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Fundamental principles of network formation among preschool children

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ABSTRACT

The goal of this research was to investigate the origins of social networks by examining the formation of children's peer relationships in 11 preschool classes throughout the school year. We investigated whether several fundamental processes of relationship formation were evident at this age, including reciprocity, popularity, and triadic closure effects. We expected these mechanisms to change in importance over time as the network crystallizes, allowing more complex structures to evolve from simpler ones in a process we refer to as *structural cascading*. We analyzed intensive longitudinal observational data of children's interactions using the SIENA actor-based model. We found evidence that reciprocity, popularity, and triadic closure all shaped the formation of preschool children's networks. The influence of reciprocity remained consistent, whereas popularity and triadic closure became increasingly important over the course of the school year. Interactions between age and endogenous network effects were non-significant, suggesting that these network formation processes were not moderated by age in this sample of young children. We discuss the implications of our longitudinal network approach and findings for the study of early network developmental processes.

1. Introduction

Despite the importance of social networks, surprisingly little is known about the basic processes that generate them. Studying social network *formation* is complicated by the fact that relatively few easily observed instances occur in the natural world. It is rare that a set of strangers come together with the motivation and interaction opportunities that are necessary to form a new set of relationships, and rarer still that a researcher can arrange to observe the process. A few such situations have been examined, for example, students entering a university (Eagle, 2005; Newcomb, 1961; Van Duijn et al., 2003), summer camps (Parker and Seal, 1996; Savin-Williams, 1979), and police officer training academies (Conti and Doreian, 2002). These studies provide some insight into the network formation process, but potential confounds remain. For example, researchers must typically establish a false network boundary (Marsden, 2004) and have difficulty accounting for socialization in previous relationships. Uncontrolled heterogeneity exists because participants in most social network studies typically come with complex and highly elaborated schemas, thus diminishing the importance of endogenous sorting into relationships through structural processes.

Our objective is to understand the fundamental principles that drive social network formation. We propose that utilizing a sample of preschool children provides us with a means to overcome the aforementioned confounds because preschool is the time when children begin to form relationships with peers. Preschool affords new social opportunities for children who are just reaching a level of development that supports enduring peer relationships (Fabes et al., 2004; Martin et al., 2005). We hypothesize that several well-known principles of network formation, namely reciprocity, popularity, and triadic closure will vary in importance throughout the network formation period as the structure itself evolves.

2. Studying network formation with preschool children

Preschool children provide a unique opportunity to observe the fundamental principles that drive social network development. More than half of 3–5-year-olds in the U.S. are enrolled in preschool programs, and participation in early childhood education programs has increased over the past 15 years (U.S. Department of Education, 2007). For many children, the preschool classroom is their first opportunity to regularly interact with a large number of same-age peers, which allows children to develop enduring relationships with one another. Moreover, the larger number and more diverse array of classroom peers allow children to exercise *choice* in their regular play partners (often for the first time in their lives). Unlike siblings or neighborhood children with whom children may simply

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be placed as a result of adult choices, preschool offers an overabundance of partner choices, forcing children to be selective.

In addition, the preschool classroom serves as a natural boundary for children's interactions and relationship development. Children may spend time outside the classroom in other social settings, such as church, family events, and structured activities; however, these are typically less frequent and consistent than interactions in the classroom. Lastly, the preschool period, when children are roughly between 3 and 5 years of age, marks the emergence of true social relationships with peers. During preschool, children's acquisition of social, cognitive, and communication skills allow them to move away from the general tendency to play alone or alongside peers and to begin engaging in social interactive play (Rubin et al., 2006). Children's close friendships become relatively stable (Ladd, 1990) and, relative to toddlers, preschool children display larger, denser, and more organized networks with reciprocal friendships to particular peers (Johnson et al., 1997; Snyder et al., 1996; Strayer and Santos, 1996; Vespo et al., 1996). However, their youth and developmental stage limit the extent of prior relationships and socialization. Thus, the number of pre-existing relationships and their cumulative socialization effect is less than in older populations, providing a set of individuals who are relatively "uncontaminated" by prior social experiences with peers (Snyder et al., 1996).

3. Network formation through structural cascading

Networks form through multiple endogenous processes, where emerging relationships act as a catalyst for additional relationships. An important goal for researchers is to identify the different time scales that network processes follow (Doreian, 2004; Doreian et al., 1996). Our research examines how several endogenous network processes vary in relative importance throughout the early network formation period. We expect that more complex structures, defined by the number and specificity of actors and relations involved, require more time to form and should increase in importance over time, in a process we call *structural cascading*. For instance, dyadic structures can form quickly whereas triadic structures, which build upon dyads, take longer to emerge. We propose that the following network processes are general and operate whenever strangers come together with the motivation, time, and capacity to form relationships.

3.1. Reciprocity

Reciprocity entails responding to others' gestures of friendship with like gestures (Blau, 1964). The tendency to reciprocate others' actions is a universal feature of social life (Simmel, 1950), arguably responsible for the stability of society (Gouldner, 1960). Not surprisingly, research has consistently documented the presence of reciprocity in networks (Hallinan, 1978/1979; Holland and Leinhardt, 1981; Molm et al., 2007). Indeed, by the age of 4–5 years, the majority of children have at least one reciprocated friendship in which they spend considerable time together and evaluate one another favorably (Snyder et al., 1996).

