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Transitivity Types Predict Communicative Abilities in Infants at Risk of Autism*

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Abstract

To examine predictors of preschool language abilities, thirty-seven infants at high risk for Autism Spectrum Disorder (ASD) were recorded longitudinally from 5-14 months as they interacted with their caregivers and toys at home. Triadic interactions were coded, categorized as transitive, intransitive or vacuously transitive, and then related to the MacArthur Bates Communicative Development Inventory (CDI-III) and the Mullen Scales of Early Learning (MSEL) at 36 months. The results show that prior to 14 months, early transitive interactions correlate positively and intransitive interactions correlate negatively with CDI-III and MSEL scores at 36 months. By categorizing interactions between 5-14 months by transitivity, we have demonstrated that recurring triadic patterns can predict communicative abilities at 36 months.

Keywords: Autism, high-risk, language, development, social networks, social interactions

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Introduction

Learning can be defined as an understanding of action-reaction contingencies, and being able to measure such contingencies may aid in investigating developmental processes leading to atypical outcomes. Despite the promising potential of such measurements, methods to incorporate multivariate factors, especially those beyond dyadic interactions, are few. As part of an exploratory investigation, we have developed a protocol to capture all actions and reactions as they occurred temporally between three actors without regard for the information they held. All behaviors, whether social, directed, or seemingly random, were included in this protocol to create a real-time stream of action-reaction sequences.

Analysis of Multirelational Valued Temporal Triads

The Analysis of Multirelational Valued Temporal Triads (AMVTT) was designed to enable the generalized coding of all species across all contexts, developmental stages, behaviors, and environments (White et al., 2014). This method captures all behaviors as interactive links between organisms and their environment. AMVTT measures all interactions, whether they are communicative, social, or attentional, and classifies these interactions as repeatable patterns over time.

Triadic sequencing was useful in studying the brown-headed cowbird, a highly social species (White et al., 2014). By constructing triadic interaction patterns of male-male and male-female song, for example, we could organize a potentially random string of events into meaningful units of interaction that allowed us to predict the birds' reproductive success. Applying this method to infancy research was an exploratory undertaking. Parallels between cowbird and human social and communicative development demonstrated by Goldstein et al. (2003) led to the current hypothesis that a method predictive of effective communication and reproductive outcomes in birds may be able to predict social and communicative outcomes in humans. To ensure substantial variation in social and communicative outcomes in humans, we explored human infants at risk for developing autism. Studying this population allowed the investigation of non-autistic infants (those who did not receive a diagnosis), infants with communicative delays (those diagnosed with language delays), and infants with social and communicative atypicalities (those diagnosed with autism).

The interactions analyzed occurred in home settings, in which infant and caregiver were told to interact and play normally with their own set of toys. The observed behaviors were recorded in real time in an ecologically valid setting, potentially producing more representative results. This social network analysis was designed to incorporate both social and non-social stimuli by considering all behaviors between caregivers, infants, and surrounding objects as equal, rather than weighting specific behaviors (White et al., 2014). Each directed behavior occurring between the three was counted as a behavioral link. In a mutually exclusive manner, links were combined based on sequence and timing to form interaction patterns, or triads. The resulting triads were then categorized by the completion of transitivity, and assessed by directionality and reciprocity (Butts, 2008; Wasserman & Faust, 1994).

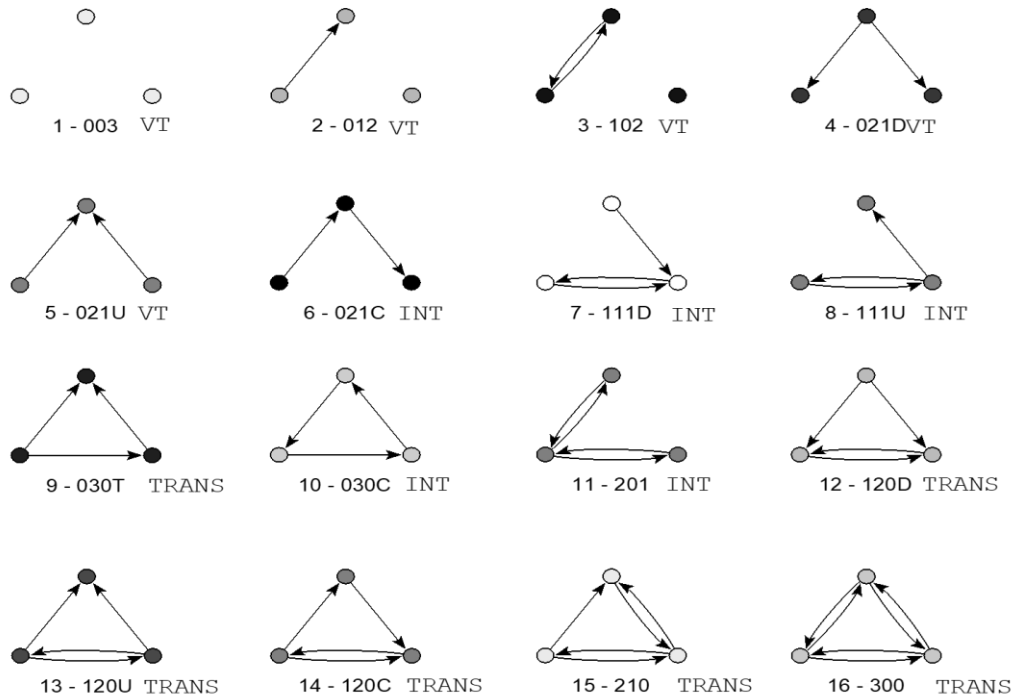


Figure 1: Interactions are sorted into one of 15 triads (003 is not an interaction). Letters correspond to shape characteristics: D=down, U=up, C=cyclical, T=transitive. Numbers correspond with link characteristics: First digit=number of reciprocal links, second digit=number of unidirectional links, third digit=number of null links.

