Journal Articles   Department of Biomechanics

12-2016

Indifference to Chaotic Motion May Be Related to Social Disinterest in Children With Autism

Joshua L. Haworth

Anastasia Kyvelidou

Wayne Fisher

Nicholas Stergiou

Indifference to Chaotic Motion May Be Related to Social Disinterest in Children with Autism

Joshua Haworth, Kennedy Krieger Institute
Anastasia Kyvelidou, University of Nebraska–Omaha
Wayne Fisher, University of Nebraska Medical Center
Nicholas Stergiou, University of Nebraska–Omaha

Abstract

Children with autism spectrum disorder tend to have little interest in the presence, actions, and motives of other persons. In addition, these children tend to present with a limited and overly redundant movement repertoire, often expressing hyperfixation and aversion to novelty. We explore whether this is related to a more fundamental lack of appreciation for various temporal dynamics, including periodic, chaotic, and aperiodic motion structures. Seven children with ASD (age, gender, and height matched with children without ASD) were asked to stand and watch the motion of a visual stimulus displayed on a large (55") video monitor. Gaze and posture movements were recorded and assessed using cross recurrence quantification analysis for qualities of coordination, including rate and duration of bouts of coordination. Results showed that children with ASD do not express an affinity to chaotic motion of the stimulus in the same way as children without ASD. We contend that this indifference to chaotic motion is foundational to their general disinterest in biological motion.

Keywords: eye tracking, posturography, imitation, perception

Autism spectrum disorder (ASD) is identified as a mixed set of general social communication deficits combined with a propensity toward restricted or repetitive behaviors (American Psychiatric Association, 2013). Some children with ASD may have severe language and social deficits, which makes diagnosis fairly straightforward. However, others may have much more subtle impairments, being commonly described as high-functioning children (Attwood, 2007), which are less noticeable but still cause significant impairment in the realms of self-care and quality of life. Many times, these children are able to acquire speech in a basic functional manner, yet lack the transition to the social functional value of speech and the interpersonal interaction that it affords (Baron-Cohen, 1988). Often, the nonverbal aspects of interactions are particularly inhibited. This includes a lack of attention to the nonverbal behaviors of others (such as pointing to objects, facial expression, and eye contact), a lack of socioemotional reciprocity, and a general lack of peer relationships (Sullivan et al., 2007).

These tendencies may impact the behavior of the child at any given moment, and they are likely to have compounding detriment on the child's developmental trajectory as well. Recently, Bhat, Landa, and Galloway (2011) proposed that in order for an

individual to understand the communicative gestures of others, it is required that the individual have a complete movement repertoire. More specifically, it was suggested that there is a direct developmental link between motor and social communication deficits in ASD (Bhat et al., 2011), which highlights the multi-interactive nature of the perception-action-cognition cycle. For example, some children experience social isolation due to lack of motor coordination competence (e.g., never being chosen to play in team sports), or when they avoid playtime in kindergarten and preschool years, which is correlated with their lack of typical movement coordination (Bar-Haim & Bart, 2006; Piek, Bradbury, Elsley, & Tate, 2008; Smyth & Anderson, 2001). Healthy motor development, then, seems to have a dramatic impact on the subsequent cognitive and social behaviors of a child.

Hadders-Algra (2010) describes typical motor development as a two-phase process beginning with a period of primary variability during which self-generated, nonadaptive movement experience is pursued. Transitions to the secondary variability phase tend to occur at function-specific ages, when the demand for task accomplishment begins to outweigh the value of continued exploration. It seems to be around these time periods that observational interest increases toward peer behavior. Sanefuji, Ohgami, and Hashiya (2008) demonstrate that children are particularly interested in watching the skill behavior of peers when it matches their own skill. Given the opportunity, toddlers will prefer to observe another toddler, instead of a crawler, and vice versa.

So, what exactly is gained by watching others? Observing another's behavior allows the viewer to gain task-relevant experience, without the need to perform the task on their own. Interestingly, this gives the viewer a particular perspective that cannot be achieved otherwise—namely, insight into the various sources of variance in an instance of movement. Observation permits "repetition without repetition" (Bernstein, 1996). More specifically, it affords awareness of the essence of a given problem's solution, which maps into the full set of actionable solutions. In this way, associated modeling and imitation play might directly support typical development by providing a new means for understanding self-driven behavior and its consequences (Meltzoff & Moore, 1992; von Hofsten, 2004). According to Hadders-Algra (2008), task motives are what propel us toward the secondary variability phase of development, from which our behaviors become purpose driven. Yet, imitation requires a connection to the attributes of motive and intentionality in the viewed behavior.

In contrast, children with ASD are often impaired in their attention to, and understanding of, the behavior of others. This appears related to undeveloped joint (or shared) attention—that is, coordinating one's attention to an object in accord with another's attention to that same object (Whalen & Schreibman, 2003). Lack of joint attention is implicated in the inhibited development of imitative play skills (Charman et al., 1997), language development (Mundy, Sigman, & Kasari, 1990), and a general theory of mind (Baron-Cohen, 1993). Deficiencies in the development of these skills may be directly linked to the socioemotional deficits that are characteristic of ASD. Specifically, though, reduced interest in the movement behavior of others leaves the child with autism at a loss for the benefits of imitation learning that would otherwise be available. For these children, this seems to pose yet another layer to the challenge of acquiring a rich behavioral repertoire. Developing a distinct awareness of self and

others may be a critical juncture for children with autism, especially for the refinement of movement skills.

We propose that this reduced social awareness may be attributable to a more fundamental aspect of visual attention of children with ASD. Researchers have previously shown that children with ASD have a general lack of preference to biological motion (Blake, Turner, Smoski, Pozdol, & Stone, 2003). This occurs, even when there is no sign of perceptual deficit, as children with ASD still demonstrate the ability to respond to nonsocial, physical contingencies of object motion (Klin, Lin, Gorrindo, Ramsay, & Jones, 2009). It appears then, that biological motion must contain some characteristic quality, which allows for its differentiation from nonbiological motion. We propose that awareness of temporally contingent variability may be the differentiating factor that affords visual attention selective to biological agency. Biological motion contains particular inherent features describable through mathematical chaos and complexity metrics (Haworth, Vallabhajosula, Tzetzis, & Stergiou, 2013; Stergiou, Buzzi, Kurz, & Heidel, 2004). Healthy biological motion exhibits a complex variability, meaning it is neither too rigid nor too random (Stergiou & Decker, 2011; Stergiou, Harbourne, & Cavanaugh, 2006). Complexity of particular movements has also been described by other mathematical constructs—for example, two-thirds power law (hand motion, Viviani & Flash, 1995) or 1/f noise (gait; Rhea, Kiefer, D'Andrea, Warren, & Aaron, 2014). In this study, we consider the double pendulum model of chaotic motion, which has been shown to effectively model the postural sway dynamics of an upright human (Suzuki, Nomura, Casadio, & Morassa, 2012). The ability to perceive and identify this complexity has previously been observed in typically developing children (Haworth, Kyvelidou, Fisher, & Stergiou, 2015), and could potentially be a discriminating factor in the ability to identify biological motion.

