Social Science & Medicine 125 (2015) 40–50

Contents lists available at ScienceDirect

Social Science & Medicine

journal homepage: www.elsevier.com/locate/socscimed

Mental health and social networks in early adolescence: A dynamic study of objectively-measured social interaction behaviors

Mark C. Pachucki [a,*], Emily J. Ozer [b], Alain Barrat [c,d], Ciro Cattuto [d]

[a] Mongan Institute for Health Policy (Massachusetts General Hospital), General Academic Pediatrics (Massachusetts General Hospital for Children), Harvard Medical School, 50 Staniford Street, 9th Floor, Boston, MA 02114, USA
[b] University of California, Berkeley School of Public Health, Department of Community Health and Human Development, USA
[c] Aix Marseille Université, Université de Toulon, CNRS, CPT, UMR 7332, 13288 Marseille, France
[d] Data Science Laboratory, ISI Foundation, Torino, Italy

ARTICLE INFO

Article history:
Available online 15 April 2014

Keywords:
Social networks
Self-esteem
Depression
Early adolescence
Stochastic actor-based modeling

ABSTRACT

How are social interaction dynamics associated with mental health during early stages of adolescence? The goal of this study is to objectively measure social interactions and evaluate the roles that multiple aspects of the social environment – such as physical activity and food choice – may jointly play in shaping the structure of children's relationships and their mental health. The data in this study are drawn from a longitudinal network-behavior study conducted in 2012 at a private K-8 school in an urban setting in California. We recruited a highly complete network sample of sixth-graders ($n = 40$, 91% of grade, mean age = 12.3), and examined how two measures of distressed mental health (self-esteem and depressive symptoms) are positionally distributed in an early adolescent interaction network. We ascertained how distressed mental health shapes the structure of relationships over a three-month period, adjusting for relevant dimensions of the social environment. Cross-sectional analyses of interaction networks revealed that self-esteem and depressive symptoms are differentially stratified by gender. Specifically, girls with more depressive symptoms have interactions consistent with social inhibition, while boys' interactions suggest robustness to depressive symptoms. Girls higher in self-esteem tended towards greater sociability. Longitudinal network behavior models indicate that gender similarity and perceived popularity are influential in the formation of social ties. Greater school connectedness predicts the development of self-esteem, though social ties contribute to more self-esteem improvement among students who identify as European-American. Cross-sectional evidence shows associations between distressed mental health and students' network peers. However, there is no evidence that connected students' mental health status becomes more similar in their over time because of their network interactions. These findings suggest that mental health during early adolescence may be less subject to mechanisms of social influence than network research in even slightly older adolescents currently indicates.

1. Introduction

As children develop, they pass through a series of sensitive periods in which their lived experiences can have disproportionate and lasting impacts on future health (Hertzman and Boyce, 2010). The onset of adolescence – typically between 9 and 12 years of age – has been recognized as a critical inflection point for the emergence of depression and other symptoms of distress (Andersen and Teicher, 2008; Brooks-Gunn and Petersen, 1991; Steinberg, 2005). During this time, hormonal transformations accompany a reorientation of motivation, decision-making, and risk-taking behaviors (Dahl, 2004; Eccles et al., 1993), and children on the cusp of adolescence are increasingly responsive to peer interaction and social influence (Forbes and Dahl, 2010; Steinberg and Monahan, 2007).

Additional attention to these peer dynamics is warranted due to a growing body of evidence connecting social relationships with social cognitive development. At the onset of adolescence, changes in social interaction behaviors are occurring alongside complex physiological transformations. Early adolescence is a period

* Corresponding author.
E-mail address: mpachucki@mgh.harvard.org (M.C. Pachucki).

