between the groups for the

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trunk. In these plots, each dot represents a participant, and an asterisk denotes statistical significant differences (p < 0.05) between groups

III. RESULTS

A. Multisensory Temporal Acuity

An unpaired t-test between the width of the best-fit Gaussian's for participants with ASD (M = 350.43ms, S.E.M. = 27.35ms) and TD subjects (M = 223.61ms, S.E.M. = 19.93ms) demonstrated the ASD group to possess larger TBWs for judging the simultaneity of audiovisual speech pairs ($t(25) = 3.86$, $p < 0.001$, see Figure 1b). This result replicates prior findings [32, 35] evidencing poorer multisensory temporal acuity in individuals with ASD.

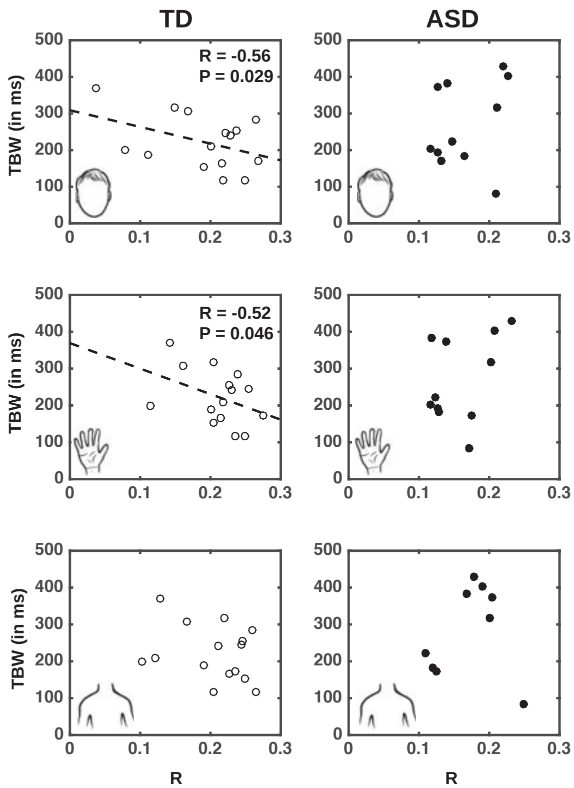

Figure 3. Relationship between multisensory temporal acuity and nonverbal synchrony for TD (left) and ASD (right) subjects divided by body part. Plots illustrate the correlation between the size of the TBW (y-axis) and the degree to which participant's movements correlated with the experimenter's movements (x-axis) for head ROI (top), hand ROI (middle) and trunk ROI (bottom).

B. Non-Verbal Synchrony and Complexity

Synchrony of movements across the different body parts and between participants (ASD or TD) and the naïve experimenter was quantified via a 2 (group: ASD vs. TD) X 3 (body part: head, hand, trunk) mixed-model ANOVA. This analyses demonstrated a significant main effect of group ($F(1, 25) = 5.58$, $p = 0.026$, partial eta = 0.18), as well as a significant group x body part interaction ($F(2, 50) = 2.84$, $p = 0.042$, partial eta = 0.12; see Figure 2c, left column). There was no main effect of body part ($F(2, 50) = 0.409$, $p = 0.667$). In order to elucidate the root of the interaction, separate independent samples t-test were conducted contrasting ASD and TD group for each body part. This analyses demonstrated increased interpersonal synchrony for TD participants when compared with the ASD participants for the head ($t(25) = 3.29$, $p = 0.003$) and the hand ($t(25) = 2.00$, $p = 0.045$), but not for the trunk ($t(25) = 1.04$, $p = 0.30$).