Difficulty with complex, chaotic motion structures may also explain the tendency toward motor redundancy in children with ASD. An inability or aversion to the experience of chaotic motion would require some alternate tendency for structure of movement variability. Random variation would make it extremely difficult to plan and execute purposeful movements, leaving it reasonable that an effort would be given to the production of less variant behaviors. For example, children with ASD seem to exhibit more rigid and less adaptive posture (Kohen-Raz, Volkmar, & Cohen, 1992). It is plausible that children with ASD fixate on repetitive aspects of motion (e.g., watching wheels spin) and engage in repetitive motor responses (e.g., rocking), and that this perceptual and motor rigidity interferes with their attention to, and perception of, the complex variability found in the motion of others and, thus, with their ability to discriminate biological from nonbiological motion.

Further, this perspective provides a theoretical link between cognitive social deficits and behavioral redundancy, which, together, constitute the diagnostic criteria for ASD (DSM, 1994). Under this theoretical approach, it is entirely reasonable that posture (a continuous gross motor behavior that relies heavily on coordination with the viewed environment) would suffer in persons with ASD. This has been shown to be the case by Molloy, Dietrich, and Bhattacharya (2003), who report drastic effects on posture under conditions of modified vision. In addition, children with autism exhibit hyporeactive postural response to motion of the visual environment (Gepner & Mestre, 2002; Gepner, Mestre, Masson, & de Schonen, 1995). However, none of the aforementioned studies

fully resolve whether the observed postural deficits are due to diminished visual motion perception or disordered integration of the temporal aspects of visual information.

The current study focuses on the influence of perceived object motion on concurrent sensorimotor behavior; specifically, on whether children with autism are able to distinguish chaotic movement variability (characteristic of biological motion), and whether this information is able to guide typically responsive strategies for postural movements. We propose a two-factor design to compare the responses of children both with and without ASD (group) across three separate stimulus motion conditions (stimulus includes periodic, chaotic, and aperiodic motion structures). Previous studies have used these stimuli to explore differences in gaze and posture behavior in adults (Haworth, Vallabhajosula, & Stergiou, 2014) and typically developing children (Haworth et al., 2015). These studies indicate a particular capacity to appreciate chaotic motion dynamics in the gaze response of both children and adults. Adults did not appear to reciprocate stimulus complexity with postural changes, though the children did to some extent. Based on the differences in preferred attention to biological motion and the tendency toward motor rigidity in ASD, we anticipate an interaction effect to show that children with ASD will not have increased coordination of gaze or posture with chaotic motion, whereas children without ASD will increase coordination with chaos. In addition, we anticipate that posture will coordinate differently in response to stimulus motion structure, with a possible group effect.

Finding a deficiency in the detection or production of stimulus movement characteristics, as they modulate gaze or posture, may help explain the behaviors of those with ASD. In addition, assessment of these behaviors at very young ages may prove to be useful as an early indicator of atypical development. This analysis may provide further information regarding discontinuities in the dynamic structure of motion perception and production of typical complex biological motion in children with ASD, holding considerable promise for significantly improving the lives of persons with ASD and allowing for early detection of risk and treatment.

Methods
Participants

Fourteen children participated in this study (see Table 1 for descriptive statistics). Seven were reported to have ASD diagnosis (from clinic or school-based assessment, via parent report) and expressed at least reciprocal phrase speech. Seven gender-, height-, and age-matched typically developing children were included for comparison. Each group consisted of six boys and one girl. The ASD group did turn out to be slightly heavier, by roughly 4 kg (independent t test, p= .031). All children were verified to have normal vision, no further neurological history, and otherwise typical development confirmed by using the Denver II scale (Frankenburg, Dodds, Archer, Shapiro, & Bresnick, 1992). All children actively engaged in toy play and/or use of an art easel (chalk or marker drawing) during preparation and testing intervals. Procedures were approved by the Institutional Review Board of the University of Nebraska Medical Center, and consent was obtained from the parent(s) of each child before the beginning of this study.

Procedure

Children were asked to stand in front of a 55" 1920 × 1200 pixel LCD display, which was adjusted vertically to match the midline of the monitor to the height of the child's eyes. Children stood on a force platform (Advanced Mechanical Technology Inc., OR6–7, with MSA-6 amplifier), that measured posture sway motion (center of pressure; COP) at 50 Hz. FaceLab 4.5 (Seeing Machines, Acton, MA) eye-tracking equipment was mounted on the monitor stand and was used to track eye movements (Gaze) also at 50 Hz. Figure 1 shows the experimental setup with relevant dimensions regarding monitor position with respect to the participants. Lights were dimmed throughout the collection, and a black curtain surround was in place to minimize the sight of objects in the peripheral visual field. Three conditions were presented in random order, with time to rest and play in between. A minimum of 1 minute between trials was observed to reduce carryover between conditions and to foster maintained interest of the children. Foot position was marked before the first condition, and was returned to for each subsequent condition.

Each condition consisted of the presentation of a stimulus image (Elmo character, with 25 pixel radius) that moved only horizontally on the screen, while concurrent measurement of mediolateral aspects of Gaze and COP were recorded. All data were managed with custom software written in Labview (National Instruments, Austin, TX). The motion of the stimulus differed across three conditions—namely, periodic (Sine), pseudoperiodic (Chaos), and aperiodic (Brown Noise) motion structures. The Sine signal represents the simplest form of redundant movement structure, and was generated using the sin() function in Matlab (MathWorks, Natick, MA). This type of motion is too perfectly rhythmic to appear as animate motion. Chaos is a much more complex motion structure that expresses pseudorandom fluctuations, but is actually deterministically organized and representative of the variability found in animate motion. The chaos signal was generated as the horizontal motion of the distal segment of a double pendulum model, shown previously to express chaotic dynamics (Shinbrot, Grebogi, Wisdom, & Yorke, 1992) and emulate upright human postural sway (Suzuki et al., 2012). For additional verification, surrogation testing was performed to affirm that our signal exhibited chaos (Theiler, Eubank, Longtin, Galdrikian, & Farmer, 1992). Brown Noise (equivalent to integrated white noise) presents aperiodic, stochastic structure, and is generated by the iterative addition of a random perturbation (within specified bounds) to the original point position. Brown noise is argued to be too erratic to represent controlled postural motion. This signal structure allows for smooth pursuit gaze following, as the change of stimulus position was bounded to prevent a velocity that would require saccadic eye movement (velocity < 30°/s).