For analysis, triadic interactions are laid out in 15 simple patterns, or types. For a full list of potential triad types, see Figure 1. Each type represents a set of possible links between all three nodes. One triad type can have several different states based on which node first linked to another. The interactive links between each node are assembled into triad types.

For the current research, the three nodes within a triad always represented an infant, a caregiver and an object. To apply this method, a thorough protocol defining behavioral links between the three nodes was implemented. Specific parameters for what constitutes a behavioral link were set for each of the three potential nodes. For example, while touches from either caregiver or infant were always considered links, infants' subtle directed behaviors (e.g., eye gaze, head turns) were also coded as links, whereas caregivers' behaviors had to be more pronounced (e.g., vocalizations) to qualify. For objects, only those with state-changing properties could form outbound links, while static ones could not. For further descriptions of these parameters, see Appendix A.

Triadic Census

For this exploratory project, social networks of triads were measured representing interaction patterns between an infant, a caregiver and surrounding objects (Holland & Leinhardt, 1971;

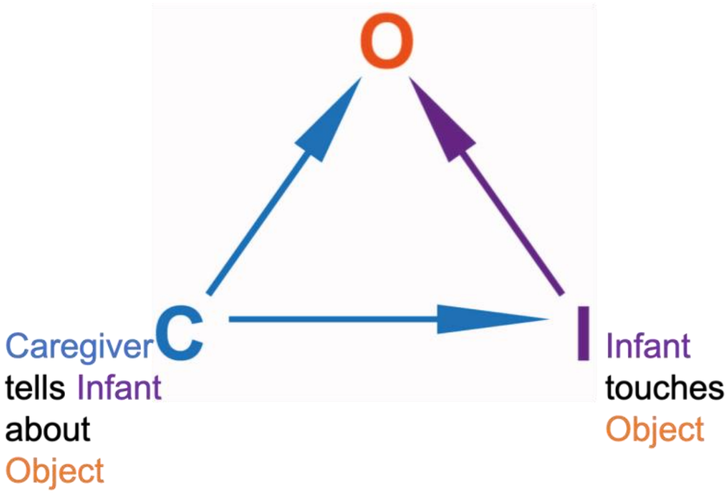


Figure 2: Triadic representation of joint attention. The Caregiver is linking to both Infant and Object, while the Infant is linking to Object. Traditionally, this instance would be referred to as a moment of joint attention because both caregiver and infant are attending to the same third entity. In triadic analysis, this interaction is a transitive (TraT) 030T triad.

White et al., 2014). This type of interactive triad has been shown to demonstrate the most consistency across ages 6 through 18 months, when infants display social and object-oriented engagement (Bakeman & Adamson, 1984).

Focusing on triads, interaction patterns were assessed for whether transitivity was present as dictated by the presence or absence of structural balance, or transitivity. The theory of transitivity is used in social network analysis, as well as in the current project, to categorize these patterns into three types of transitivity as defined by Wasserman & Faust (1994): transitive, intransitive, and vacuously transitive. Interaction patterns are defined by whether transitivity was absent (vacuously transitive), violated or incomplete (intransitive), or present (transitive) (Wasserman & Faust, 1994).

In a balanced structure, when element A is related to B and C, B and C are also related creating a transitive property (Heider, 1946; Holland & Leinhardt, 1971). Transitivity has been used, by applying balance theory, to assess the structural integrity and balance of social networks pertaining to transmission of communication, interactions, friendships, etc. (Moore, 2013; Schimada, 2013; van den Oord et al., 2000). According to balance theory, relationships between elements can exhibit or lack balance based on their structural makeup. Across domains, balanced relationships remain while unbalanced ones either disintegrate or are transformed into balanced configurations.

The most well-known and well-studied instances of transitive interactions are those of joint attention (Figure 2). Transitive interactions include instances in which two participants direct their attention toward a third entity, and either both or only one direct their attention toward the other participant as well. Such transitive interactions have been documented to develop around 9 and solidify at 18 months of age (Carpenter et al., 2002).

Spiro et al. (2013) have described processes of brokerage, in which one of the three entities within a triad can facilitate balance through bridging behaviors. Matchmaking brokerage, for example, occurs in joint attention instances when caregivers name objects for infants, encourage their infants to play with an object, or simply shift their attention between infant and object. The current research analyzes instances of joint attention and bridging behaviors as they occur dynamically in real time and across months with respect to communicative development.

Transitivity and Joint Attention

The study of joint attention has been especially prevalent as it pertains to Autism Spectrum Disorder (ASD) (Bruinsma et al., 2004). ASD is a neurodevelopmental disorder that is four times as common in males than in females with an overall prevalence of one in 59 children in the United States of America (Baio et al., 2018; Lord & Bishop, 2010). Usually diagnosed in children between three and five years of age (3.8 years in males, 4 years in females), symptoms of ASD include fixated interests, repetitive behaviors, and atypicalities in socio-communicative development, including social gazes, reciprocity, and joint attention (American Academy of Pediatrics, 2015; Baio et al., 2018; Lord & Bishop, 2010).

Although numerous studies have demonstrated the predictive and salient quality of joint attention in communicative and social development, especially as it pertains to ASD, the differential effects of whether joint attention is responded to or initiated by the infant remain a debated subject (Bruinsma et al., 2004; Markus et al., 2000). While some studies suggest infant-initiated joint attention to predict language skills and caregiver-initiated joint attention to predict social skills (Malesa et al., 2013), others have shown that infant-initiated joint attention levels were the most predictive of later ASD symptomology (Ibañez et al., 2013). The following study addresses this debate by including both versions, among many other forms of transitive interactions.