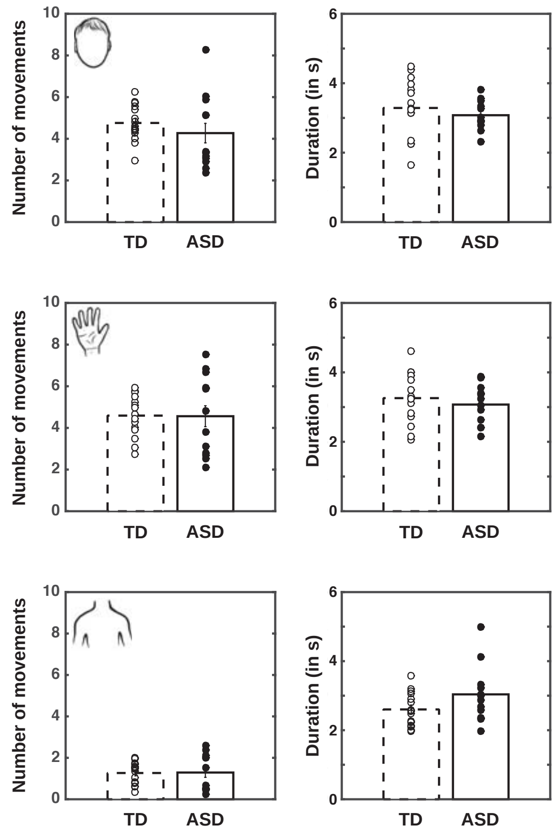

Figure 4. Control analyses of motor behavior. TD (dashed lines) and ASD (full lines) participants did not differ in either the amount of movement per 30 seconds interval (left column) or the duration of movements (right column) for any of the body part ROIs. Data from individual participants are plotted as individual dots.

One possibility is that the difference in interpersonal synchrony between groups may be in the nature of the movements themselves that TD and ASD participants performed. Hence, we quantified the complexity of the movements performed for each group and body part. This analysis employs an objective measure of whether participant's movements were rhythmic and easily predictable (low complexity) or whether movements were non-stereotyped, non-rhythmic, and not easily predictable (high complexity). As above, we conducted a 2 (group: ASD vs. TD) x 3 (body part: head, hand, trunk) mixed-model ANOVA. Similar to the synchrony results, this analysis demonstrated significant main effects of group ($F(1, 25) = 35.44$, $p < 0.001$, partial eta = 0.68), a significant group x body part interaction ($F(2, 25) = 13.00$, $p = 0.001$, partial eta = 0.34), as well as a

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main effect of body part – which was not present in the synchrony results ($F(2, 25) = 54.46$, $p < 0.001$, partial eta = 0.31, see Figure 2c, right column). The body part main effect was driven by a difference in the mean complexity of movements performed with the head and hand relative to the trunk (paired-samples t-test; head vs. trunk, $t(26) = 6.47$, $p < 0.001$; hand vs. trunk, $t(26) = 6.78$, $p < 0.001$; head vs. hand, $t(26) = 1.59$, $p = 0.12$). The significant interaction, in turn, was driven by differences in movement complexity between ASD and TD for the head ($t(25) = 4.20$, $p < 0.001$) and hand ($t(25) = 2.61$, $p = 0.015$), but no difference in trunk movement complexity ($t(25) = 0.15$, $p = 0.87$). Where these differences were found, the complexity of movements for TD participants was greater than that for ASD participants.

Interestingly, however, there was no significant correlation between interpersonal synchrony and the complexity of movements they performed (all $R < 0.37$, all $p > 0.16$). Thus, although ASD and TD participants did exhibit distinct movement patterns with differing degrees of complexity, the nature of the movement performed by the participants did not explain a significant portion of the synchrony differences observed. That is, the distinction in interpersonal motor synchrony between ASD and TD participants was uncoupled from differences in movement complexity. This implies that differences in movement complexity are not sufficient to account for differences in interpersonal synchrony between ASD and TD groups.

An alternative explanation for the differences in interpersonal synchrony lay outside of the motor domain, and revolves around possible differences in sensory function. Extending beyond simple sensory function is the importance of multisensory integration, as such integration is a critical element of both verbal and non-verbal communication signals. To explore the potential multisensory contributions to the observed differences in synchrony, we correlated individual participant's audiovisual temporal acuity (i.e., TBW size) with measurement of non-verbal interpersonal synchrony. The results demonstrated significant negative correlations for the TD participants for head ($R = -0.56$, $p = 0.029$) and hand ($R = -0.52$, $p = 0.046$) ROIs, but not for the trunk (although a trend was present, $R = -0.41$, $p = 0.12$; See Figure 3, left column). On the other hand, there appeared to be an uncoupling between the multisensory TBW and non-verbal synchrony in ASD participants, as none of the ROIs demonstrated a significant correlation (all $|R| < 0.40$, all $p > 0.14$, see Figure 3, right column). Interestingly, there was no correlation between measures of motor complexity and TBW size for either TD (all $|R| < 0.35$, all $p > 0.26$) or ASD (all $|R| < 0.13$, all $p > 0.64$) subjects.