Each stimulus display lasted for 3.5 minutes. Often, children did not remain still and attentive throughout this entire duration. All children, however, maintained at least one 30 s segment of continuous engagement (with steady stance and forward head orientation) during each condition. Postprocessing included video-based selection of these segments for further analysis, with care given to exclude occasions when the child was speaking or making overt motions with their head or arms. Some of these segments contained instances of sustained blink, where no viable gaze position data were available. A fifth order cubic spline was applied to resolve these periods. Gaze and COP data were both filtered using a double-pass Butterworth filter with a 10 Hz cutoff,

and normalized to a common scale from zero (0) to one (1) for subsequent comparability.

Table 1   Group Statistics, Including Independent *t* Test Comparisons Between Typically Developing (TYP) and Autism (ASD) Subgroups

	Group (*n* = 7)	*M*	*SD*	Sig. (2-tailed)
Age (years)	TYP	5.61	0.73	.943
	ASD	5.58	0.81	
Height (cm)	TYP	114.14	6.47	.070
	ASD	120.29	4.89	
Mass (kg)	TYP	18.81	2.31	.031*
	ASD	22.85	3.59	

Note. Sig. = significance.
* indicates significance with alpha = .05.
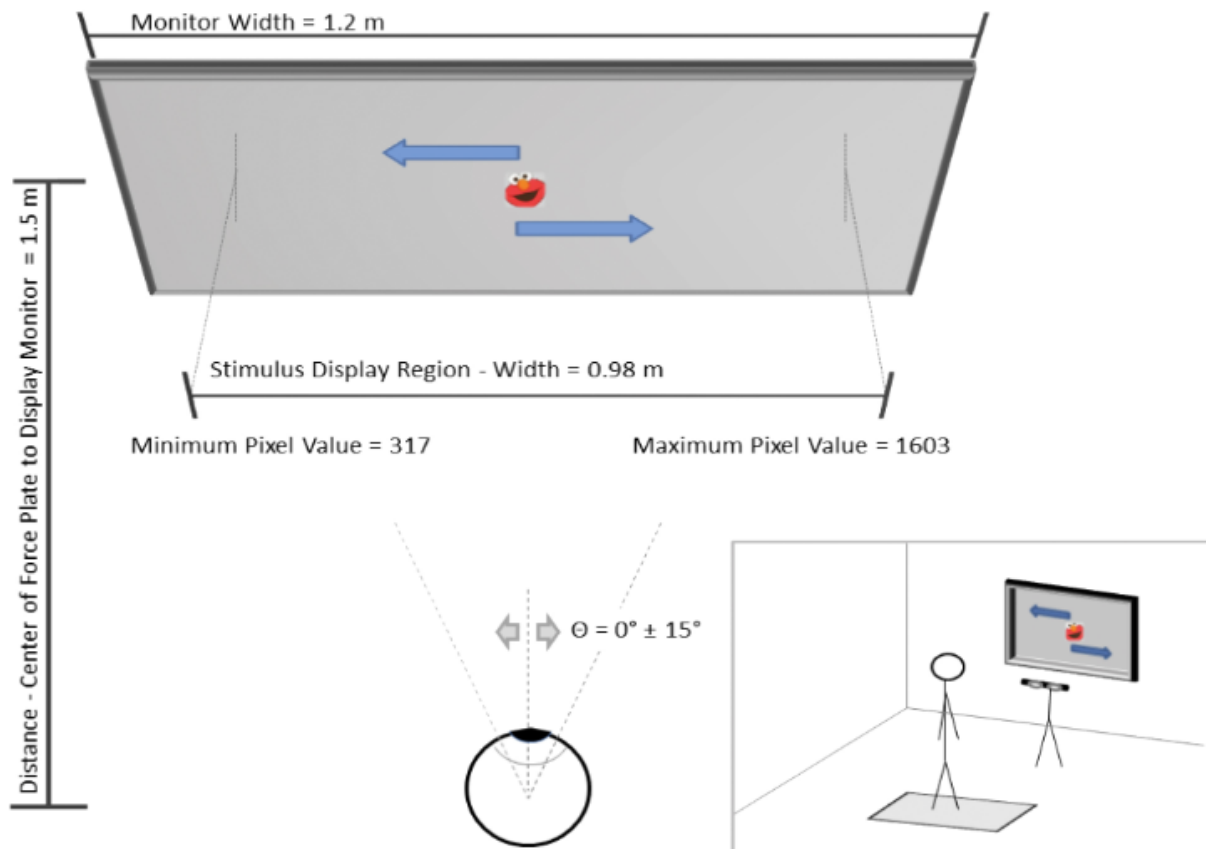
Figure 1 — Diagram of the experimental setup, with relevant dimensions indicated.

Recurrence Quantification

Gaze and COP were then submitted to cross recurrence quantification analysis (cRQA), by which each was assessed for coordination with the viewed stimulus motion position data. Further, the two measured behaviors were submitted to cRQA to be compared against each another, providing a proxy metric of the sensorimotor coordination (SensMot) of the child during each condition. Outcome metrics from cRQA were calculated using custom Matlab software (Shockley, Butwill, Zbilut, & Webber, 2002; Shockley, 2005).

The cRQA tests the relative likelihood that two time series visit similar posi-tions in a common, multidimensional phase space. To accomplish this, each time series must first be "embedded" into this space (Takens, 1981). This is done using parameters of delay and embedding dimension, which are calculated from the average mutual information (AMI; Fraser& Swinney, 1986) and the False Nearest Neighbors (FNN; Abarbanel, 1996) algorithms, respectively. In our case, values of 15 and 6, respectively, were found to be appropriate for embedding. After embed-ding, additional parameters must be selected to ensure that proper resolution is given to the analysis of recurrence. Specifically, these include one parameter to throttle the rate of recurrence and one to define the minimum criteria for continual recurrence. Rate of recurrence is regulated through establishing an appropriate radius, or distance, within which points are considered recurrent (Shockley, 2005). In our study, we chose time series–specific values of radius to limit each analysis to a 5% recurrence rate. Minline is the parameter set to define the minimum criteria for recurrence, representing the shortest duration (in data points) within which the two signals are sequentially recurrent that will be considered in subsequent computations. We set Minline to 25, which relates to 0.5 s duration of experiment time. We chose this on the logic that smooth pursuit and saccadic eye movements can both occur in shorter time spans, but the saccades would not last longer. Preliminary analyses suggested that this value would provide more stable and comparable outcome measures across the three conditions.