http://dx.doi.org/10.1016/j.socscimed.2014.04.015
0277-9536/

marked by heightened neurological plasticity (Choudhury et al., 2012), growth in social cognitive reasoning skills (Blakemore and Choudhury, 2006), and increased neurological sensitivity to social influences (Grosbras et al., 2007). Changes in social-affective processing that begin around puberty include refinements in how children interpret rewards and threats, self-perception, and seek inclusion in peer groups. Consideration of others, interpretation of their intentions, and reciprocation of trust and judgments of fairness begin to mature during early adolescence (Crone and Dahl, 2012). Socially, susceptibility to peer influence grows during childhood and peaks in adolescence. At the same time, parental influence begins to wane as children express a heightened desire for independence (Dishion and Tipsord, 2011; Gifford-Smith et al., 2005; Steinberg and Monahan, 2007). Early adolescent relationships are dynamic (Cairns et al., 1995; Chan and Poulin, 2007) as adolescents develop sophistication in their interpersonal behaviors (Brown, 1990), and increase in sensitivity to others' actual and perceived appraisals of themselves (Hergovich et al., 2002). These complexities of interpersonal behavior may affect mental health through a variety of status and reputation processes associated with group membership.

Relative to other periods of the life course, there has been surprisingly little research that takes account of the dynamism of human interactions to investigate how early adolescent relationships may contribute to mental health. While a large body of developmental research documents how generalized peer acceptance and friendship quality contribute to disordered mental health in children (Parker et al., 2006), less is understood about how specific patterns of social interaction, and changes in these interactions, may be implicated (Chan and Poulin, 2009). Network perspectives on early adolescent development thus hold potential to clarify links between externalized social behaviors and internalized cognition. Moreover, advances in measurement technologies enable us to identify behavioral social networks in more precise and unobtrusive ways than ever before.

These concerns motivate the present study of how social interaction dynamics are associated with mental health during the onset of adolescence. We partnered with a school to examine changes in social interaction patterns and mental health indicators of a nearly complete cohort of 6th-graders over a three-month period. One contribution of this study is the use of a novel electronic technology to objectively gather network data among this age cohort. A second contribution is to use these network data to examine how multiple personal and peer characteristics may shape two indicators of early adolescent mental health: self-esteem and depressive symptoms. While depression has been a subject of some investigation in a social network framework, especially among older adolescents, few network studies have examined relational determinants of self-esteem during any stage of adolescence. To the best of our knowledge, this is the first use of objectively-gathered micro-social interaction data in a study of adolescent mental health.

2. Review: relevance of social networks for distressed mental health

A rapidly-expanding body of research attests to the fact that because humans are connected, their health can also be connected (Smith and Christakis, 2008) in ways that differ across the life course (Umberson et al., 2010). Relational methods of social network analysis have provided insight into interpersonal influences on mental health among adolescents. Because depression and self-esteem during early adolescence are understudied from a network perspective, this study focuses on these two constructs.

2.1. Depression and social networks in adolescence

Adolescent social relations are correlated with depressive symptoms, often due to reputation and status mechanisms connected with peer acceptance and rejection. This phenomenon has been examined using several different approaches. Dyadic studies that investigate psychometric properties of a sample of peers are more common among the limited number of early adolescent studies of depression. Regression-based studies and actor-based studies are more common among middle and later adolescents.

In the first approach, the dyadic relationship between a given individual and the attributes of that individual's single friend (or small group of friends) are typically examined using a correlation or multiple regression analysis. For example, a study of 11th graders found that girls' social anxiety is associated with her immediate peer's social anxiety (Prinstein, 2007). For boys, depressive symptoms tended to be linked with low friendship quality and having friends who are highly popular. Researchers examining friendship changes among 6th-graders found that friendship instability is significantly related to subsequent depressive symptoms, and particularly sensitive to best friend instability (Chan and Poulin, 2009). A study of non-suicidal self-injury (NSSI) among 6th to 8th graders found that girls' friends affect their propensity to enact non-suicidal self-injury behaviors, while there is no similar phenomenon among boys (Prinstein et al., 2010).

A second relational approach employs a regression-based framework to examine health among a larger proportion of an individual's social network than just a best friend or close friends, sometimes taking into account the broader network structure in which individuals are embedded. In a study of suicide using data from the National Longitudinal Study of Adolescent Health (Add Health), Bearman and Moody (2004) found that having a friend who commits suicide increased the likelihood of ideation and attempts. Another line of investigation concerns the relationship between the size of the network and mental health. Using the same dataset, Ueno (2005) discovered that among late adolescents, higher levels of social integration were associated with fewer depressive symptoms. Falci and McNeely (2009) extended this work by showing that the relationship between social integration and depression is not linear, but convex. In other words, having either too many or too few friends increases one's risk of depression among teens, a phenomenon that depends both on gender and the density of one's personal network. Other research using Add-Health data has shown that teenagers with depressive symptoms who report same-sex and both-sex attraction are more socially isolated, have lower social status, and have fewer network connections than opposite-sex attracted youths. These effects are especially pronounced in females (Hatzenbuehler et al., 2012).