C. Motor behavior: Control Analyses

In addition to examining motor complexity, we considered that it was important to rule out the possibility that differences in non-verbal synchrony between ASD and TD groups were driven by either the amount of the movements performed or their duration. Hence, we quantified these variables and performed two separate (for number of movements and duration of movements, respectively) 2 (group: ASD vs. TD) x 3 (body part: head, hand, trunk) mixed-model ANOVAs. Regarding the number of movements, results showed a main effect of body part ($F(2, 50) = 128.06$, $p < 0.001$), but no main effect of group ($F(1, 25) = 0.15$, $p = 0.70$), nor a body part x group interaction ($F(2, 50) = 1.07$, $p = 0.37$, see Figure 4, left column). The main effect of body part was driven by the fact that there were more movements performed with the head and hand than with the trunk (all $p < 0.001$). In terms of the duration of movements, the mixed-model ANOVA revealed no main effects, neither of body part ($F(2, 50) = 1.89$, $p = 0.07$) nor group ($F(1, 25) = 0.004$, $p = 0.952$), nor an interaction between these variables ($F(2, 50) = 2.57$, $p = 0.18$; See Figure 4, right column).

IV. DISCUSSION

Overall, the results of the current study suggest that non-verbal synchrony with an interacting interlocutor, as well as the complexity of movements of distal body-parts (head and hand), are reduced in a population known to exhibit socio-communicative deficits (i.e., ASD). Importantly, an explanation based purely on motor factors is insufficient to account for the reduction in dyadic non-verbal synchrony in the ASD group, as these individuals show similar 'first-order characteristics' (i.e., total number and duration) of movements when compared with the TD group. Further, findings showed no correlation between the reduction in motor complexity and synchrony of movements. On the other hand, at the group level, participants with ASD demonstrate poorer audiovisual temporal acuity (i.e., enlarged TBW; replicating prior work, [32, 35]), and most strikingly, show an uncoupling between multisensory perceptual ability as indexed via the TBW and motor synchrony. Thus, in the TD individuals, at least for the head and the hand, the narrower the participant's temporal binding window, the greater their interpersonal synchrony. This makes good ecological sense, in that one would expect that the capacity to process and integrate sensory information (in this case within the temporal domain) should significantly impact the manner in which one relates to the environment. This relationship was not seen in individuals with ASD.

The current findings build off of prior work highlighting that individuals with ASD show impairments in multisensory processing, particularly within the temporal dimension, and that these sensory changes closely relate to verbal communicative deficits within this population [31, 32, 41, 51]. Here we argue that communication is neither purely verbal nor static, and show that individuals with ASD also demonstrate impairments in a particular aspect of non-verbal communication, namely, non-verbal synchrony. In contrast to prior work that illustrated a strong relationship between multisensory temporal acuity and verbal communication in ASD [31, 32, 41, 51], here we found a lack of relationship between multisensory temporal acuity and non-verbal

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synchrony in our ASD participants (a relationship that was indeed found in our TD participants). Thus, the current findings seem to implicate that there is a lack of (adaptive) coupling between multisensory perceptual skill (i.e., temporal acuity) and non-verbal synchrony in ASD, as if these individuals do not make use of (multi)sensory evidence in building higher-order cognitive representations. These results are in line with recent "hypo-prior" accounts of ASD [76, 77], which suggest that ASD may be rooted in a fundamental inability to use sensory evidence to build a strong representation of prior history about the sensory world (see [42, 43, 78, 79] for recent empirical evidence in this regard).