The emergence of reciprocity can be seen in Fig. 1, which provides a hypothetical example of the network formation process. At time 1, A and D have each exhibited a preference for one other person. Once at least one relation has formed the structural prerequisite for reciprocity exists—C and E need only return their partners' gestures to establish a reciprocal relationship. Because C and E do not need to be aware of anyone else in the network, the information-

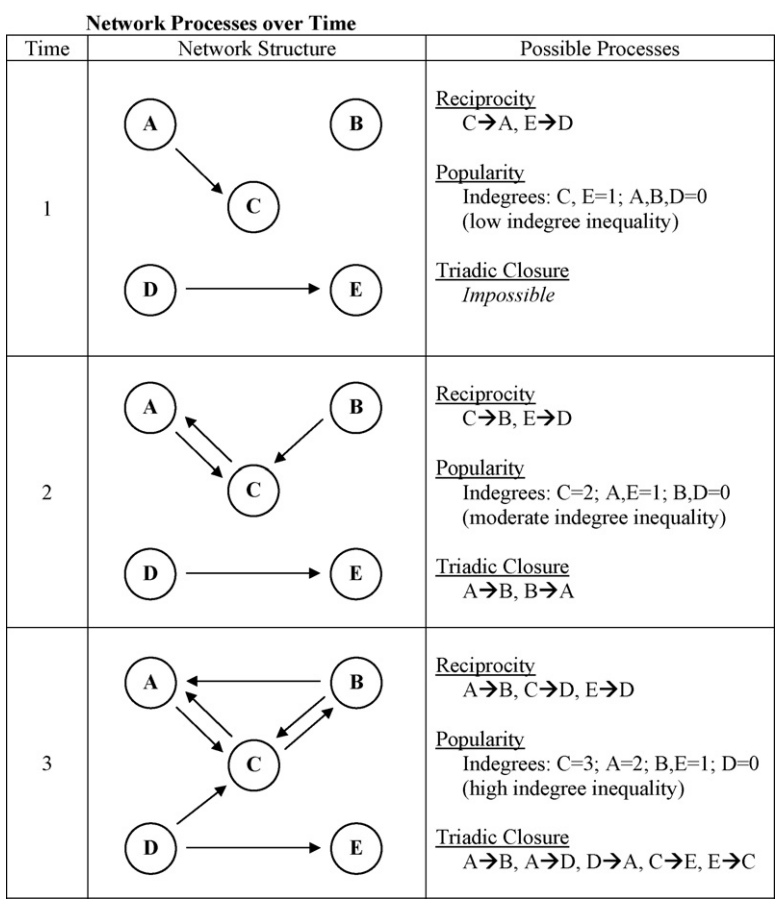

Fig. 1. Network processes over time.

processing requirements of reciprocity are minimal. C and E have an incoming relation in time 1, making them eligible for reciprocity, while everyone but D is eligible to reciprocate by time 3.

Reciprocity is the simplest element of network formation as it only involves two individuals coordinating their behavior toward one other. Individuals need only be aware of one other person's behavior towards them and respond in kind. Consequently, reciprocity should be one of the earliest structural features to appear in a newly forming network (Doreian et al., 1996; Newcomb, 1961; Wasserman, 1980). In addition, its universal, normative status and early appearance should produce a stable level of reciprocity throughout the network formation process (Doreian et al., 1996). The pace of relationship formation through reciprocity may slow; but, as individuals begin to form long-term commitments to one another the maintenance of reciprocated relationships should ensure that a high level of reciprocity persists in the network.

3.2. Popularity

Popularity drives relationship formation when individuals with more incoming relations, or 'ties,' receive additional friendship initiations at higher rates than others through preferential attachment (Barabási and Albert, 1999) or prefer one another at greater rates (van den Oord et al., 2000).[1] Popularity may be based upon individual attributes (personality, physical attractiveness, etc.), an endogenous product of early interaction patterns, or a cumulative effect of social evaluations and influence (Gould, 2002).

Popularity is a more complex process than reciprocity. Popularity requires an unequal indegree distribution (i.e., inequality in the volume of incoming ties), which presupposes the formation of at least one relationship, excluding one's own. Fig. 1 illustrates how popularity can affect friendship formation as an unequal indegree distribution appears. At time 1, two relations have formed, giving C and E higher indegree than the others. Though inequality is low, once some individuals receive more ties than others, popularity can drive future relationship formation. Importantly, once some relations form, *all individuals* can form additional relationships through popularity. For example, at time 2, anyone can choose the more popular C or E (which B does). By time 3, the indegree distribution displays the greatest inequality, with C having 3 incoming ties and D having none.

An unequal indegree distribution is quite likely early in the network formation process as individuals seek others based upon external status characteristics or behavior, which themselves are unevenly distributed. However, early in the network formation period relations are unstable and perceptions of them are based on limited information. This uncertainty leaves little basis for consensus and makes it likely that relative popularity will fluctuate as individuals learn about one another. As relationships materialize, individuals' assessments of popularity are more likely to agree and, to the extent partner choices are driven by popularity, children will increasingly choose the same peers. Therefore, unlike reciprocity, popularity should become increasingly important over time as the network structure and children's perceptions of it crystallize.

3.3. Triadic closure

A third commonly observed feature of networks is the tendency toward closure, or 'transitivity,' whereby an individual's friends are also friends with one another (Davis, 1970; Hallinan, 1974). Research on preschool children has found transitivity in their relations (van den Oord et al., 2000) and increasingly higher rates of transitivity among older children (Leinhardt, 1973; Parker and Seal, 1996; Strayer and Santos, 1996; Vespo et al., 1996). By the time children reach junior high-school *in*transitivity is low (Hallinan and Felmlee, 1975; Lubbers, 2003; Lubbers and Snijders, 2007) and remains low through high-school (Goodreau, 2007; Mouw and Entwisle, 2006).

One mechanism leading to triadic closure is the increased propinquity of individuals who share a mutual friend. Two children who are not friends but have a relationship with a common friend are more likely to come into physical contact with each other than individuals without a mutual friend. This process is especially likely for bounded populations, such as the preschool setting, where activities are geographically confined and face-to-face interactions prevail.

Triadic closure can also be produced by the psychological need for balance (Heider, 1946; Cartwright and Harary, 1956). Intransitive relations – where friends' evaluations of third parties diverge – create emotional tensions, making them unstable and leading individuals to change their perceptions or relations in order to restore balance (Kumbasar et al., 1994; Sørensen and Hallinan, 1976).

Either triadic closure mechanism requires the existence of at least two relationships that connect exactly three individuals, one being common to both relations. Moreover, the common individual must interact frequently enough in both relations that the others become aware of one another or exposed to one another through common activities. Examining Fig. 1, these structural elements appear in time 2, where C is common to relations with A and B and an A–B relation would create triadic closure.

Triadic closure's greater structural requirements combined with the need for consistent interactions in multiple relations make it a more complex structure than reciprocity and popularity and should take longer to unfold. Unlike reciprocity and popularity, which can operate as soon as one friendship is formed, triadic closure requires the formation of at least two relationships in the network. Moreover, individuals can only create relationships through triadic closure when it is one of their friends specifically who has established at least two relationships. Thus, triadic closure only becomes possible at time 2 and, even then, only A and B are eligible. In general, the set of individuals eligible to form relationships through triadic closure expands more slowly than for reciprocity and popularity. Only at time 3 is it possible for C, D, and E to form relationships through triadic closure.