A third type of study uses a stochastic actor-based model (SABM) framework that can evaluate changing social connections and a given individual-level health condition as inter-related outcomes (Snijders et al., 2010). This simulation-based approach capitalizes on longitudinal sociocentric (whole-network) data, and allows investigators to evaluate the contributions of common endogenous social mechanisms (i.e. reciprocity, transitivity, preferential attachment) to an outcome. A benefit of this approach is that it explicitly models the interconnectedness and temporality inherent to social life, as opposed to making post-hoc adjustments for the statistical dependence of observations (a limitation of regression-based approaches). This framework has been useful for testing the reasons that depressed friends affiliate with one another through systematically evaluation of alternative mechanisms for network formation and behavior change. For instance, in a study of approximately 850 Swedish 14-year olds, peer depressive

symptoms were predictive of adolescents' depressive symptoms, after adjusting for network selection and de-selection effects over a four-year period (van Zalk et al., 2010). This is consistent with a social contagion explanation for why depressed friends affiliate, and the authors also find evidence that this process varies by gender.

In a study of American adolescents, Schaefer et al. (2011) extended earlier regression-based research on the link between network size and depression with an actor-based framework. They tested several competing explanations for depressive similarity among 9th to 11th-grade friends, finding that connected adolescents are similar in depression due to withdrawal from broader social networks. A study of nearly 1000 Finnish 16-year-olds revealed that depression tends to converge over time within friend groups (Kiuru et al., 2012). The authors evaluated the relative strength of social selection and social influence explanations, finding that depression convergence is not explained by social contagion processes but because individuals select friends with similar depressive symptoms. van Workum et al. (2013) examined network processes that explain similarities in happiness among a group of approximately 400 socially-connected 15-year-olds. The authors observed that while adolescents do not form friendships with similar-happiness peers, being similarly happy is an explanation for friendship maintenance, and happiness differences are a reason for friendship termination. Additionally, they observed that a given individual's happiness becomes more similar to the average level of her friends' happiness.

In sum, while the body of longitudinal studies of mid- and late-adolescent depression that make use of sociocentric network information is relatively well-developed, the same level of attention has not yet been given to early adolescent depressive symptoms. The present study aims to extend knowledge in this area by using longitudinal data to conduct sociocentric analyses of changing social ties and depressive symptoms of a cohort of 6th-grade students. Moreover, because the network data is gathered objectively, many of the biases associated with self-reported information can be avoided.

2.2. Self-esteem and social networks in adolescence

Self-esteem in early adolescence is linked to social relationships through feelings of peer support, and self-perception of one's place in peer groups and social status hierarchies. Self-esteem is considered to be an important indicator of personal resilience, defined as adaptability in the face of adversity, risk exposure, or disadvantage (Dumont and Provost, 1999; Fergus and Zimmerman, 2005). Thus, to the degree that social network structure is linked with self-esteem, it may provide insight into strategies for promoting resilience during early adolescence and beyond.

Social network research on self-esteem and peer relationships has been relatively rare, though correlational studies of peer-derived psychological constructs are more common. For example, early work on the transition from 6th to 7th grade documents strong associations between survey measures of peer support and self-esteem (Hirsch and Rapkin, 1987). In a study of the peer relationship quality and health of chronically ill 5th-graders, McCarroll et al. (2009) found that self-reported high self-esteem is linked with teacher-reported pro-social behavior and low aggression. A recent study of changes in mutual friendship patterns found that peer acceptance, friendship quality, and number of friends are associated with loneliness (Kingery and Erdley, 2007). To the best of our knowledge, no studies of early adolescent self-esteem have made use of detailed longitudinal network data (nor objectively-gathered social interaction data, used here) to conduct sociocentric analyses of changes in self-esteem.