A benefit to the transitive theorem is that specific definitions of behavioral patterns deemed important during communicative and social development become obsolete once an underlying pattern is found to incorporate them all. For example, the definition of joint attention differs widely across fields (e.g. shared versus reciprocated attention, initiated versus followed, social versus imitative), making it difficult to form interdisciplinary statements about development and intervention (Bruinsma et al., 2004). Identifying a pattern that can include all joint attention definitions, for example, opens the door to a broader approach to the study of development and possible intervention strategies.

Using the broader categorization of transitivity, our analysis leaves room for undiscovered interaction patterns to be identified. These patterns can include all forms of joint attention, whether initiated or responded to by the infant, and all interactions that represent balance, whether traditionally defined as communicative or not (Csibra, 2010). Because predictive atypicalities have been found to span various forms of communicative and non-communicative behavior, using transitivity as a classification system may prove more effective given the level of heterogeneity of ASD symptomology (Zwaigenbaum et al., 2005).

Hypotheses and Aims

Butts (2008) studied temporally and sequentially constructed triads among human adults and found that triadic interactions contributed little to communication dynamics when compared to reciprocal dyads. In contrast, the current research investigated temporally and sequentially constructed triads among three entities that represent immense stability across a child's first 1.5 years of life and may consequently constitute important building blocks of communicative development (Bakeman & Adamson, 1984). Triadic interactions were thus predicted to play a significant role in communication dynamics in human infants and their social and physical surroundings.

Intransitivity and transitivity were hypothesized to affect infants differently based on the infants' propensities toward social versus physical stimuli. While intransitive interactions most commonly represent a lack of contingent responses to the social bids for joint attention between caregiver and infant, transitive interactions contain contingent responses enabling the identification of action-reaction relationships. These contingent responses can occur with social (caregiver and infant) or non-social (infant and object) stimuli. There is evidence that females develop and maintain a higher sensitivity to social stimuli early in life in comparison to males (Connellan et al., 2001). Less frequent social input was thus hypothesized to have a greater negative impact on females, and less socially sensitive males were hypothesized to benefit more from transitivity available via both social and non-social stimuli.

Because triadic interactions move toward transitive patterns that enable effective exchange (van den Oord et al., 2000), we hypothesized those interactions that were more conducive to communicative development would exhibit transitivity. Interaction patterns, in which transitivity was present, were thus predicted to represent instances in which communicative learning is more readily achieved.

For this pilot study, 37 infants, for whom we had developmental outcome information at the time, were studied, and their average proportions of transitivity types obtained between 5 and 14 months were correlated with their developmental outcome measures at 36 months.

As male and female infants have been shown to develop communicative skills differently, correlations for each gender were run separately (McGillicuddy-De Lisi & De Lisi, 2002). Despite the discrepancy in ASD prevalence between males and females, gender differences in symptomology do not seem to appear until later in development (Reinhardt et al., 2015). Some scholars posit that biases in ASD diagnosis toward males may be related to more readily identified hyperactivity or aggression in males in contrast to a higher social and communicative sensitivity cultivated in females (Connellan et al., 2001; Halladay et al., 2015). The male prevalence of ASD may thus have to do with typically occurring differences between genders rather than anything specific to ASD itself (Messinger et al., 2015). Specifically, it may be due to a divergence in sensitivity to social and physical stimuli affecting male and female language development (Connellan et al., 2001). In addition, where females may acquire language more holistically across syntax, semantics, and pragmatics, males may learn language in a more compartmentalized manner (McGillicuddy-De Lisi & De Lisi, 2002).

Table 1. Demographic information for families

Demographic information	Families (n=37)
Sex	
Male (%)	19 (51)
Female (%)	18 (49)
Racial or ethnic minority (%)	4 (11)
Multiplex family (%)	3 (8)
Mean age for mothers (SD)	33.95 (3.93)
Mean age for fathers (SD)	36.73 (5.15)
Maternal education	
Graduate or professional school (%)	15 (41)
Some college or college degree (%)	17 (46)
High school (%)	5 (13)
Paternal education	
Graduate or professional school (%)	10 (27)
Some college or college degree (%)	21 (57)
High school (%)	6 (16)
Mean paternal occupational prestige (SD)	55.84 (16.25)

This study tested the predictive effectiveness of AMVTT by measuring the relationship between transitivity types and developmental outcomes. Hypotheses of this study posited that transitivity and intransitivity proportions would correlate with developmental measures positively and negatively, respectively.

Methods

Participants

Thirty-seven infants (18 females) and their caregivers were video-recorded in their homes. Families were recruited through an Autism Research Program, parent support organizations, and local agencies and schools serving families of children with ASD (Iverson & Wozniak, 2007). All infants were at risk of developing ASD because they were later-born siblings of children with ASD (e.g., Ozonoff et al., 2011). Older sibling diagnoses were confirmed prior to enrollment by a trained clinician for the Autism Diagnostic Observation Schedule (ADOS; Lord & Bishop, 2010). All infants came from full-term, uncomplicated pregnancies, and all families spoke primarily English. Demographic information is presented in Table 1 (Parladé & Iverson, 2015). Diagnostic outcomes of participants can be found in Table 2 (Iverson & Wozniak, 2007).

Communicative Data

Communicative development was assessed using MacArthur-Bates Communicative Development Inventory, or CDI-III, at 36 months and Mullen Scales of Early Learning (MSEL) at 36 months (Fenson et al., 2007; Wan et al., 2012). The CDI-III uses parent-report to assess three categories: a 100-item vocabulary checklist, 12 sentence pairs assessing grammatical complexity, and 12 yes/no questions concerning semantics, pragmatics, and comprehension. It was designed with 30 to 37-month-old toddlers in mind (Parladé & Iverson, 2015). Subnormal scores from this measure were also used to determine language delay.