Triadic closure through heightened proximity should follow shortly after the formation of the requisite structural preconditions. These preconditions are more specific than those for reciprocity and popularity and should take longer to appear in the network. The emergence of triadic closure through the need for cognitive balance carries the additional requirements that individuals monitor their friends' behavior, identify friends' interaction partners, and infer an underlying relationship. These more intensive information processing tasks should take longer than the inferences behind reciprocity and popularity, further supporting the claim that triadic closure becomes more important later in the network formation period (Doreian et al., 1996). In sum, because the structural prerequisites take longer to emerge and the cognitive processes themselves are more demanding, triadic closure should increase in importance over time more slowly than reciprocity or popularity.

3.4. Developmental considerations

Some of the processes we investigate may also have a cognitive element that varies according to children's developmental stage. Reciprocity is the simplest network process, requiring that individuals only identify the source of positive interactions and respond in

[1] Though related, our definition of popularity differs from *sociometric* popularity, which utilizes ratings of peers as "liked most" and "liked least" (Coie et al., 1982), and *perceived* popularity, which is based on student reports of who are the "popular" or "not very popular" kids (LaFontana and Cillessen, 2002).

kind. Correspondingly, evidence for this pattern of behavior appears early in childhood. For instance, infants expect reciprocity of affect: they become upset, wary, and withdrawn when mothers respond to their smiles with inappropriate affect (Cohn and Tronick, 1983). As the ability to understand emotional displays and social intent increases and children develop perspective-taking skills, reciprocated friendships develop. Thus, the capacity for reciprocity should be more or less well-developed in preschool-children.

Popularity also has relatively simple cognitive requirements. Children must recognize that some individuals are more attractive than others and act accordingly. When such attraction is based on others' innate characteristics or observable behavior the information-processing requirements are minimal. However, if popularity forms because children choose peers to be friends whom many other children have also chosen (e.g., Gould, 2002), then the cognitive burden increases. Children must observe the interactions of multiple other children and record their distribution.

Perhaps the greatest cognitive requirements accompany triadic closure through balance, where individuals must reach a stage of development that enables them to perceive and react to relationships between their friends. Within their first year, infants faced with unfamiliar objects rely upon trusted others for emotional cues (Campos and Stenberg, 1981). Such social referencing also occurs when infants encounter strangers (Feinman and Lewis, 1983), which suggests that by preschool-age, children may be attuned to the evaluations of other children. Whether this capacity for transitive associations has developed into the need to maintain balance between relations by the preschool years is unclear. For instance, it is generally difficult for preschool children to understand that a friend of theirs can also be friends with someone else at the same time (Rose and Asher, 2000). Although it is uncertain when these skills emerge, as children develop enhanced cognitive flexibility, emotional control, and language skills, the ability to negotiate friendship status increases and the balance process becomes more likely. Still, triadic closure can occur through heightened exposure to friends of one's friends regardless of whether children have the cognitive capacity to perceive relationships between others. Thus, the processes we examine have minimal cognitive requirements and are hypothesized to function among any individuals who have reached a developmental stage that allows social relationships.

4. Methodology

4.1. Data

We studied social network formation with observational data of children's interactions in 11 preschool classrooms throughout a school-year. Specifically, we used data from the first two years of a larger longitudinal study of young children's preparedness for school. Children were enrolled in one of 11 classrooms in Head Start preschools: 6 classrooms in Year 1 and 5 classrooms in Year 2. Classrooms ranged in size from 15 to 21 children. All children in each class were recruited for participation in the study and 100% of parents provided consent. Our full sample contained 195 children; however, student enrollment and withdrawal throughout the year resulted in fewer than 195 children being observed at any given time. Characteristics of our sample and their networks are presented in Table 1. The sample was nearly evenly divided by sex, with slightly more males than females. Children ranged in age from 37 to 60 months, with an average age just over 4-years-old. The majority of the sample was Hispanic and economically disadvantaged, which is representative of the composition of Head Start schools in the area from which they were selected. Average family income was near the poverty line at US$ 25,000 and average parental education corresponded to between high-school and some college.

Table 1
Descriptive statistics.

Individual (N = 195)				
Female	45.6%			
Race/Ethnicity				
Black	5.1%			
White	10.8%			
Hispanic	77.3%			
Other	6.8%			
Average Age (Months)	51.93 (5.23)			
Average Social Interactions	112.39 (80.19)			
Network				
Average Classroom Size	17.91 (2.12)			
	Wave 1	Wave 2	Wave 3	Wave 4
Number of Children	187	185	177	168
Average Degree	5.81	5.45	5.92	5.99
Reciprocity Index	.701	.725	.666	.733
Transitivity Index	.435	.416	.427	.463
Network Change[a]	Period 1	Period 2	Period 3	
Children Joining	4	4	0	
Children Leaving	6	12	9	
Ties Maintained	50.69%	51.54%	58.78%	
Jaccard Index	.357	.338	.428	

Note: Standard deviations in parentheses.
[a] Periods reflect changes between waves.

4.1.1. Observation procedure

We used observations of children's interactions to determine the pattern of relationships among children within each classroom. Throughout the school year (September–May), trained research assistants followed an established observational procedure to record children's activities and peer interaction partners (Hanish et al., 2005; Martin and Fabes, 2001). Observers were in children's classrooms 2–3 days per week for several hours each day. Observations were made during the hours in which most children were awake and in attendance and during structured (e.g., teacher-led story-time) as well as unstructured (e.g., free play) activities in the classroom and on the playground. To ensure that we only captured interactions between children that were consensual, we excluded from our analyses any observations made during structured activities, when teachers typically gathered children together in groups.