2.3. Behavioral and social environment correlates of mental health in adolescence

Common correlates of mental health status are behaviors such as eating and physical activity; see Salvy et al. (2012) for an extensive recent review. Bruening et al. (2012) showed that best friends tended to have similar healthy choices (whole-grain and dairy), and tended to eat breakfast. Recent actor-based network research on 8th-grade low-nutrient energy-dense food consumption revealed that friends tend to emulate each other's junk food consumption in a way more "mindless" than deliberatively cognitive. In other words, adolescents were not thinking about their friends' choices and then acting, but rather acting and then modifying behaviors (de la Haye et al., 2013). Network research on physical activity in an after-school program among a range of adolescents demonstrates peer influence on physical activity levels (Gesell et al., 2012).

Two important social environment correlates of mental health in adolescence include social status position and level of school connectedness. Research by Goodman et al. (2001) showed that older adolescents' perceived socioeconomic status is related with depressive symptoms and self-esteem. Feelings of connectedness with one's school environment have been found to be associated with lower likelihood of risk behaviors and distressed mental health (Resnick et al., 1997).

2.4. Gaps in research and focus of present study

The growing literature on teens' social networks provides insight into how mental health is related to different aspects of social connectedness. However, our review reveals several conceptual and methodological gaps. First, there is a relative shortage of early adolescent social network research, which leaves knowledge of how relationships among this age cohort shape mental health (and vice versa) relatively underdeveloped. For instance, social networks of 6th graders tend to be more horizontally organized, while by 8th grade (and even more strongly in high school years) networks ossify into clique-based, mixed-gender, and more hierarchical structures (Steinberg and Morris, 2001). Thus, it may be inappropriate to generalize network findings from later adolescent cohorts to those in early adolescence, since interaction patterns change rapidly as children develop. Second, much prior network research tends to rely solely on self-report of friendships, which can be highly sensitive to recall bias and context effects. Third, scholars have used the term "peer studies" in an inconsistent manner to mean anything from an amorphously defined group of age-similar individuals, to a specific cohort of individuals considered friends, to studies involving a single peer (Fitzgerald et al., 2012). This problem of definition undermines efforts to compare study settings and precisely identify causal effects.

Methodologically, many studies do not assess attributes or behaviors of the complete range of all of an individual's alters, but rather only those of a close friend (i.e. Prinstein, 2007), a small number of closest friends (i.e. Kiuru et al., 2012), or a delimited number of alters (all research that uses Add-Health data, and other sophisticated designs, i.e. van Workum et al., 2013; van Zalk et al., 2010). This type of missing data presents a challenge to causal inference when a large part of a child's social network is not represented in analyses. Last, with the exception of Chan and Poulin (2009), many of the studies that employ a longitudinal perspective rely upon long follow-ups, for example 12 months (Kiuru et al., 2012), or 18 months (Prinstein, 2007). This is problematic because it is well-known that during adolescence relationships can change very quickly, on the timescales of days or weeks (Poulin and Chan, 2010). This variability is obscured by designs with a lengthy follow-up horizon.

The present study seeks to address these concerns by investigating the following questions: (1) How are network characteristics of young adolescents associated with depressive symptoms and self-esteem? (2) How might network-based social selection and social influence operate as mechanisms that contribute to change in self-esteem or depressive symptoms? Face-to-face social interaction behaviors are electronically measured between two individuals to generate social tie data. As others have argued, durable social relationships are built over time from repeated prior interactions, and understanding how patterns emerge over time is of crucial importance (Collins, 2004; Hinde, 1976). Although we do not claim that interaction networks proxy the social relationship of friendship, examination of objective interaction measurements reveals a high degree of correspondence with participants' self-reports of friendship (see Supplementary Data, Section 1).

Another contribution of this design is to examine early adolescent network structure in an educational setting at a finer temporal granularity than prior research. Here, this temporal granularity was operationalized in terms of 20-second interaction measurement intervals, within nine days of observation, over a three-month period. Although many others have conducted repeated measurements of social structure in schools (e.g. Clack et al., 2005; McFarland, 2001), this is the first study to our knowledge to objectively examine the evolution of interaction networks in the context of early adolescent mental health, and to examine self-esteem in a sociocentric network setting.