Because CDI-III data were generated by parents, and then compared to triadic interactions including parent behavior, the shared method variance needed to be addressed. To do so, a standardized developmental measure, the MSEL, was included. The MSEL represents a standardized test of early cognitive and motor development as assessed by a trained practitioner. For this study, the MSEL was used to measure receptive and expressive language, fine motor skills, and visual reception in infants at 36 months (Wan et al., 2012). CDI-III measures are gender-normed while those of the MSEL are not (Fenson et al., 2007; Wan et al., 2012).

Finally, ADOS severity scores were obtained at 36-month visits via structured observation and interaction during which different modules are used based on present language ability (Rogers et al., 2012). The ADOS scale ranges from 1 to 10, and an ASD diagnosis is given at a score of 4 or higher (Gotham et al., 2009).

Behavioral Data

Interactions between infants, caregivers, and objects were recorded monthly during home visits from 5 to 14 months. Recordings occurred within three days of the monthly anniversary of the infant's birthday and at a time of day when caregivers expected their infants to be most alert and playful. Caregivers were instructed to play naturally with their infants. Audio/video recordings contained approximately 45 minutes of structured and unstructured play. Structured play involved experimenter provided age-appropriate toys, including rattles, books, and picnic, ring, and barn sets. Unstructured play involved the caregiver and infant playing with or without their own toys.

Coding

Coders completed semester-long training and several inter-rater-reliability (IRR) tests before coding videos. To code videos independently, coders were required to maintain an IRR score average of 0.9 using ICC and Cohen's Kappa. ICC and Kappa scores were obtained weekly in which all coders coded a randomly selected 1-2 min section for comparison. ICC scores were based on total link frequencies, and Kappa scores were based on link sequences. All coders were kept blind to the risk status and outcomes of all infants. Videos were coded using ELAN linguistic annotator (Sloetjes & Wittenburg, 2008). The onset of each directed behavior, i.e., the moment at which a behavior aimed at infant, caregiver, or object began, was coded as a link from either caregiver, infant, or object, to one of the other two (see Appendix A).

Each infant had 10 monthly videos (except for five infants who lacked one monthly recording). A coder not assigned to code a monthly video marked the codeable sections of the entire video, resulting in an average length of 30 minutes per video. Non-codeable sections included instances in which triadic formations were compromised, e.g., a restrained infant unable to move freely, pets in the frame, instances in which either caregiver or infant was not visible, or low-quality audio/video. Then, the assigned coder scored the codeable sections for all observable caregiver, infant, and object links. Links followed different criteria based on whether they were produced

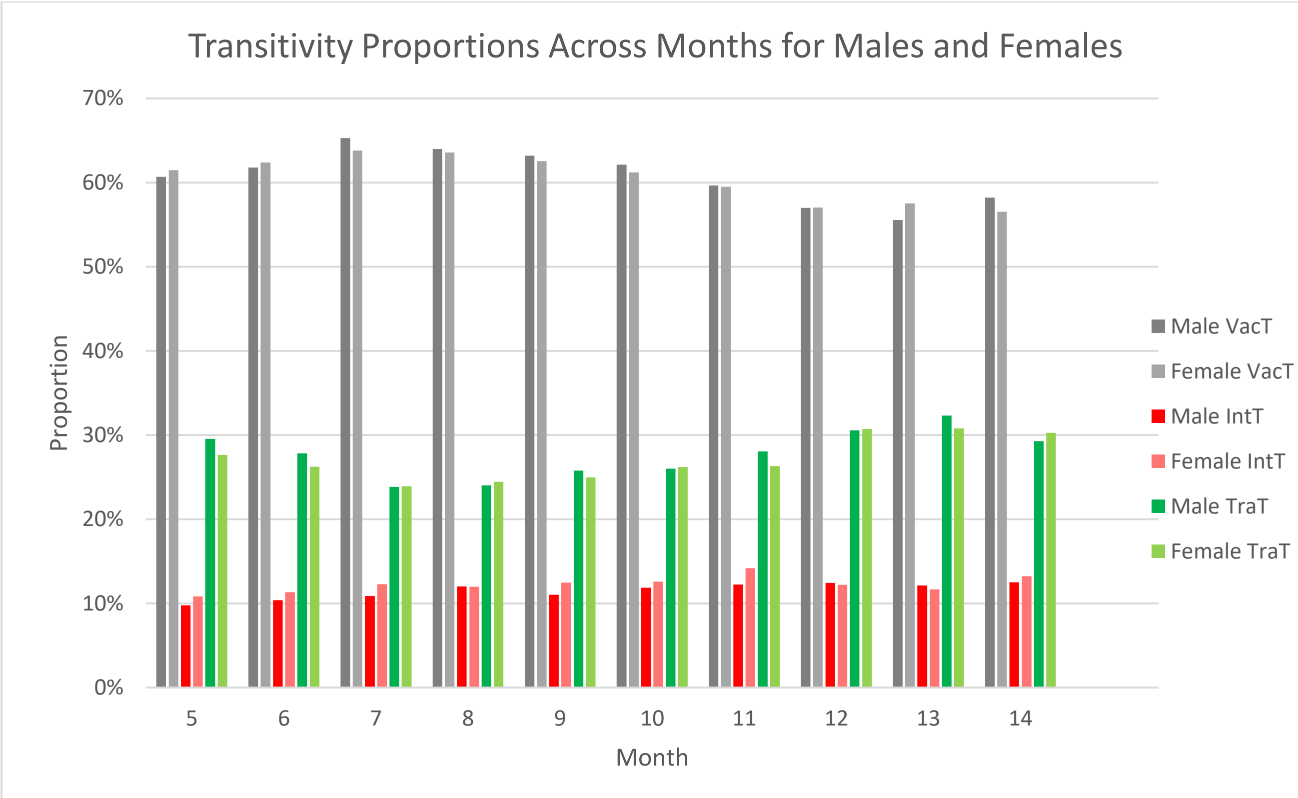


Figure 3: Transitivity type proportions across months for males and females. The x-axis represents months 5 through 14, and the y-axis represents the proportions each transitivity type constitutes. Male and female proportions are displayed side by side for better comparison across months.

by the caregiver, infant, or object (see Appendix A). To capture the various ways in which objects could interact with their human counterparts and form outbound links, specific object-linking rules were developed, which derived from the objects' abilities to provide contingent responses via electronic, mechanical, or combinatory properties (see Appendix A).