Outcomes of cRQA include percent determinism and maxline (Shockley, 2005). Each outcome gives a unique description of the cross recurrence. Percent determin-ism is the ratio of recurrent points that form lines divided by the total number of recurrent points, and it is reported from 0 to 100%, representing the proportion of trial time spent in coordination, without sensitivity to intermittency. If every point of recurrence between two signals is part of a bout of continuous coordination (i.e., gaze coordinates with the stimulus throughout the trial), percent determinism would report as 100%. It is possible that none of the recurrent points are part of a continuous coordination (line), in which case percent determinism would report as 0%. If within a single trial gaze were to coordinate with the stimulus on 10 separate occasions, 5 of which lasted longer than 0.5 s and 5 of which were shorter, then percent determinism would be roughly 50%. Essentially, percent determinism represents the relative rate of coordination of behaviors. Maxline is the length of the longest line formed by recurrent points, expressing the maximum extent of coupling between the two signals, reported in number of data points. With minline set at 25, the smallest value of maxline possible is also 25. The upper limit is the length of the data in phase space, which would occur if the two behaviors were continuously coordinated throughout every time step of the trial. Larger values of maxline indicate longer bouts of continuous coordination between the

compared behaviors. Data are collected at 50 Hz, so each increment of 50 data points for maxline represents one second of signal coordination.

Statistical Analyses

Separate 2 × 3 (Group × Stimulus) Mixed ANOVAs assessed the dependent measures of percent determinism and maxline. This analysis was performed for each of Gaze, COP, and SensMot. The two-way design tests for a main effect of stimulus (whether children responded differently to each stimulus), a main effect of group (whether children with ASD responded differently than those without), and interaction (whether having ASD impacts the response to each stimulus). Follow-up t tests were used to elucidate identified differences. All statistical tests were conducted using IBM SPSS Statistics software (IBM Corporation, Armonk, NY, Version 18), with an alpha level set at .05.

Results

Stimulus

A main effect of stimulus was found for Gaze and COP, for both percent determinism and maxline (Figure 2). Children exhibited different rates of coordinated Gaze to different stimuli (percent determinism; $F(2, 24) = 16.7$, $p < .001$, $\eta p2 = 0.583$, 99.9% observed power). Post hoc analysis showed similar rates for Sine and Chaos stimuli ($p = .528$), while significantly less percent determinism was found for the Brown Noise stimulus ($p = .001$ to Sine; $p < .001$ to Chaos). Simi-lar results were found for duration of coordination to different stimuli (maxline; $F(2, 24) = 5.8$, $p = .009$, $\eta p2 = 0.326$, 82.4% observed power), with the longest coordination bouts in response to Chaos. Post hoc analysis showed no significant difference between Sine and Brown Noise stimuli ($p = .98$), near difference between Sine and Chaos ($p = .062$), and significant difference between Chaos and Brown Noise ($p = .016$).

COP percent determinism was different in response to stimulus, $F(2, 24) = 20.0$, $p < .001$, $\eta p2 = 0.625$, 100% observed power, showing a decreasing trend as the stimulus motion became less periodic. Significant differences were found between Sine and Chaos ($p = .042$), Sine and Brown Noise ($p < .001$), and Chaos and Brown Noise ($p = .002$). COP maxline, $F(2, 24) = 3.8$, $p = .037$, $\eta p2 = 0.240$, 63.2% observed power, showed the opposite trend, with the shortest maximum in response to the Sine stimulus. Significant differences were found between Sine and Chaos ($p = .049$), Sine and Brown Noise ($p = .021$), but not Chaos and Brown Noise ($p = .496$). No main effect of stimulus was found for either SensMot measure.

## Group

Although no main effect of group was identified for COP or SensMot, a near significant difference is acknowledged for Gaze maxline, $F(1, 12) = 4.4$, $p = .059$, $\eta p2 = 0.267$, 48.5% observed power. The influence of group is likely better interpreted in light of the noted interaction effect.

Interaction

An interaction was found for Gaze maxline, $F(2, 24) = 3.8$, $p = .036$, $\eta p2 = 0.243$, 64.0% observed power, indicating that children with and without ASD expressed

different responses to the set of stimulus motions. As seen in Figure 3, this difference can be found in the response to the Chaos stimulus motion.
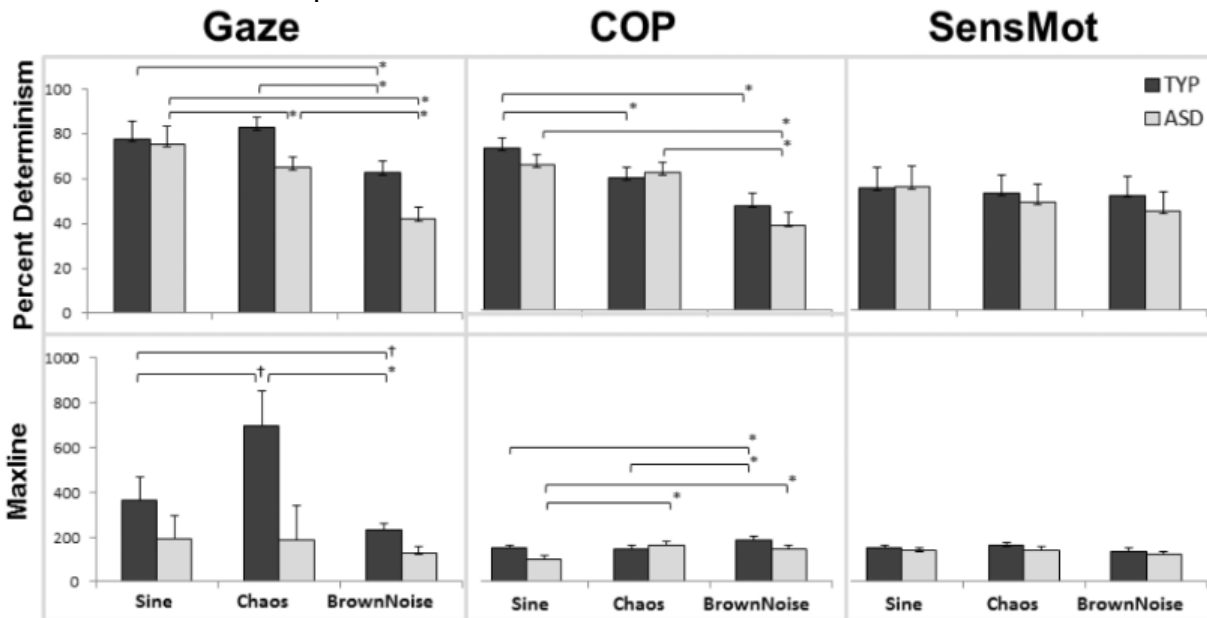
Figure 2 — Results from cRQA; percent determinism is shown in the top row, with maxline (in number of data points) across the bottom. Each comparison is listed including Gaze (to stimulus), COP (to stimulus), and SensMot (Gaze to COP). * indicates differences with $p < .05$, with † indicating $p < .10$.