Objective measurement of behaviors makes this study distinctive from prior research on network processes in mental health, in that the research literature does not offer strict guidance as to how behavioral (as opposed to self-report) measures of children's networks might change, nor how these changes might be related to their mental health. Propositions formed on the basis of self-report data in adolescent mental health research suggest that individuals who are positionally more peripheral in their school-based social network may be higher in depressive symptoms, and lower in self-esteem. Research on peer socialization in later adolescent cohorts suggests that socially-connected individuals are likely to have similar levels of depression. Because it has been demonstrated that both depressive symptoms and more sophisticated forms of social behaviors increase between late childhood and early adolescence, it is hypothesized that there will be similarity in mental health status among socially-connected adolescents in this study population.

3. Methods

3.1. Overview

The data in this study are drawn from the Pre-Adolescent Eating and Exercise Network Study (*preTEENS*), conducted in 2012 by the authors at a private K-8 school in an urban setting in California (hereafter referred to as "Cal School"). preTEENS is best characterized as a "network-behavior panel study" (Steglich et al., 2010) of early adolescent socialization, health behaviors, and key indicators of physical and mental health. Based upon a review of the child development literature, a sixth-grade student sample was recruited because students in the 10–12 year-old range fall within a hypothesized transition zone between decreasing parental influence and increasing peer influence (Dishion and Tipsord, 2011).

3.2. School selection and partnership development

Criteria for study site selection were small grade size (less than 50 students), a school administration with interest in our research questions about student wellness, and stability in teaching and administrative staff so that the study could be sustained over the yearlong study setup and longitudinal data collection period. Selecting for a stable and supportive school environment was prioritized in order to avoid challenges that can prevent collection of high-quality network data, such as absenteeism, severe behavior problems, and lack of general interest by students and teachers. Because of the complexity of the methods being tested (i.e. collecting objective social interaction network and physical activity data), we did not prioritize the selection of a research site to be representative of urban middle schools, nor did we seek to conduct this phase of the research at multiple sites.

The approach to partnership with Cal School was collaborative and iterative. Following several meetings with Cal School's administrative leadership, school psychologist, and 6th-grade teaching staff, a presentation about the research was made to the students to explain the purpose of the study and to answer their questions. Appropriate participation incentives were provided commensurate with standards in the field. A follow-up debrief providing initial observations to children was conducted in small focus groups at the completion of observations, and a pizza party was provided to the students as a further thank-you for their participation. The Committee for Human Subjects at University of California, Berkeley approved the study protocol.

4. Design and procedure

Students provided multiple types of data, including (i) self-report questionnaire data concerning their health, eating, and exercise, (ii) objectively measured physical activity using accelerometers; and (iii) objectively measured social interaction data with wearable proximity sensors using active radio-frequency identification (RFID) technology, Parents of students were first required to provide written consent for their child's participation as minors, and students completed an age-appropriate assent form when they volunteered. Children were granted anonymity and informed their real names would not be used in presentations or publications, and that their responses to questionnaires and identified social interaction data would not be shared with parents, teachers, or peers. Following data-collection, responses associated with each child were coded to an electronic file using a unique random ID. Hard-copy questionnaires that listed students' real names were then destroyed.

Because study aims were to focus upon short-term changes in network structure, health behaviors, and health status, social interaction network data were collected for three consecutive days at monthly intervals for three months during the second half of the 6th-grade schoolyear. Nine days of measured interaction data were thus collected. To capture network socialization processes, an entire grade level of early adolescents was contacted to participate in the study. By the commencement of the study, 90.9% ($n = 40$) of the 44 students in the sixth grade had volunteered. One of the consented students was absent during the second observation period, and another declined to participate in the third period owing to perceived response burden. Non-participating students were not significantly different than participating students in terms of age or gender (using t-tests and χ^2 tests). Further consultation with teaching staff suggested no significant differences in other social or behavioral dimensions.