Triadic Analysis

All links gathered from monthly audio/video recordings were used to form triads, which comprised as many as one to six links (Figure 1). Using a 4D programmable database, all links formed triadic patterns in a mutually exclusive manner based on their temporal sequencing and interlink intervals (for examples, see Table 2). The same type of link could thus never occur within the same triad. Because of the temporal variation in behavioral sequences across development and participants, the time window used to define whether behavioral links were pulled into the same triad was adjusted to each participant and month. The time window was determined by calculating the interlink interval that incorporated 85% of all interlink intervals (average time window=2031 msec). If a link occurred outside of the determined interlink interval, it started a new triad. An infant's month yielded an average of 920 triadic patterns (i.e. ~9,200 triadic patterns across months per infant, and ~340,040 triadic patterns across all infants and months; for a full list of frequencies and proportions, see Figure 3 and Appendix B).

Table 2: Six examples in which the same initial action lead to either a VacT, ntT, or TraT triad

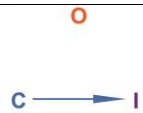
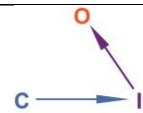
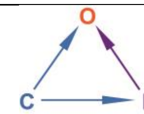
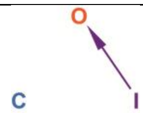
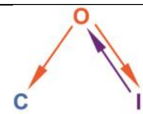
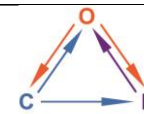
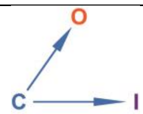
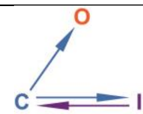
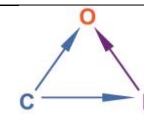
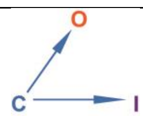
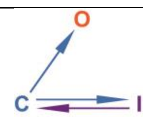
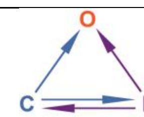
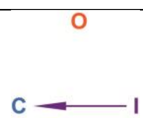
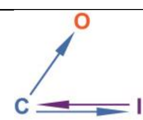
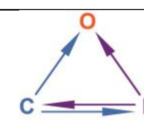
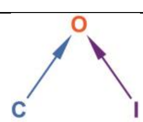
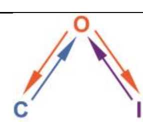
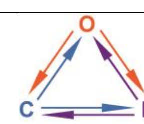
Example	VacT	IntT	TraT
A Behavior	1.Caregiver calls Infant's name	1.Caregiver calls Infant's name 2.Infant touches Object	1.Caregiver calls Infant's name 2.Infant touches Object 3.Caregiver plays with Object
Triad			
B Behavior	1.Infant shakes Object	1.Infant shakes an Object 2.Object rattles in earshot of Infant and Caregiver	1.Infant shakes Object 2.Object rattles in earshot of Infant and Caregiver 3.Caregiver talks to Infant about Object
Triad			
C Behavior	1.Caregiver shows Object to Infant	1.Caregiver shows Object to Infant 2.Infant looks at Caregiver	1.Caregiver shows Object to Infant 2.Infant looks at Object
Triad			
D Behavior	1.Caregiver shows Object to Infant	1.Caregiver shows Object to Infant 2.Infant looks at Caregiver	1.Caregiver shows Object to Infant 2.Infant looks at Caregiver and Object
Triad			
E Behavior	1.Infant looks at Caregiver	1.Infant looks at Caregiver 2.Caregiver speaks to Infant about Object	1.Infant looks at Caregiver 2.Caregiver speaks to Infant about Object 3.Infant looks at Object
Triad			
F Behavior	1.Infant and Caregiver both touch Object	1.Infant and Caregiver touch Object 2.Object lights up for Infant and Caregiver	1.Infant and Caregiver touch Object 2.Object lights up for Infant and Caregiver 3. Caregiver and Infant look at each other
Triad			

Table 3: Transitivity types and outcome measures

Transitivity Types and Outcome Measures	*Males (n=19)*	*Females (n=18)*
Transitivity		
VacT average proportion mean (SD)	0.60 (0.04)	0.60 (0.03)
IntT average proportion mean (SD)	0.11 (0.01)	0.12 (0.02)
TraT average proportion mean (SD)	0.27 (0.03)	0.27 (0.03)
CDI		
CDI-III raw word count (SD)	51.21 (27.97)	53.17 (24.51)
CDI-III complexity number (SD)	5 (3.83)	7.06 (4.09)
CDI-III complexity percentile (SD)	14.47 (18.48)	27.06 (34.41)
CDI-III using language number (SD)	6.89 (3.60)	6.94 (2.94)
CDI-III using language percentile (SD)	28.68 (28.81)	17.17 (25.32)
CDI-III longest sentence mean (SD)	6.93 (3.00)	7.48 (1.96)
MSEL		
Visual Reception (SD)	52 (15.99)	57.53 (13.61)
Fine Motor (SD)	43.89 (16.31)	44.78 (15.69)
Receptive Language (SD)	48.72 (12.41)	47.44 (13.26)
Expressive Language (SD)	53.72 (10.17)	52.23 (12.84)
ADOS	2.47 (1.81)	2 (1.75)
Diagnostic outcome information		
ASD (%)	2 (11)	2 (11)
Language delayed (%)	9 (47)	6 (33)
No symptoms (%)	8 (42)	10 (56)

All triads were then categorized into one of three transitivity types based on whether transitivity was complete (transitive=TraT), incomplete (intransitive=IntT), or absent (vacuously transitive=VacT). Due to the exhaustive nature of triadic formation, proportions were calculated for individual triads and overall transitivity types. Proportions were computed by dividing the raw number of one transitivity type by the total number of interactions. Transitivity type averages were calculated by averaging 5-14-month proportions per infant. These averages represented a time window before and during a time in which first words typically begin to appear (Waxman & Gelman, 2009).