Observers rotated through a randomly ordered list of children, observing each child for 10 seconds, recording their data, and then observing the next child on the list. Once observers reached the bottom of the list, they waited approximately 5 min and then repeated their observations from the top of the list. Observers completed the entire list multiple times on each day they observed a classroom. To minimize possible order effects, coders were instructed to complete their list before they left for the day and the list was reversed midway through the semester. Using handheld computers, observers recorded whether each child was present and available for coding, present but unavailable (e.g., in the bathroom), or absent. Peers were coded whenever the target child's predominant activity during the 10-s observation involved direct interaction with one or more classmates (e.g., social conversation, any form of play, aggression). Observers recorded up to five peer partners during each observation. Because our focus was on peer-peer interaction, we excluded observations of solitary, teacher-involved, and parallel play (playing alongside but not with another child) from our analyses and focused only on observed social interactions. Of the 21,365 observations collected during free-time, 7969 (37.3%) captured the child interacting with at least one peer partner.

Observers were extensively trained on the coding procedures. Reliability was assessed on a regular basis by having two indepen-

dent observers simultaneously code the same child (obtained on 8.9% of all observations). Reliability estimates for the peer partner estimates were high; agreement was 93.8% for *number* of peer partners and 93.5% for *identity* of peer partners. These observational procedures have been used in previous studies and have demonstrated very good reliability and validity (Fabes et al., 1997; Hanish et al., 2005; Martin and Fabes, 2001).

Only children who were observed at least 12 times during the school-year were retained for the analysis. Thus, we excluded children who were visiting the school, changed schools shortly after enrolling, or were otherwise only in the classroom briefly. On average, 214 observations were collected for each child (ranging from 12 to 423). Because some of the same classrooms were observed in consecutive years, the eight children who repeated preschool were observed twice. To capture the formation and evolution of networks as accurately as possible, it was essential to include all actors. To test for possible bias due to eight duplicate actors, we recorded which children were repeats and controlled for this in all models.

Our analyses require that we transform the continuous observations of children's interactions into discrete waves that represent the network at different time points. For each time point, we measure relationships based upon the number of social interactions within a 'window' of time. Specifying an appropriate window is a complicated issue (Moody et al., 2005). There is an inherent tradeoff between observing enough interactions within a window to infer that a relationship exists and dividing observations into windows narrow enough to capture relationship change. With too many windows there are not enough observations within each to reliably measure ties and with too few windows the change process is obscured. As Table 1 shows, on average we observed each child in social interactions 112 times. Dividing by four gives us 28 observations per wave, which we believe is adequate to infer the pattern of relationships that constitute the network. Thus, our dataset contains four waves: two from the fall (essentially corresponding to September–October and November–December) and two from the spring (February–March and April–May). In all classes, the transition from wave 2 to wave 3 coincided with winter break. The other transitions were determined by dividing the number of observations during the semester in half (which maximizes the number of observations in each wave).

4.1.2. Network measurement

We use the number of times children were observed together as an indicator of relationship strength. Although contact is not necessarily a reliable indicator of relationship quality for adults, who may see close friends and family infrequently but spend considerable time with less important acquaintances (Marsden and Campbell, 1984), this is not the case for children in preschool. Compared to the multiplex relations that characterize most adult relationships, children's relationships are uniplex. Although peer interactions at this age tend to be more fluid than later in later childhood or adolescence (Bierman and Erath, 2006), there is enough stability to infer general preferences among peers. Thus, for preschool children, time together is a reliable indicator of their preference for one another and the quality of their relationship. This approach has been used to infer children's classroom network structures in several studies (Ladd, 1983; Strayer and Santos, 1996), and has been validated in a direct comparison with other established network measurement techniques (Gest et al., 2003).

The model we used requires that ties be unweighted. Thus, we dichotomized the matrix of interaction frequencies for each wave into a binary matrix. Nearly all children within a classroom interact simply by chance as they move through the classroom. Only when children play together more often than expected by chance do their interactions likely represent an underlying relationship. Thus, we conceptualized a relationship as one child's behaviorally exhibited preference for another child relative to the total amount of time that child spent in social interaction with all classmates, calculated as follows:

$$a_{ij} = 1 \leftrightarrow \frac{o_{ij}}{o_{i+}} > \frac{1}{N-1} \tag{1}$$

A tie from child i to child j (a_{ij}) existed if the number of times i was observed with j (o_{ij}) divided by the number of times i was observed with any child (o_{i+}) exceeded the proportion expected by chance ($1/N-1$, where N equals the number of children in the classroom). Thus, ties represented a child spending more free-time playing with a particular other child than would be expected if play partners were randomly selected. Friendship thus constructed can potentially be asymmetric. Compared to a less social child, a very sociable child must spend relatively more of his or her time with a particular classmate for a relationship to be inferred.

One benefit of this procedure is that it compensates for an unequal number of observations of each child, which is unavoidable when studying naturalistic classroom interactions. Some children are absent, unavailable, or in the class for shorter periods of time than others. Children who are observed less often will likely have fewer observations of social behavior, resulting in a smaller denominator in Eq. (1). Considering interactions as a proportion of the number of social interactions when inferring relationships allows us to capture relationships that are important for all children, regardless of their attendance.

Over 1000 ties were observed during each wave, which equates to an outdegree that varies between 5.45 and 5.99 across waves (see Table 1). Two-thirds or more of children's ties were reciprocated and over 40% of triads were transitive (if $a_{ij} = 1$ and $a_{jk} = 1$ then $a_{ik} = 1$). We describe changes in network structure between consecutive waves as occurring within a *period* (with 4 waves of data there are 3 periods). More than half of the ties persisted across consecutive waves and the Jaccard Index, which captures ties that persist as a proportion of all ties that exist at either of two consecutive waves, ranged between .34 and .43. For both measures, the greatest turnover in relationships occurred in the second period, between waves 2 and 3, which corresponded with winter break and the largest pause in data collection. The greatest stability appeared during the final period.