In addition to furthering our understanding of the pathophysiology of autism, we believe that these findings also have strong implications for the development of novel technologies and the study of robot-human interactions, in particular within a therapeutic context. We propose that by studying human systems that are 'typical' and 'atypical', we can derive important characteristics that are needed for appropriate non-verbal social interactions. The first major point of the current work is that non-verbal communication plays an important and often under-recognized role in social function. Hence, we argue that the deficit in non-verbal synchrony observed in ASD may be a contributor to the poor social competence seen in this population (similarly, see [59, 80, 81] for a direct analysis of the relation between non-verbal synchrony and social competence, as opposed to the relation between non-verbal synchrony and multisensory temporal function studied in the current work). This is an important point, as implementing human-like non-verbal features in robotic devices is likely to be an important element in the efficiency of the communicative exchange. Further, while the use of interactive robots is arguably a promising therapeutic development [82] as implied by evidence suggesting that: i) individuals with ASD are particularly suited in understanding the physical as opposed to social world [82, 83], ii) are more responsive to (social) feedback when administered via technology [85], and iii) are intrinsically motivated by treatment involving electronic or robotic components [86], the use of robotics in ASD treatment may also pose special challenges. For example, the current results point toward a disconnect or uncoupling between sensory ability and non-verbal behavior in ASD. Thus, while the use of robots may be of benefit in ameliorating differences in non-verbal behavior in ASD, it is unclear whether these benefits would cascade to sensory domains – domains that have been argued to scaffold the higher-order deficits observed in ASD [e.g., 31]. Indeed, the second emphasis of the current work is that sensory and in particular multisensory perceptual skills may play a central role in mediating adequate social interactions. Here we highlight that the current results demonstrate a relatively strong and *specific* association between multisensory temporal acuity and non-verbal synchrony in adequately functioning social communicative systems (i.e., TD individuals). Our correlative relationships suggest that the multisensory temporal acuity seen in TD individuals is associated with the normal non-verbal synchrony that characterizes a typical social communicative interaction. It is likely that such a relationship is built through experiential interactions with the world. Again, such a view is consistent with in the hypo-prior account of ASD [76, 77]. In such a framework, it is acknowledged that sensory and multisensory information builds and maintains sensory representations, and this learning process ultimately drives linkages with motor representations – linkages that are disrupted in ASD because of the poor temporal fidelity of multisensory integration. Finally, the results of the current study support no difference between 'atypical' (e.g., ASD) and 'typical' (e.g., TD) systems regarding the synchronicity of trunk-movements. Further, although a trend was present, multisensory temporal acuity and synchrony of the trunk ROI did not appear to relate to one another in the TD population (as opposed to the results for the head and hand). Thus, it is possible that synchrony in trunk movements is not a major contributor for engendering positive social interactions. If true, there is little motivation in developing humanoid robots with this latter capacity, but there should be a strong impetus to focus on synchrony between hands and heads. The observation that the trunk seemingly does not significantly impact non-verbal communication is in line with prior clinical observations. That is, [87] indicated that while dyadic synchronization of distal body parts (in particular the head) predict long-term and permanent outcomes of psychotherapy, trunk synchronization or whole-body synchronization did not (see [88] for discussion regarding the importance of head synchronization in human-robot interaction). It must be noted, nonetheless, that the sample of autistic individuals studied were relatively high functioning, and that high- and low-functioning ASD individuals demonstrate distinct differences in postural (in)stability [89, 90]. Thus, the current conclusions regarding movement synchrony, particularly for the trunk, may not generalize to lower functioning individuals with ASD.

Future experiments will be required in order to address some of the acknowledged limitations of the current study. Most pressingly, in the current approach we have simply taken TD and ASD groups as representing instances of systems in which both verbal and non-verbal communication are, respectively, typical and atypical. However, we did not directly employ measures that indexed the efficacy of the communicative exchange. Thus, while the current findings strongly support prior work detailing poorer multisensory temporal function in ASD than TD, and extend this work by showing that multisensory acuity is related to non-verbal synchrony for distal body-parts in TD but not in ASD, the direct impact of differences in multisensory temporal acuity on (non-verbal) social competence remains to be elucidated. Indeed, future work should extend the current observations to quantify the information exchanged during the interactions between individuals.

In conclusion the current study demonstrates an association between a specific perceptual skill, multisensory temporal acuity, and what is an important informational component of social communicative exchange, non-verbal synchrony. Further, this association was present for distal body-parts (head and hand) in TD individuals, but was uncoupled in those with ASD, suggesting an uncoupling between perception and communication in ASD.

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