Statistical Analysis

Males and females were analyzed separately, since preliminary combined analyses of males and females indicated a self-cancelling effect of opposing TraT and IntT trends. Additionally, the CDI-III has separate norms for males and females (Fenson et al., 2007). For these reasons, males and females were analyzed separately.

Table 3 shows means, percentiles, standard deviations, percentages, and scores for the transitivity measures, CDI-III, MSEL, ADOS, and diagnostic outcomes split by gender. Mean transitivity proportions were correlated with subcategory scores from the CDI-III, MSEL total and subcategory scores, ADOS severity scores, and demographic data using Pearson correlations. Following multiple correlations, p-values were adjusted using the Benjamini-Hochberg procedure (Benjamini & Hochberg, 1995).

Table 4: Significant correlations between transitivity types and outcome measures for males and females

Significant correlations	Males (n=19)	Females (n=18)
TraT and CDI-III raw word count	cor=0.53, p=0.03	
IntT and CDI-III raw word count		cor=-0.51, p=0.04
IntT and CDI-III number of complex language used		cor=-0.62, p=0.03
IntT and CDI-III number of times language used		cor=-0.55, p=0.03
IntT and CDI-III longest sentence means		cor=-0.55, p=0.03
IntT and MSEL standard score		cor=-0.56, p=0.03
IntT and MSEL fine motor score		cor=-0.55, p=0.03
IntT and MSEL receptive language score		cor=-0.55, p=0.02
IntT and MSEL cognitive sum		cor=-0.53, p=0.03

Results

No significant differences were found between males and females and their transitivity type proportion averages or their developmental outcome measures. The way in which transitivity types and developmental outcome measures associated, however, differed by gender.

For males, neither VacT (cor=-0.36, p=0.16) nor IntT (cor=0.00, p=0.99) proportions between 5-14 were predictive of CDI-III subcategory scores at 36 months. TraT proportions between 5-14 months were, however, strongly positively correlated with CDI-III raw word count (cor=0.53, p=0.03).

For females, neither VacT (cor=0.16, p=0.56) nor TraT (cor=-0.20, p=0.48) proportions between 5-14 were predictive of CDI-III raw word count. IntT proportions between 5-14 months were, however, strongly negatively correlated with CDI-III raw word count (cor=-0.51, p=0.04). This strong negative correlation existed across all other subcategories of CDI-III, including number of complex language used (cor=-0.62, p=0.03), number of times language was used (cor=-0.55, p=0.03), and longest sentence means (cor=-0.55, p=0.03).

These results do not simply reflect inter-correlations among CDI-III subcategories: VacT interactions among females correlated significantly with only one of the many subcategories, indicating that while they are all related, they are not necessarily all predicted by the same factors (times language was used: cor=0.55, p=0.03).

There were no significant correlations between male interactions and MSEL scores. Female IntT proportion averages correlated negatively with MSEL standard scores (cor=-0.56, p=0.03). Subcategories of the MSEL also correlated with average intransitivity proportions in females (Fine Motor: cor=-0.55, p=0.03; Receptive Language: cor=-0.55, p=0.02; Cognitive Sum: cor=-0.53, p=0.03). ADOS severity scores ranged from 1 to 7, and all infants but one, who scored 5 or higher (n=4), had ASD. There were no significant correlations between male or female proportions and their ADOS severity scores or their demographic data, as measured by years of maternal education and paternal occupational prestige. See Table 4 for a list of all significant correlations split by gender.

Discussion

The proportions of interactions in three categories of transitivity that were observed in infants at 5-14 were correlated with their CDI-III, MSEL and ADOS scores. Although males and females did not differ in their averages for transitivity type proportions or developmental outcome measures, TraT correlated positively with a CDI-III measure in males, and IntT correlated negatively with communicative outcome in females across CDI-III and MSEL measures.

The transitive theorem appeared to manifest itself in a complementary fashion in both genders. Where females seemed to be more strongly affected by the negative impacts of IntT, the positive effects of TraT impacted males more. IntT interactions most commonly represent a lack of contingent responses to the social bids for joint attention between caregiver and infant, as well as primarily describing play with a highly interactive (often electronic) object. TraT interactions contain contingent responses enabling the identification of action-reaction relationships. These contingent responses can occur with social (caregiver and infant) or non-social (object) stimuli. There is evidence that females develop a higher sensitivity to social stimuli earlier in life than males (Connellan et al., 2001). Interactions mainly generated through object play may thus have a greater negative impact on socially sensitive females, and less socially sensitive males may benefit more from transitivity available via both social and non-social stimuli. This gender difference, considering that it is present when correlating gender-normed outcome measures (namely, CDI-III) with similar transitivity proportions for males and females, speaks for a substantial finding representing differing learning and interactive sensitivities in males and females. It is possible that similar findings would have become apparent in the MSEL correlations, had those measures been gender-normed as well.

In this exploratory project, we set out to measure patterns so basic and intrinsic to development, that they could be found in any learning organism at any developmental stage. The hope was to develop a method predictive of behaviors without the presence of their precursors or related behaviors. The current study found that intransitive patterns in 5-14-month-old females predicted not only language use (CDI-III), but also communicative and social understanding (MSEL), both assessed at 36 months. The relationship between these early interaction patterns and later, more sophisticated outcome measures shows promise that our method may indeed capture an underlying strategy fundamental to the general development of learning itself. Engaging in certain interaction patterns may set the stage for infants to apply early relational understanding to other, more specific types of understanding, such as those required for communicative and social development.