Simple main effects of stimulus results showed that children with and without ASD did not differ in response to the Sine stimulus motion, $F(1, 12) = 1.40$, $p = .260$, $\eta p2 = 0.104$, 19.3% observed power, though they differed in their response to the Chaos, mean difference = 509.4 ± 220.0; $F(1, 12) = 5.36$, $p = .039$, $\eta p2 = 0.309$, 56.7% observed power, and Brown Noise, mean difference = 104.1 ± 43.0; $F(1, 12) = 5.88$, $p = .032$, $\eta p2 = 0.329$, 60.6% observed power, stimuli.

Simple main effects of group-wise results showed that typically developing children differed in their response to the three stimuli, $F(2, 11) = 5.64$, $p = .021$, $\eta p2 = 0.506$, 74.5% observed power, though children with ASD did not, $F(2, 11) = 0.32$, $p = .736$, $\eta p2 = 0.054$, 8.8% observed power. The typically developing group had much longer maxline in response to the Chaos stimulus motion when compared with Sine (mean difference = 332.5 ± 113.2, $p = .012$) or Brown Noise (mean difference = 466.5 ± 133.2, $p = .004$). Children with ASD did not show this elevated maxline in response to Chaos stimulus motion.
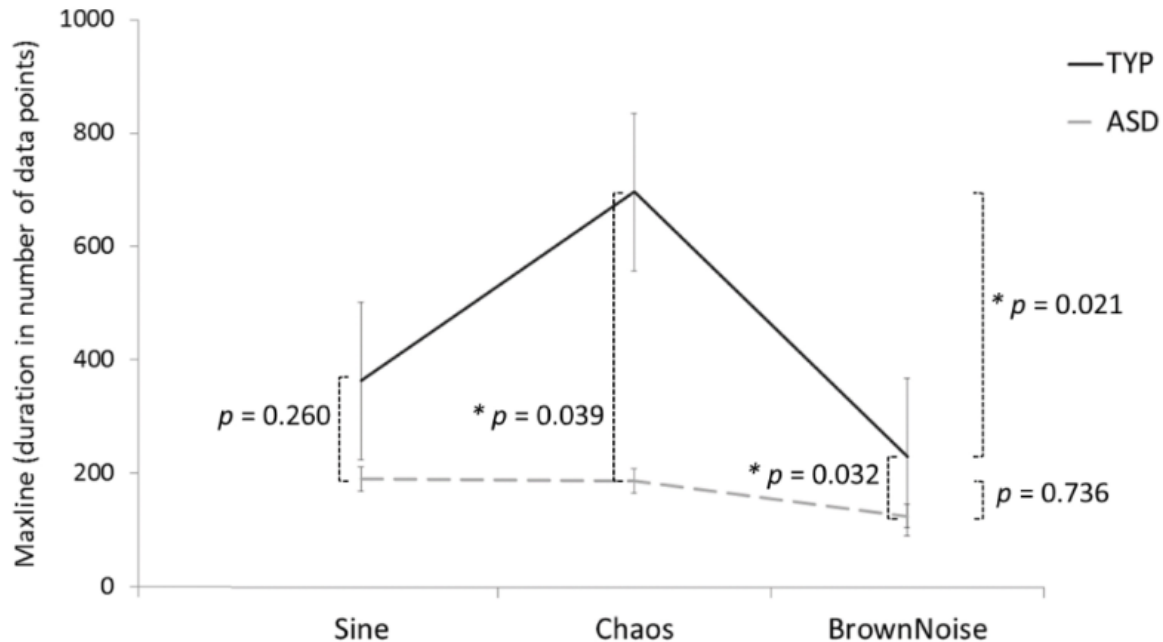
Figure 3 — Maxline gaze response by each group to each stimulus condition. Maxline represents the longest duration of continuous coordination of gaze with stimulus motion, shown in number of data points. At 50 Hz, two hundred data points is 4 s of task time. Simple main effects are indicated for group comparison of each stimulus, as well as group-wise effect across stimuli (shown to the right). * indicates significance at $p < .05$, with exact p value listed.

Typically developing children coordinate their gaze for longer bouts (higher maxline) in response to the Chaos stimulus, relative to other stimulus motion conditions. However, children with ASD do not express this increased coordination to the Chaos stimulus motion. Gaze behavior for this group is consistently coordinated to the motion of the stimulus for a relatively short duration (at 50 Hz, 200 data points is 4 s of task time). No other interactions were identified in our data.

Discussion
Gaze
The results of this study confirm our hypothesis that children with and without ASD express different patterns of gaze coordination based on the temporal structure of the motion of a viewed stimulus. In general, children expressed a similar rate of coordination (percent determinism) to the rhythmic and chaotic stimuli, with lower rate toward the aperiodic stimulus. Further, they showed an affinity for longer coupling of their gaze (maxline) with the motion of a chaotic stimulus, relative to fully periodic or aperiodic motions. These findings corroborate those of Haworth et al. (2015), who found similar effects in a group composed only of typically developing children.

In the current study, though, we found an additional interaction effect of stimulus conditions and group. It is noteworthy, according to simple main effects analysis, that children with ASD did not share this propensity for coordinating their gaze with the

motion of the chaotic stimulus. Children with ASD did express ability to coordinate their gaze to each stimulus motion; roughly, 160 data points, averaged across all conditions, at 50 Hz relates to periods of more than 3 s. Given this, it seems reason-able to suggest that observed indifference to chaos is not resultant from a general inability to coordinate gaze to the motion of a viewed stimulus. We contend that our results point to a specific difference in the groups' appreciation of chaotic motion. Whether this data represent a disinterest or an inability remains unresolved. We will proceed later with a look to the literature for clarity on this matter.

Posture

We found a main effect of stimulus on the rate of coordination (percent determinism) and duration of the longest coordination (maxline) of posture with stimulus motion. Percent determinism indicates a decreasing rate of coordination as the stimulus motion became less periodic, with the most frequent rate in response to the most rhythmic stimulus (Sine). Maxline, however, indicates the shortest maximum in response to the Sine stimulus, and is longer for the less periodic stimuli. With no main effect of group, or interaction, we conclude that these effects hold true for both typically developing children and those with ASD. Thus, it appears that there is some dynamic informational interdependence of stimulus motion complexity and the subsequent organization of posture, a finding consistent with Haworth et al. (2015).