4.2. The SIENA modeling framework

We used the actor-based Simulation Investigation for Empirical Network Analysis (SIENA) modeling framework (Snijders, 2001; Snijders et al., 2008) which was developed specifically for statistical modeling of longitudinal network dynamics. The SIENA model posits a multinomial probability model for an individual to develop and modify relationships through the creation and dissolution of ties, and is fully explicated in Snijders (2001, 2005). The heart of the model is the evaluation function, which specifies the network and individual attributes hypothesized to affect network change. For individual i, the following evaluation function captures the value of network x:

$$f_i(\beta, x) = \sum_{k=1} \beta_k s_{ki}(x) \tag{2}$$

Several possible effects ($s_{ki}(x)$) represent aspects of network structure and individual attributes (we describe specific effects below). The importance of each effect is represented by the β_k parameters. It is helpful to think of these parameters as reflecting a "preference" of the average network member for forming and maintaining ties based on the effect. Higher parameter values imply

that ties producing the effect are more likely to exist.[2] For example, the reciprocity parameter would be positive if changes in ties that created or maintained reciprocated relationships were more likely to occur than changes that did not produce reciprocity. Effects may be classified into 3 types for our purposes:

(1) *Rate effects* are based upon the empirically observed rate of changes in network ties from wave to wave. The actor-based model gives each child multiple opportunities to change ties either by dropping existing ties or adding new ties. The rate parameter indicates the number of *opportunities* for change for each child, though the number of observed changes for each child is not as high (the same tie could be dropped and added multiple times, or not change at all).
(2) *Structural effects* capture a number of commonly observed network processes and are the focus of our study. We examined reciprocity, popularity, and two measures of triadic closure: transitive triplets and dense triads (described below).
(3) *Individual effects* incorporate individual covariates such as age or gender. Effects can apply to either self (ego) or others (alters); for instance, if older children are more likely to form ties than younger children, we would expect a positive ego effect of the variable age. Individual covariates can also be used to estimate homophily effects, that is, whether children are more likely to form relationships with others who are similar to them in that regard (i.e., selection). Individual actor covariates can be fixed, such as age or gender, or time-varying, such as the number of times a child was observed each wave.[3]

We estimate SIENA models using the method-of-moments approach (see Snijders et al., 2010).

4.3. Modeling procedure

To evaluate our questions about the emergence and importance of different network processes, we estimated a series of models that included parameters for different structural effects and their change over time. We describe the measures for reciprocity, popularity, and triadic closure below (formulas available in Snijders et al., 2010, 2008). The main effect for each network process indicates whether it operated with our sample of preschool children. To determine whether a process changed in importance over time, we included an interaction between the parameter and a linear term for period. Period is an exogenous individual covariate coded [1 2 3] to correspond to the three periods between waves. To evaluate parameter estimates, we use *t*-type tests and a generalized Neyman–Rao score test (Schweinberger, 2005). The *t*-test provides an estimate of individual parameters whereas the score test estimates how well the inclusion of one or more parameters improves model fit. When significant, an interaction between period and a structural effect indicates how the network process increased or decreased in importance over time.

All models included parameters for the rate of change in ties and the average tendency to form ties. In addition, we controlled for age, gender, classroom presence (the proportion of time that each child was observed in the classroom during the wave), and whether or not the child was in the classroom for a repeated second year. These controls take the form of ego, alter, and homophily effects, which represent their effect on children's propensity to form ties, receive ties, and choose similar others, respectively. We estimated homophily for each possible dyad using the *similarity* effect, which calculates the absolute difference between each individual's score. For the gender and repeated year variables, the similarity effect evaluates to a dichotomous value representing similar or dissimilar. For the remaining quantitative variables, the homophily effect captures the absolute difference between scores. For estimation purposes, effects were centered within SIENA.

It is possible that children's development across the school year may contribute to changes in the importance of network processes over time. If children's social and cognitive abilities developed over the time period being studied they could confound our ability to infer that the changes in the importance of distinct network processes were fundamental to network formation. The timespan under study – 9 months – is short in the developmental context, yet there is a possibility for increases in cognitive and social abilities over the period. To control for individual differences in level of development we included effects based upon ego and alter age and age homophily. Age is an imperfect measure of social and cognitive development, but on average should reflect development sufficiently for this purpose. To determine whether age moderated network processes, we added interactions between age, network processes, and their change over time to each of the models presented below. The two-way interactions capture whether the importance of the structural effect varies according to the age of the child. The three-way interactions capture whether any differences by age change at different rates during the year. None of these interactions were significant and their inclusion did not improve model fit, indicating that these processes were not moderated by children's age.

The classroom-based networks in our sample are relatively small, which can make it difficult to obtain reliable parameter estimates. If one is willing to assume that parameter values are equal across classrooms then the best option is to analyze all networks simultaneously (Snijders et al., 2008).[4] We followed this approach by arranging our data as one large matrix with structural zeros (permanent null ties) between children in different classrooms. The limitation of this approach is that we are unable to identify processes unique to specific classrooms. However, if the processes we investigate are indeed fundamental to network formation, then their effects should emerge from the combined analysis and our assumption is warranted.

5. Results

5.1. Reciprocity

We first examined reciprocity, calculated as an outgoing tie matched by an incoming tie. As shown in Table 2 (Model 1), the positive effect of reciprocity indicated that children were more likely to form ties to alters who preferred ego as a play partner. We then examined how the effect of reciprocity changed over time by entering an interaction between reciprocity and period. The interaction captures any linear change in the importance of reciprocity over time, while the main effect of reciprocity reflects the average level of reciprocity throughout the year (the main effect of period is meaningless and is excluded from the model). Results indicated a constant effect of reciprocity over time. The interaction parameter

[2] Although "preference" is a convenient metaphor for SIENA-type models, the term does not imply any underlying rational choice model. Rather, model estimation proceeds by simulating network evolution in which actors are randomly given the "opportunity" to change one tie (i.e., "make a preferred choice") with a probability based on the current values of the effect-related parameter vector.

[3] SIENA can also estimate effects for individual covariates that change endogenously through socialization. We are currently modeling several such processes related to development, however their investigation goes beyond the scope of this paper.

[4] SIENA offers a multilevel approach; however, it is unable to overcome estimation difficulties with small networks because it relies upon first estimating separate parameters for each network.

Table 2
Models of network processes.