In the current study, the potential for a broader connection between different types of learning, however, only applies to the female infants. Male effects were found only on raw word count, whereas for females, effects were found across all CDI-III and some MSEL subcategories. These gender differences may not necessarily be specific to the high-risk infants studied as much as they may reflect typically occurring divergence in male and female language development (Messinger et al., 2015). Where females may acquire language more holistically across syntax, semantics, and pragmatics, males may learn language in a more compartmentalized manner (McGillicuddy-De Lisi & De Lisi, 2002). Nevertheless, patterns categorized by transitivity allowed us to measure early patterns predictive of later outcomes in both genders.

Usually, transitivity analyses are applied to static structures. Interested in developmental processes, we applied a technique to take time into account while using the concept of transitivity (White et al., 2014). Additionally, in studying learning mechanisms, our technique was sensitive to contingencies by using action-reaction sequences to form interaction patterns. We thus used sequentially formed triads to analyze real-time interactions as action-reaction units. Instead of modeling singular actions in sequence, as has been done using a Relational Event Model when examining social interactions in jackdaws, for example, (Butts, 2008; Tranmer et al., 2015), we wanted to capture possibly transitive interactions as a whole as they occurred in real time between infants and their social and physical surroundings. Just as cowbird social behaviors could predict reproductive outcome when organized into units, categorizing infant-caregiver-object interactions by transitivity allowed us to predict communicative outcomes (White et al., 2014). In addition, our results provide a noteworthy addition to Butts' (2008) findings in which transitivity had little effect on communicatively skilled adult humans. By the time communicational abilities have been established, transitivity may not be as important as reciprocity, for example, as demonstrated by Butts (2008). Our results, on the other hand, indicate that transitivity may represent a fundamental process when first learning how to communicate. By applying the theory of transitivity, we may have developed a method of identifying early interaction patterns indicative of communicative development in infants at risk for ASD.

Our method allowed us to categorize interactions patterns based on whether they represented mutuality (and/or symmetry) in dyads or transitivity in triads (Heider, 1946; Wasserman & Faust, 1994). Across several studies, results have shown that social structures move toward mutuality in dyads (A and B interact mutually) and transitivity in triads (e.g., A interacts with B and C, and B interacts with C) as children develop more complex communication and play systems (McGrew, 1972; van den Oord et al., 2000).

As we have mentioned before, joint attention represents a key example of transitivity, and thus typifies the kind of social pattern infants would ideally move toward across development. It follows then that the absence of joint attention has been used as an early indicator of potential deficits later in life. In literature, however, distinctions have been made between joint attention instances in which the infant engages with only the third entity versus with both participant and third entity. While the former has been deemed non-social with respect to the infant's involvement, the latter has been considered social due to the synchronized social interaction between both participants while attending to a third entity (Moore & Dunham, 1995). It is debated whether this distinction is useful (Yu & Smith, 2013), especially as joint attention, in its various manifestations, may represent such a potent indicator of later development.

AMVTT was designed to either consider this distinction (as tested in further studies) or override it by examining overall transitivity types and consequently weighing both joint attention instances equally (current study). In doing so, we may have created a new method of assessing and identifying various patterns conducive to communicative development in young infants at risk of ASD. Using this method may provide possibilities to not only identify early intransitive patterns that may be indicative of communicative deficits, but also train parents to implement the types of transitive patterns associated with communicative abilities. The findings of the current study emphasize the wide variety with which joint attention and the like can occur, and that when taken as a whole, these instances may predict and possibly further communicative development in infants.

It is important to note that some of the significant relationships measured occurred between two parent-generated variables, namely CDI-III scores and triadic interactions. The possible co-variance between the two variables was partially addressed by adding another trainer-assessed variable, MSEL. Because MSEL scores only correlated with triadic interactions involving female infants, CDI-III correlations in males and females must be viewed with a level of caution. Nevertheless, possibly telling relationships were identified between early interaction patterns and two separate assessments of development two years later.

The audio/video recordings used for behavioral coding of links represent a limitation of our study. We placed great value on obtaining the most ecologically valid recordings by looking at caregiver-infant interactions as they occurred in the home setting. To preserve the validity of such a setting, it was important to keep research personnel at a minimum. This restriction meant using only one camera person per caregiver-infant interaction. The resulting recordings thus likely failed to capture certain gazes, touches, and other pragmatic subtleties important for effective social communication. Ideally, caregiver and infant would have been recorded and coded separately to ensure the most accurate depiction of their behavioral links during interactions.

Another limitation is represented by the small sample size of only high-risk infants. We recognize that our results pertain only to a highly specific population of humans and thus can only speculate on the generalizability of our results to typically developing infants and children. Further studies are needed to assess the applicability of our current results to larger populations and typically developing children. Nevertheless, the findings provide first insights into how triadic analysis and transitivity can shed light on early interactive factors essential to communicative development.

Using the comprehensive approach of triadic analysis to incorporate all behaviors occurring between infant, caregiver, and objects, we aimed to investigate a broader concept of how learning occurs within interactions that include both verbal and non-verbal social and non-social exchange. In the current analysis, categorizing interactions by transitivity allowed us to predict words before words were present, possibly revealing a mechanism representative of something broader than word learning and/or language delays. Rather than measuring how infants specifically learn words, we may have found a way to measure how infants, by engaging in different types of behavioral patterns, learn about learning.