SensMot

No main effects or interactions were found for the rate (percent determinism) or duration (maxline) of coordination of gaze and posture to one another (SensMot). The rate of coordination appears modest (51.2% ± 21.8%) across all participants and conditions, which indicates that gaze and posture were infrequently coordinated in a similar way during all trials. Consistent maxline values of 141.5 ± 35.2, nearly 3 s, suggest that nontrivial coordination of these behaviors was present during the trials. This suggests a stable coordination between gaze and posture, which is resistant to the local motion presented by our stimuli. This could be due to the stability of the mechanism across persons, or a contextual dependence on its informational usefulness. It would be interesting to follow up with more elaborate stimuli that serve to emulate environmental motion, as these have been found to effect postural sway behavior in kids with and without autism (Gepner et al., 1995; Gepner & Mestre, 2002). These types of conditions might have a bigger impact on internal sensorimotor coordination that is represented by our SensMot measure.

General Discussion

Contrasting views have been presented to explain altered perceptual abilities observed in persons with ASD, including an enhanced perceptual functioning model (EPF; Mottron & Burack, 2001; Mottron, Dawson, Soulieres, Hubert, & Burack, 2006) and a weak central coherence model (WCC; Happé & Frith, 2006). EPF describes that a hyperfixation on particular aspects of the experienced world drive the child with autism into the behavioral redundancy that characterizes the disorder. In other words, an overdeveloped interest in local details keeps the child from exploring the remaining available information in their environment. Following the EPF model, we would expect

children with ASD to have demonstrated an increased tendency to fixate on the motion of the stimuli, particularly the periodic motion of the Sine stimulus. However, we did not find such to be the case. Our data show a similar response to all motion types by these children, and that being in the form of only short bouts of coordinated interest. Notably, the longest duration of coordination of Gaze to any stimulus is shorter than that of the shortest duration coordination of the typically developing children.

Our findings suggest that attention to the temporally contingent variability found in chaos is not part of the sensory motivation of children with ASD. Further, they suggest that visual stimulation alone is insufficiently motivating of sensorimotor coordination. The weak central coherence (WCC) hypothesis argues that persons with ASD appear overly fixated on the local features of objects, because they are unable to extract an essence (or formulate a Gestalt) of higher meaning. In this view, the "excessive" variation of the Chaos stimulus presented in our study may have been dismissed due to a lack of perspective shift of the viewer. Chaos exhibits redundancy on multiple time scales, and a focused microperspective would certainly miss out on this observation and its meaningfulness. Bertone, Mottron, Jelenic, and Faubert (2003) discussed a similar reflection to a lack of perceptual engagement with complex motion visualizations. Furthermore, they point out that limitations on the perceptual processing of complex information appear in other sensory modality domains, as well. They lead further into the notion that compromised integrative processing may be a root agent in the child's apparent disinterest in complex information within his or her environment.

In contrast, other works have indicated that multisensory integration provides advantageous "sparks" of coherency to the perceptual processes of children with ASD. Klin and colleagues (2009) describe this in conjunction with the common observation that biological motion preference is lacking in children with autism. When presented with side-by-side movies of point-light motion, one upright and the other inverted, children with autism showed no preference to either movie. Typical controls and delayed, nonautism controls both showed preference toward upright biological motion. In response to one of the animations (the actor was playing pat-a-cake, a highly audiovisual synchronous activity), an ASD participant jumped to 93% preference to the "correct" upright video. Klin et al. suggest that a mechanism for this preference is an affinity for the causal physical contingency—that is, awareness that the motion caused the sound. This led to further evaluation with new animations scaled across audiovisual synchrony (AVS), with level of AVS calculated as the product of change in velocity and change in sound amplitude. Behavior of the second cohort fit their predictions with 90% correct viewing during the preferential looking task (preference to upright animation), with highest rates in response to the animations with highest AVS. This finding lends explanation to the study by Klin, Jones, Schultz, Volkmar, and Cohen (2002) showing that children with ASD fixate the mouth (instead of the eyes) of an actor within their environment, supporting the notion of searching for high AVS cues.

Thus, it appears that children with autism are not actually averse to complex information (a possible interpretation of our data), but instead seem to prefer it to come in coherent multimodal format. This insight could lend new perspective to understanding the appreciation of biological motion by those with ASD. In addition, this could help explain the attribution of agency onto the actions of others. Neri, Morrone, and Burr (1998) present an interesting look on how individuals typically see movement.

Specifically, they report on the natural sensitivity of individuals to perceptions of biological motion. Using point-light animations of human walkers, embedded in a noise field, they demonstrate a couple of interesting observations. They show a seemingly obvious finding that biological motion is more readily identified when greater numbers of point-light markers are present. The less obvious caveat is that this enhanced sensitivity (due to increased available information) increases more rapidly for biological motion than for simple, nonbiological motion. In other words, the information threshold for identifying biological motion is lower (possibly just more adaptive, as we will discuss shortly) than that of nonbiological motion. Their second major finding was that the temporal summation of visual information had a dramatically longer interval (up to 3 s) for biological motion than it was for simple motion: nearly an eightfold difference. They suggest that the increased time required for assessment is due to the greater number of dependent couplings of the various joint centers needed to form a complete percept. It is interesting to note here the differences in Gaze maxline that we found for children with and without ASD. Those with ASD showed little more than 3 s of coordination (average across all conditions), whereas children without ASD engaged more than 4.5 s and as high as 14 s (to Chaos) to stimulus motion. Perhaps, these results combine to suggest a reduced capacity for temporal summation of motion information in children with ASD.

Neri et al. (1998) draw the conclusion that biological motion detection does not depend on hard-coded neural architecture. Instead, they propose that accurate biological motion detection is reliant on a "very sensitive, but flexible, mechanism with variable efficiency." They further explain that a system that is able to adjust its internal noise could lead to this variable efficiency, and thus have the capacity to demonstrate optimum recognition under any visual conditions. Further advantage (over simpler matched-filter systems) would be that minimal neural resources would be necessary to yield information from a vast array of potential stimuli. This suggests that a flexible and adaptable brain is thus more likely to navigate its way through the noise field and ultimately land on the identification of relevant information. Based on the results of our study, we propose that this is one feature that is not available to the autistic brain. A lack of dynamic optimal neural activations would lead to deficient flexibility and adaptability, which would manifest in a hyper-rigid motor repertoire combined with the inability to recognize complex motions—that is, the motions of others. Grice et al. (2001) explored the connection between visual processing and oscillatory brain activity, and conclude that atypical neural burst patterns have an effect on binding visual information into a coherent percept in children with ASD. These results further support the notion that errant temporal processing is an underlying feature of ASD.