	Model 1			Model 2			Model 3			Model 4		
	$\hat{\beta}$	SE	t	$\hat{\beta}$	SE	t	$\hat{\beta}$	SE	t	$\hat{\beta}$	SE	t
Rate Parameters												
Period 1	14.528	1.015	14.31***	15.138	1.060	14.29***	15.345	1.111	13.81***	14.957	1.037	14.43***
Period 2	14.482	.969	14.95***	14.656	1.007	14.56***	15.215	1.089	13.97***	15.330	1.122	13.66***
Period 3	11.484	.752	15.28***	10.997	.712	15.44***	11.356	.762	14.89***	12.029	.845	14.24***
Network Structural Processes												
Outdegree (Density)	−1.310	.036	36.49***	−1.781	.066	27.07***	−1.575	.041	38.61***	−1.322	.036	36.51***
Reciprocity	2.118	.064	33.35***	2.125	.061	34.95***	2.074	.058	35.95***	1.797	.073	24.55***
Reciprocity × Period	.012	.035	.34	−.112	.061	1.86†	−.106	.056	1.89†	−.123	.061	2.03*
Popularity				.073	.008	8.88***						
Popularity × Period				.011	.005	2.13*						
Transitive Triplets							.046	.004	11.50***			
Transitive Triplets × Period							.010	.004	2.48*			
Dense Triads										.228	.027	8.62***
Dense Triads × Period										.080	.033	2.45*
Controls												
Female Alter	.017	.044	.37	.033	.042	.78	.024	.045	.54	.017	.045	.37
Female Ego	−.003	.044	.06	.000	.045	.00	.008	.043	.19	.008	.047	.17
Female Similarity	.439	.031	14.21***	.467	.032	14.49***	.393	.031	12.53***	.403	.032	12.71***
Age Alter	.011	.005	2.32*	.007	.004	1.50	.008	.005	1.76†	.009	.005	1.98*
Age Ego	−.001	.005	.11	.000	.005	.02	−.004	.005	.80	−.003	.005	.60
Age Similarity	.220	.089	2.48*	.205	.085	2.41*	.188	.090	2.09*	.203	.092	2.20*
Repeat Alter	−.162	.149	1.09	−.205	.143	1.43	−.234	.148	1.58	−.224	.151	1.48
Repeat Ego	.082	.147	.56	.053	.150	.35	−.006	.151	.04	.035	.155	.23
Repeat Similarity	−.193	.127	1.52	−.179	.125	1.43	−.197	.127	1.55	−.197	.129	1.52
Classroom Presence Alter	.527	.129	4.09***	.330	.126	2.63**	.467	.126	3.70***	.473	.129	3.66***
Classroom Presence Ego	−.300	.133	2.25*	−.269	.136	1.98*	−.370	.129	2.86**	−.358	.135	2.66**
Classroom Presence Similarity	.407	.136	2.99**	.342	.140	2.45*	.273	.136	2.00*	.338	.136	2.49*
Score Test for Period Interaction (χ^2)[a]		.105			5.456*			5.938*			6.207*	

[a] Score tests all have df = 1.
* $p < .05$.
** $p < .01$.
*** $p < .001$.
† $p < .10$.

was only slightly larger than zero, and not statistically significant based on the score test. Reciprocity was thus an important predictor of ties from the first period onward and at about the same level throughout the school year. Because reciprocity is such a fundamental process, we included its effect and its interaction with period in all subsequent models.

5.2. Popularity

In-degree related popularity captures whether children become more attractive as friends as their number of incoming ties increases. Model 2 reveals a significant, positive main effect, indicating an increased likelihood of forming ties with popular children relative to less popular children. We expected popularity to become more important over time as relationships emerged and the network stabilized. The interaction between popularity and the linear period term is positive and the score test indicates it significantly improves model fit. Thus, popularity became increasingly important throughout the year. Because it takes time for relationships to form and for the unequal distribution of incoming ties that is the basis for popularity to form, popularity has a greater tendency to shape relationships later in the year.

Standardized coefficients do not exist with SIENA. However, to help interpret change in parameter magnitudes over time we can calculate the odds of forming a tie through a process, relative to forming a tie *not* through the process. This type of comparison assumes that the frequencies of all other network statistics remain constant. For popularity, the comparison is between two alters whose indegrees differ by one. For example, in Period 1 the popularity-related effects for a tie to a child with indegree of 1 contribute .062 (equal to .073 + (.011 × −1) [because effects are centered, Period 1 becomes −1]) more to the evaluation function than a child with no incoming ties. This difference is a log odds ratio that can be exponentiated to provide an odds ratio of 1.064. Thus, as a peer's indegree increases by one, the probability of a relation with that peer is 1.06 times higher. In contrast, in Period 3, the probability of adding a relation with a peer is 1.09 (equal to exp[.073 + .011]) times higher for each one unit increase in the peer's indegree. The effects of larger differences in indegrees are multiplicative. For a child with an indegree of 6, which is close to average, the probability of receiving an additional tie in Period 1 is 1.45 (equal to exp[6 × .062]) times higher than a child with no incoming ties, and increases to 1.66 (equal to exp[6 × .084]) times higher by Period 3.

5.3. Triadic closure

5.3.1. Transitivity

Transitivity produces triadic closure when (1) what was previously an indirect connection from i to k through j becomes direct through the addition of a tie from i to k or (2) i and j both have ties to k, and i adds a tie to j. The transitive triplets effect in SIENA counts the number of closed triads in which ego is in position i. The positive main effect suggests that children were more likely to select others as play partners when those ties increased the number of transitive patterns in the network (Model 3). The significant positive interaction between transitive triplets and period indicates that transitivity became more important over time. Throughout the year, children became increasingly likely to form relationships with the friends of current friends. In Period 1, relations that created one transitive triplet were 1.04 times more likely than relations that

Table 3
Non-linear change in network processes.

	Main effect			Interaction with Period 2			Interaction with Period 3			Joint Score Test[a]
	$\hat{\beta}$	SE	t	$\hat{\beta}$	SE	t	$\hat{\beta}$	SE	t	χ^2
Processes (Separate Models)										
Reciprocity	2.120	.060	35.33***	.010	.067	.15	.015	.069	.22	.123
Popularity	.071	.008	8.88***	.031	.010	3.10**	−.008	.009	.89	10.566**
Transitive Triplets	.046	.004	11.50***	.011	.008	1.38	.009	.009	1.00	5.801†
Dense Triads	.233	.027	8.63***	.021	.057	.37	.140	.064	2.19*	7.506*

[a] Joint score tests for period interactions all have df = 2.
* $p < .05$.
** $p < .01$.
*** $p < .001$.
† $p < .10$.

did not, whereas in Period 3, transitive relations were 1.06 times more likely. As the number of transitive triplets a tie contributes to increases, the probability increases multiplicatively. For instance, the probability of forming a tie that created the average number of transitive triplets per child (5) relative to a tie that created none was 1.20 (equal to exp [5 × .036]) times higher in Period 1 and 1.32 times higher in Period 3.