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Appendix A

The following is a condensed version of the protocol used to code videos of infants from 5-14 months of age. To maintain consistency and reliability in coding, the protocol was designed with both ecological validity and coding replicability in mind. Due to its needed restraining factors, this protocol emphasizes the occurrence of certain triads (e.g., 210 and 111U) and decreases the possibility of others (030C).

1. General Coding Protocol
    1. Changes in behavior are coded.
        a. A link connotes a change in behavior directed toward Caregiver, Infant, or Object, each of which can act as a node for triadic analysis.
        b. A link occurs when a node:
            i. Looks,
            ii. Orients,
            iii. Touches,
            iv. Speaks to Infant (link to Infant),
            v. Speaks about Object to Infant (link to Object and Infant),
            vi. Changes its state (for Objects).
    2. Start times of links are important and need to be precise as this is what is used in analysis.

2. Reliability and Quality Control
    1. Sometimes coders will switch off videos to other coders, allowing for at least 2 separate coders to review and add to coding while completing them.
    2. At least 5 different coders code the ten months from 5 to 14 while coding alternate months. Thus, for any given infant, a given coder would usually only code 2 months.

3. Infant Link Coding
    1. Code changes in behavior.
    2. Code Infant tracking.

3. Caregiver Link Coding
    1. All individuals older than Infant are coded as Caregiver and are not distinguished.
    2. Only code changes in behavior.
    3. Caregivers often narrate their actions – narration and action do not need to be coded separately. Code them as part of one complete behavior.

4. Context and Object Link Coding

Free Play sessions are separated into 3 different contexts that define object-linking rules. Repetitive object actions are coded as 1 link. An obvious break in behavior and interaction starts a new link. Objects link when they change state. A change of state occurs only when components of Object change. This does not include a change of state pertaining to the object in its entirety (throwing/dropping/knocking over an object). It does include the following:

a. Electronically reactive toys
b. Objects that can be opened and closed (e.g. books, boxes, bags)
c. Pop-up or press-in toys
d. Blocks falling over
e. Rattles
f. Individual parts spinning (e.g. doctor’s toy)
g. Mirrors (link back to the individual whose reflection can be seen)

   h. Any 2 objects that are brought together or taken apart to form a new object or function (banging toys together, stacking toys, opening/closing toys, putting toys in bags/taking them out).
   i. Objects (usually untraditional toys) that are made of materials that make noise upon manipulation and whose noise-making property is referred to by the caregiver.

1. Independent Play: Any play in which Infant or Caregiver is engaging with an object separately or independently of the other is Independent Play. An object links back to either Caregiver or Infant when it changes its state.
   a. Rattle Sessions: Occur in 5-11 months. Even though Caregiver is present, these sessions heavily focus on Infant exploring different rattles. These sessions are coded as Independent Play, and thus the rattle links only to Infant.
      i. As soon as Caregiver is actively involved in some way, it links back to both.
2. Coordinated Play: Any play that involves both Caregiver and Infant interacting with the same toy most of the time is Coordinated Play. Whenever the "shared" Object changes state, it links to both Caregiver and Infant even if either one is not actively interacting with it.
3. Book Reading: A book links back when it is read from or when it is the focus of visual, auditory, and haptic attention.
   a. To signify the high interactivity of book reading, nearly all links to the book are reciprocated, i.e. Object always links back to both Caregiver and Infant when linked to by either.

Appendix B

Monthly frequencies for links and triads and proportions for transitivity types.

Male Dataset Months	Mean Link Rate	SD	Link Sum	Mean Triad Rate	SD	Triad Sum	VacT Proportion	IntT Proportion	TraT Proportion
5	56.81	7.83	1759	24.19	3.31	748	60.67%	9.77%	29.56%
6	59.60	14.95	1696.79	25.36	4.70	722.89	61.79%	10.38%	27.82%
7	58.57	14.40	1990.37	26.52	5.18	899.26	65.28%	10.89%	23.83%
8	61.77	13.28	2021.37	27.76	4.52	916.89	63.98%	12.00%	24.02%
9	65.17	8.25	2150.58	28.96	2.81	954.59	63.21%	11.02%	25.77%
10	68.30	11.44	2236.68	30.06	5.20	997.42	62.12%	11.88%	25.99%
11	69.30	12.05	2336.21	29.53	4.52	1002.47	59.67%	12.25%	28.08%
12	73.55	14.40	2573.24	31.26	4.53	1097.13	56.99%	12.44%	30.57%
13	72.93	11.05	2766.42	30.75	4.17	1163.79	55.54%	12.14%	32.32%
14	67.89	15.07	2632.42	29.34	6.11	1134.37	58.21%	12.51%	29.28%
Female Dataset Months	**Mean Link Rate**	**SD**	**Link Sum**	**Mean Triad Rate**	**SD**	**Triad Sum**	**VacT Proportion**	**IntT Proportion**	**TraT Proportion**
5	61.92	15.81	1759.47	26.28	5.12	756.00	61.49%	10.85%	27.66%
6	60.69	12.18	1863.72	26.69	5.44	826.67	62.41%	11.35%	26.24%
7	57.73	14.40	1824.28	25.70	5.16	819.83	63.81%	12.27%	23.92%
8	57.04	10.77	1740.82	25.18	4.00	775.59	63.58%	11.98%	24.44%
9	65.57	10.34	1990.94	29.05	4.22	881.53	62.54%	12.49%	24.97%
10	64.31	10.94	1787.44	27.96	3.95	784.78	61.22%	12.59%	26.19%
11	69.18	14.97	2201.83	29.53	5.41	936.72	59.50%	14.18%	26.32%
12	69.07	14.49	2496.61	29.48	6.01	1062.67	57.04%	12.22%	30.74%
13	69.56	14.75	2690.17	29.72	5.79	1151.50	57.54%	11.66%	30.80%
14	66.91	12.29	2458.89	28.57	5.19	1048.72	56.53%	13.23%	30.25%