We consider that motion detection might be less related to an interest or attention deficit, but instead arises from a sort of filter malfunction, which precludes the identification of relevance from noisy incoming information. This coincides with what we have seen about the perceptual processing behavior of children with ASD. More information of the same modality is not better; in fact, it seems to drive an aversion. More information across multiple sensory modalities appears to advantage the perception of biological motion (Wuerger, Crocker-Buque, & Meyer, 2012), particularly by those with ASD (Klin et al., 2009). This is especially the case when high-velocity components of the separate modalities coordinate in time. Under such events, it may

seem to the child that the world itself has become more coherent, and thus finally perceivable above the previous state of near-random complexity. This perspective affords an entirely new interpretation of the hyperfixation behaviors seen in children with ASD. We see this as an effort by the children to seek coherency among the noise field of their sensory universe. Under normative circumstances, this occurs quite often, albeit not necessarily in a continuous fashion. This may be part of what leads to the isolated and discontinuous social interest of children with ASD. Other people may just not be constantly coherent enough to provoke sustained attention.

Ultimately, we conclude that our investigation has provided a novel effort toward the understanding of complex motion perception in children with ASD. We have presented a methodology that can be used for further research including the exploration of perceptual response to visual signals of differing dynamical structure. Future studies may also be informed by some of the limitations of the current study, including the modest sample size (considering also the reported effect sizes) and the limited characterization of the ASD group. Furthering the current paradigm with an ASD group with expanded characterization and the incorporation of multiple sensory modalities would be great next steps to verify the claims made herein. In addition, brain imaging techniques could be used during replications of the current study, which could provide an extremely fruitful insight into the temporal dynamics of the underlying neural architecture.

References
Abarbanel, H.D.I. (1996). Analysis of observed chaotic data. New York: Springer-Verlag. doi:10.1007/978-1-4612-0763-4

American Psychiatric Association. (2013). Diagnostic and statistical manual of mental disorders.4th ed. Washington, DC: American Psychiatric Association (older editions: 1952, 1968, 1980, and 1994).

Attwood, T. (2007). The complete guide to Asperger syndrome. London: Jessica Kingsley Publishers.

Bar-Haim, Y., & Bart, O. (2006). Motor function and social participation in kindergarten children. Social Development,15, 296–310. doi:10.1111/j.1467-9507.2006.00342.x

Baron-Cohen, S. (1988). Social and pragmatic deficits in autism: Cognitive or affective? Journal of Autism and Developmental Disorders,18(3), 379–402. doi:10.1007/BF02212194

Baron-Cohen, S. (1993). From attention-goal psychology to belief-desire psychology: The development of a theory of mind and its dysfunction. In S. Baron-Cohen, H.

Tager-Flusberg, & D. Cohen (Eds.), Understanding other minds: Perspectives from autism (pp. 59–82). Oxford: Oxford University Press.

Bernstein, N.A. (1996). On dexterity and its development. In M.L. Latash & M.T. Turvey (Eds.), Dexterity and its development (pp. 1–244). Mahwah, NJ: Erlbaum.

Bertone, A., Mottron, L., Jelenic, P., &Faubert, J. (2003). Motion perception in autism: A "complex" issue. Journal of Cognitive Neuroscience,15(2), 218–225. doi:10.1162/089892903321208150

Bhat, A.N., Landa, R.J., & Galloway, J.C. (2011). Current perspectives on motor function-ing in infants, children, and adults with autism spectrum disorders. Physical Therapy,91(7), 1116–1129. doi:10.2522/ptj.20100294

Blake, R., Turner, L.M., Smoski, M.J., Pozdol, S.L., & Stone, W.L. (2003). Visual recognition of biological motion is impaired in children with autism. Psychological Science,14(2), 151–157. doi:10.1111/1467-9280.01434

Charman,., Swettenham, J., Baron-Cohen, S., Cox, A., Baird, G., & Drew, A. (1997). Infants with autism: An investigation of empathy, pretend play, joint attention, and imitation. Developmental Psychology,33, 781–789. doi:10.1037/0012-1649.33.5.781

Frankenburg, W.K., Dodds, J., Archer, P., Shapiro, H., & Bresnick, B. (1992). The DENVER II: A major revision and restandardization of the Denver Developmental Screening Test. Pediatrics,89, 91–97.

Fraser, A.M., & Swinney, H.L. (1986). Independent coordinates for strange attractors from mutual information. Physical Review A.,33, 1134–1140. doi:10.1103/Phys-RevA.33.1134

Gepner, B., Mestre, D., Masson, G., & de Schonen, S. (1995). Postural effects of motion vision in young autistic children. Neuroreport,6, 1211–1214. doi:10.1097/00001756-199505300-00034

Gepner, B., & Mestre, D.R. (2002). Brief report: Postural reactivity to fast visual motion differentiates autistic from children with Asperger syndrome. Journal of Autism and Developmental Disorders,32(3), 231–238. doi:10.1023/A:1015410015859

Grice, S.J., Spratling, M.W., Karmiloff-Smith, A., Halit, H., Csibra, G., de Haan, M., & John-son, M.H. (2001). Disordered visual processing and oscillatory brain activity in autism and Williams syndrome. Neuroreport,12(12), 2697–2700. doi:10.1097/00001756-200108280-00021

Hadders-Algra, M. (2008). Reduced variability in motor behaviour: An indicator of impaired cerebral connectivity? Early Human Development,84(12), 787–789. doi:10.1016/j.earlhumdev.2008.09.002

Hadders-Algra, M. (2010). Variation and variability: Key words in human motor develop-ment. Physical Therapy,90(12), 1823–1837. doi:10.2522/ptj.20100006

Happé, F., & Frith, U. (2006). The weak coherence account: Detail-focused cognitive style in autism spectrum disorders. Journal of Autism and Developmental Disorders,36(1), 5–25. doi:10.1007/s10803-005-0039-0

Haworth, J., Kyvelidou, A., Fisher, W., & Stergiou, N. (2015). Children's looking preference for biological motion may be related to an affinity for mathematical chaos. Frontiers in Psychology,6, 281. doi:10.3389/fpsyg.2015.00281

Haworth, J.L., Vallabhajosula, S., & Stergiou, N. (2014). Gaze and posture coordinate differently with the complexity of visual stimulus motion. Experimental Brain Research,232(9), 2797–2806. doi:10.1007/s00221-014-3962-5

Haworth, J., Vallabhajosula, S., Tzetzis, G., & Stergiou, N. (2013). Optimal variability and complexity: A novel approach for management principles. In S. Banerjee (Ed.), Chaos and complexity theory for management: Nonlinear dynamics. USA: IGI Global. doi:10.4018/978-1-4666-2509-9.ch017