5.3.2. Dense triads

Dense triads is an indicator of stronger, more cohesive closed triads. When relations are asymmetric, a triad can contain up to six ties, a tie sent and a tie received in each of the three relations. For a triad to be closed, there must be at least three ties, one in each relation; ties beyond the minimum of three reflect the degree to which relationships are reciprocal and the triad is strong. The density of triads is calculated as the number of existing ties relative to the number that could exist (6). When density is at its maximum in a triad, all relationships are reciprocated. Whereas transitivity can occur with non-reciprocated relationships, dense triads reflects the amount of reciprocation.

We measured dense triads as whether or not all six of the possible ties among three children existed. Model 4 reveals a significant positive main effect of dense triads and a significant interaction with period. The positive effect of dense triads indicated that relationships that created closed triads, where all of the relationships were reciprocal, were more likely to form than relations that did not produce dense triads. Moreover, the importance of the effect of dense triads increased over the course of the year. As the network stabilized and relationships strengthened during the year, dense triads became increasingly common. Relations that created one dense triad were 1.16 times more likely in Period 1 and 1.36 times more likely in Period 3 than relations that created no dense triads. Considering that children belonged to three dense triads on average, the probability of forming a tie that created three dense triads was 1.56 times higher than a tie that created none in Period 1 and increased to 2.52 times higher in Period 3.

5.4. Non-linear changes in network formation processes

The last step of our analysis was to consider whether changes in the importance of network formation processes occurred at different rates. The previous models specified change linearly, assuming that changes in each effect were the same from Period 1 to Period 2 and from Period 2 to Period 3. However, changes in the importance of network processes may proceed on non-linear timescales that depend upon the complexity of the structures that underlie them. To examine this possibility, we re-estimated our models, replacing the period variable with dummy variables that represent Period 2 (coded [0 1 1]) and Period 3 (coded [0 0 1]).

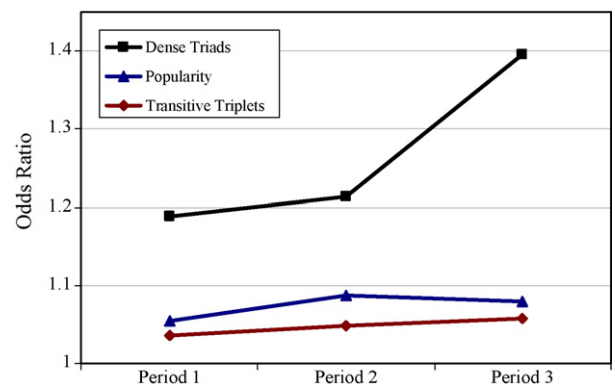

Fig. 2. Odds of relationship formation through each network process over time.

We present the results of these analyses in summary form in Table 3 (each row in the table represents a separate model). The results for reciprocity parallel those from the linear analysis: based on the joint score test the interactions with period were not statistically significant. The other network processes all changed in importance over time as indicated by the joint score tests. However, the t tests indicated effects were stronger in some periods than others.

To facilitate interpretation of the results of the non-linear analysis, we calculated the odds ratios presented in Fig. 2, which convey the trajectory each effect followed over the school year.[5] These odds ratios show the change in odds of forming relations that differ by one in the count of the relevant network statistic.

The popularity effect displayed a significant non-linear change over time; its effect increased from Period 1 to 2 then decreased slightly, though not significantly, from Period 2 to 3. Popularity effects were at their strongest midway through the year and largely sustained that level of importance for its remainder. The effects of triadic closure showed different non-linear trends depending upon their specification. The joint score test of the non-linear transitive triplets terms was marginally significant ($p = .054$) whereas the separate parameters for each period were not significant. This suggests that the effect of transitive triplets increased linearly throughout the year. In contrast, the dense triads effect increased most between the last two periods. Taken together, these effects suggest that as the network stabilized over time, children were increasingly forming and maintaining relationships that created multiple closed triads. The simpler transitive triplets effect, which requires only two pre-existing relations, increased in importance throughout the year. The

[5] Because reciprocity does not change significantly over time odds ratios for its effect, which range from 8.23 to 8.44, are omitted.

dense triads effect, which reflects the solidifying of triadic structures and requires five pre-existing relations, only reached its peak late in the year.

Importantly, the changes in triadic closure are not simply a product of the network "filling-in" by children adding relationships throughout the year—the density of the network was constant over time. Rather, the results suggest a group formation process. Children were increasingly forming relationships with others with whom they shared multiple mutual friends, leading to clustering within the network.

These findings support our view that network effects "cascade," or emerge over time in direct relation to their complexity. The simplest structure – reciprocity – remained constant throughout the school year. The relatively simple popularity effect became increasingly important from Period 1 to Period 2, but showed no further change. The more complex triadic closure effects continued to increase in importance throughout the year. Transitive triplets increased at the same rate in both periods while the dense triads effect, which carries the greatest social and cognitive prerequisites, became most important in Period 3.

6. Discussion

Our study differs from previous work primarily in its focus on changes in the relative importance of structural effects as a new social network emerges over time. This contrasts with extant literature that has been more concerned with age effects on the prevalence of network structures, but has rarely examined these changes among the same group of children longitudinally (e.g. Leinhardt, 1973; Strayer and Santos, 1996; Vespo et al., 1996). Like previous studies, we have observed the importance of structural effects on relationship formation and change. However, in addition, we found support for the hypothesis that structural effects "cascade" in importance over time, from the simple to the more complex. Thus, we echo Doreian et al.'s (1996) assertion that network processes proceed on different timescales.

Because structural cascading was observed in a sample of preschool-age children, most of whom presumably had never been part of a sizeable peer social ecology, it is reasonable to propose that structural cascading represents a *fundamental* process of social network formation. By this we mean that, in the absence of other learned "rules of thumb" that might guide network formation in groups of older and more experienced individuals, possibly also in more normatively structured environments (e.g. work groups, athletic teams, etc.), structural cascading is expected to be the "fall-back" description of network evolution.

To summarize, the structural cascading observed in this study appears to work as follows.

Reciprocity effects peak early in the school year – by the first period, if not before – when children first enter the school and began to form relationships among a new set of peers. As children begin to sort themselves into relationships, the effects of reciprocity remain constant while other network processes became relatively more important. As relationships strengthen and their distribution solidifies, children become more likely to seek and maintain relationships with popular peers. Popularity peaks in importance midway through the school year. From that point on, children become increasingly likely to form relationships with the most socially involved peers in the classroom. Unlike popularity, triadic closure increases in importance over the entire course of the school year, peaking in the final period. Presumably, as the interactions that underlie relationships become more consistent, children are increasingly exposed to other children with whom their friends are playing. Beyond mere propinquity, this selective exposure may provide children the opportunity to learn to infer relationships between other children in the class. Both of these processes would increase the likelihood of children playing with the friends of their friends at higher rates than other children. Moreover, as indicated by the dense triads effects, children become increasingly likely to form strong, closed triads composed of mutual friendships.

One limitation of this study is a product of the unique sampling design. Our observation method allowed us to identify relationships based upon repeated interactions. Although observations of interactions are more reliable than are young children's self-reports of relationships, which are subject to day to day variations (Fabes et al., 2008), we do not know how well the relationships we inferred based upon interaction frequency correspond to children's subjective preferences. Relatedly, because we defined relationships based upon interactions occurring within a specific window of time, we necessarily missed changes occurring *within* a window and may not have captured brief relationships that span two windows. Shorter windows would reduce these limitations, though they necessitate a larger sample of observations. Not enough is currently known about early network formation processes to specify the most suitable window. One avenue for future research is to address these lingering questions by observing interactions at a higher rate per unit time. This should be especially valuable early in the network formation process when relations are most fluid and reciprocity is emerging.

The study sample was exclusively comprised of Head Start classes, which could limit generalizability of these results. However, we are not aware of prior research or theory that would predict differences in fundamental relationship formation processes based on socioeconomic status. Indeed, preschools vary widely along many dimensions (e.g., demographic composition, teacher training, class size, availability of classroom resources, curriculum, etc.), yet children form friendships regardless. Some friendship formation processes – plausibly the most basic – transcend diverse contexts though the specifics may change. For instance, homophily is likely evident in all preschools, though the relative importance of sex, race, and age as salient dimensions may vary. Thus for the time being, we see no empirical basis to expect that Head Start classrooms differ systematically in ways that would be apparent in the networks children form. Although it remains to be tested, we propose that structural cascading is general in nature and should be found in any preschool context.

More important for generalizability is the focus on preschool children themselves. Network processes likely change in importance as children develop. Effects for age revealed that the processes examined here did not change within the 3–5 year age range. However, our sample is not completely homogenous with respect to prior social experiences and development. Moreover, age is only a rough indicator of development and may not be sensitive enough to capture changes that occurred over a 9-month period. Therefore, it is important for future research on network formation to include more refined indicators of development.

It is useful to consider our results relative to previous research on network formation processes, which has focused predominantly on college students. In particular, Newcomb's pseudo-fraternity (Doreian et al., 1996; Newcomb, 1961) and Van Duijn and her colleagues' study of sociology freshmen in the Netherlands (2003) both focused on previously unacquainted individuals coming together and interacting for at least a semester. Like us, these studies found no change in reciprocity over time. Our results for triadic closure and popularity, however, do not correspond with the Dutch data, where these effects became less important over time, though remaining statistically significant. Unfortunately, the Dutch data suffered from a high attrition rate, which makes it difficult to reliably estimate structural effects larger than a dyad and could be the source of the apparent decrease in the importance of these processes over time. We have greater confidence in comparing our results for the triadic closure process with those based on Newcomb's more complete data. Using those data, Doreian et al.

(1996) found that transitivity increased from random levels at the beginning of the semester to become a significant structural feature by the end of the semester, a result consistent with our findings. This convergence is especially noteworthy given the dissimilarity between studies in individuals' ages (preschool children versus college students), timeframe (school year versus semester), and network measurement methodologies (observations of interactions versus students' affective rankings of other students). The similarity in these findings is all the more remarkable given the difference in analytical techniques, our use of SIENA versus the development of custom tools to account for the ranked nature of the Newcomb data. The convergence of these results supports the structural cascading hypothesis we propose to account for the role of network structure effects in the emergence of human social ecologies where free choice of affiliation is possible. Further work will be required to test this hypothesis.

As an added consideration, it is possible that the apparent convergence between our study and Doreian et al.'s (1996) is an example of equifinality, where different processes produce the same end state. Triadic closure among preschool children may be more a product of physical proximity, whereas balancing processes may be more critical for adults. In considering the developmental context, future research should look at changes over longer, more developmentally inclusive time spans and examine interactions between measures of social and cognitive development on the one hand and network processes on the other. Such an approach could help clarify multiple possible sources of the dynamics we observed. These may include endogenous changes produced through individual experience in social settings, a process that should hold for actors of any age. In contrast, developmental changes ought to produce effects that vary by age, since older children's cognitive structures may allow more complex dynamics to develop (and perhaps more quickly) than younger children. Moreover, individual differences may emerge in propensities to form network structures at different rates and levels of complexity (e.g., Kalish and Robins 2005), effects which we would not expect to supplant the findings presented here, but which would certainly provide extra detail. Such detail could be particularly important to teachers and healthcare professionals, for example, who would be especially interested in the developmental advantages or disadvantages that result from individual differences in relational trajectories. Untangling the contributions of development, endogenous network dynamics, and their interactions remains an important task.

Our goal has been to uncover some of the fundamental processes that drive network formation. That a clear process of social network emergence appears early in development – arguably, as early as is socially and cognitively possible – is noteworthy in itself. The finding that preschool children exhibit network formation processes that are similar to older children and adults highlights their potential to affect children's outcomes and development. Even at the earliest moment that children first have autonomous choice in affiliating with peers, there is evidence of differential preferences and time spent with peers. Thus, children form ties at an early age and these affiliations set the stage for potential network effects such as social influence and behavioral contagion. Our results suggest that group level peer processes have the potential to impact young children's development and provide a research paradigm for studying such effects that moves beyond the individual and the dyad.

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