Klin, A., Jones, W., Schultz, R., Volkmar, F., & Cohen, D. (2002b). Visual fixation patterns during viewing of naturalistic social situations as predictors of social competence in individuals with autism. Archives of General Psychiatry,59(9), 809–816. doi:10.1001/archpsyc.59.9.809

Klin, A., Lin, D.J., Gorrindo, P., Ramsay, G., & Jones, W. (2009). Two-year-olds with autism orient to non-social contingencies rather than biological motion. Nature,459, 257–261. doi:10.1038/nature07868

Kohen-Raz, R., Volkmar, F.R., & Cohen, D. (1992). Postural control in autism. Journal of Autism and Developmental Disorders,22(3), 419–432. doi:10.1007/BF01048244

Meltzoff, A.N., & Moore, M.K. (1992). Early imitation within a functional framework: The importance of person identity, movement, and development. Infant Behavior and Development,15(4), 479–505. doi:10.1016/0163-6383(92)80015-M

Molloy, C.A., Dietrich, K.N., & Bhattacharya, A. (2003). Postural stability in children with autism spectrum disorder. Journal of Autism and Developmental Disorders,33(6), 643–652. doi:10.1023/B:JADD.0000006001.00667.4c

Mottron, L., & Burack, J.A. (2001). Enhanced perceptual functioning in the development of autism. In J.A. Burack, T. Charman, N. Yirmiya, & P.R. Zelazo (Eds.), The development of autism: Perspectives from theory and research (pp. 131–148). Mahwah, NJ: Erlbaum.

Mottron, L., Dawson, M., Soulieres, I., Hubert, B., & Burack, J. (2006). Enhanced perceptual functioning in autism: An update, and eight principles of autistic perception. Journal of Autism and Developmental Disorders,36(1), 27–43. doi:10.1007/s10803-005-0040-7

Mundy, P., Sigman, M., & Kasari, C. (1990). A longitudinal study of joint attention and language development in autistic children. Journal of Autism and Developmental Disorders,20, 115–128. doi:10.1007/BF02206861

Neri, P., Morrone, M.C., & Burr, D.C. (1998). Seeing biological motion. Nature,395(6705), 894–896.

Piek, J.P., Bradbury, G.S., Elsley, S.C., & Tate, L. (2008). Motor coordination and social-emotional behaviour in preschool-aged children. International Journal of Disability Development and Education,55(2), 143–151. doi:10.1080/10349120802033592

Rhea, C.K., Kiefer, A.W., D'Andrea, S.E., Warren, W.H., & Aaron, R.K. (2014). Entrainment to a real time fractal visual stimulus modulates fractal gait dynamics. Human Movement Science,36, 20–34. doi:10.1016/j.humov.2014.04.006

Sanefuji, W., Ohgami, H., & Hashiya, K. (2008). Detection of the relevant type of locomotion in infancy: Crawlers versus walkers. Infant Behavior and Development,31, 624–628. doi:10.1016/j.infbeh.2008.07.003

Shinbrot, T., Grebogi, C., Wisdom, J., & Yorke, J.A. (1992). Chaos in a double pendulum. American Journal of Physics,60(6), 491–499. doi:10.1119/1.16860

Shockley, K., Butwill, M., Zbilut, J.P., & Webber, C.L., Jr. (2002). Cross recurrence quantification of coupled oscillators. Physics Letters [Part A],305, 59–69. doi:10.1016/S0375-9601(02)01411-1

Shockley, K. (2005). Cross recurrence quantification of interpersonal postural activity. In M.A. Riley & G.C. Van Orden (Eds.), Tutorials in contemporary nonlinear methods for the behavioral sciences (pp. 142– 177). Arlington, VA: Digital publication avail-able from the National Science Foundation website: http://www.nsf.gov/sbe/bcs/pac/nmbs/nmbs.jsp

Smyth, M.M., & Anderson, H.I. (2001). Football participation in the primary school playground: The role of coordination impairments. British Journal of Developmental Psychology,19, 369–379. doi:10.1348/026151001166155

Stergiou, N., Buzzi, U.H., Kurz, M.J., & Heidel, J. (2004). Nonlinear tools in human movement. In N. Stergiou (Ed.), Innovative analyses of human movement (pp. 63–90). Champaign, IL: Human Kinetics.

Stergiou, N., & Decker, L.M. (2011). Human movement variability, nonlinear dynamics, and pathology: Is there a connection? Human Movement Science,30, 869–888. doi:10.1016/j.humov.2011.06.002

Stergiou, N., Harbourne, R.T., & Cavanaugh, J.T. (2006). Optimal movement variability: A new theoretical perspective for neurologic physical therapy. Journal of Neurologic Physical Therapy,30, 120–129. doi:10.1097/01.NPT.0000281949.48193.d9

Sullivan, M., Finelli, J., Marvin, A., Garrett-Mayer, E., Bauman, M., & Landa, R. (2007). Response to joint attention in toddlers at risk for autism spectrum disorder: A prospec-tive study. Journal of Autism and Developmental Disorders,37, 37–48. doi:10.1007/s10803-006-0335-3

Suzuki, Y., Nomura, T., Casadio, M., & Morassa, P. (2012). Intermittent control with ankle, hip, and mixed strategies during quiet standing: A theoretical proposal based on a double inverted pendulum model. Journal of Theoretical Biology,310, 55–79. doi:10.1016/j.jtbi.2012.06.019

Takens, F. (1981). Detecting strange attractors in fluid turbulence. In D. Rand & L-S. Young (Eds.), Dynamic systems and turbulence. New York: Springer Verlag.

Theiler, J., Eubank, S., Longtin, A., Galdrikian, B., & Farmer, J.D. (1992). Testing for nonlinearity in time series: The method of surrogate data. Physica D: Nonlinear Phenomena,58, 77–94. doi:10.1016/0167-2789(92)90102-S

Viviani, P., & Flash, T. (1995). Minimum-jerk, two-thirds power law, and isochrony: Converging approaches to movement planning. Journal of Experimental Psychology. Human Perception and Performance,21(1), 32–53. doi:10.1037/0096-1523.21.1.32

von Hofsten, C. (2004). An action perspective on motor development. Trends in Cognitive Sciences,8(6), 266–272. doi:10.1016/j.tics.2004.04.002

Whalen, C., & Schreibman, L. (2003). Joint attention training for children with autism using behavior modification procedures. Journal of Child Psychology and Psychiatry, and Allied Disciplines,44(3), 456–468. doi:10.1111/1469-7610.00135

Wuerger, S.M., Crocker-Buque, A., & Meyer, G.F. (2012). Evidence for auditory-visual processing specific to biological motion. Seeing and Perceiving,25, 15–28. doi:10.1163/187847611X620892