The sixth grade at Cal School had a majority of girls (F: 62.5%, $n = 25$, M: 37.5%, $n = 15$), and the mean age at enrollment was 12.3 (SD: 0.29, Range = 11.7–12.8). Self-report from students indicates that at least half of students' parents have advanced degrees, ascertained from five categories (neither parent went to college; one went to college; both went to college; one has an advanced degree; both have an advanced degree). The grade contains more students who identify as European-American (72.5%, $n = 29$) than

not (27.5%, $n = 11$), ascertained from self-report categories (African-American, Asian, Latino or Hispanic, White, Other/Write-in). There were no statistically significant differences between boys and girls in terms of age, parent education, or race/ethnic background.

4.1. Measures

4.1.1. Social environment

Two measures of children's social status are included, the first based on subjective self-report, and the second on peer nomination. Children's subjective social status was assessed using the youth ladder instrument adapted from the MacArthur Research Network on Socio-Economic Status & Health (Goodman et al., 2001). Students were shown a picture of a 10-rung ladder, and indicated which rung they would place themselves in their school environment. The stability of the measure from period 1 to period 2 was relatively high (Spearman's rho = 0.85), and also between periods 2 and 3 ($r = 0.76$). The second measure was based on perceived popularity; participants were asked to indicate the most popular students on a roster, and a summary measure was built. The stability of the measure from period 1 to 2 (Spearman's rho = 0.96) and period 2 to 3 ($r = 0.93$) was very high.

School connectedness was assessed with a measure of children's social environment, using a scale created for the National Longitudinal Study of Adolescent Health (Add Health) (Resnick et al., 1997). The instrument asks students the degree to which children feel close to people at school, are happy to be at this school, are a part of this school, feel safe, and are treated fairly by teachers. Students rate statements using a four-point Likert scale ranging from 'strongly disagree', 'disagree a little', 'agree a little', to 'strongly agree'. The connectedness scale has adequate reliability at all periods (Cronbach's alpha, $P1 = 0.80$, $P2 = 0.91$, $P3 = 0.76$). Summary scores for each measure were constructed using component questions and normalized between 0 and 1. The scale shows moderate consistency from period 1 to 2 (Spearman's rho = 0.69) and from period 2 to 3 ($r = 0.66$).

4.1.2. Health behaviors

Measures of exercise and food choice are included because low levels of exercise and unhealthy food choices have been linked with children's mental health. To obtain objective measurement of physical activity under free-living conditions, students were provided with a consumer-grade accelerometer (Fitbit®) to wear during the entire school day. While this device mainly captured incidental activity, such as travel between classes and recess time, students also wore it during physical education class. The devices yielded total steps per day and daily minutes of vigorous activity (averaged over the week of each panel). Since this device is relatively new, it has not been validated for research purposes against tools such as the Actigraph®, a more sensitive device considered the industry standard in exercise physiology (Welk et al., 2012). However, the present priority is to capture basic dimensions of physical activity, and because the same device was worn by each student, measurements are internally consistent within this population. As device measurement can vary depending upon where on the body it is worn (Vahdatpour et al., 2011), all students were required to wear it on their waistband for consistency.

The Healthy Eating Active Living (HEAL) questionnaire was used to measure food choices. This instrument is publicly available for download from the website of the Veronica Atkins Center for Weight and Health at UC Berkeley (Samuels et al., 2010). This age-appropriate questionnaire asks youths to indicate the consumption frequency of 18 common food and beverage items during the prior day. It has been recently used to assess youth attitudes and behaviors surrounding school food (Gosliner et al., 2011) and consumption changes following school nutrition reform (Woodward-Lopez et al., 2010). A typical question is: "Yesterday, did you eat candy of any kind? A: Did not eat, Ate at School, Ate at home, Ate at Some other Place" (possible frequency: 0–3). Though these questions are too broad to evaluate nutrient content, the indicators allowed the creation of simple summary measures of the consumption of healthier and unhealthier items. Healthier items included green salad, vegetables, fruit, baked chips, milk, water, fruit juice, and diet soda. Unhealthier items included French fries, hot dogs/hamburgers, fried chicken, nachos, candy, ice cream, sweets, chips, soda, and sweetened juice drinks.

4.1.3. Social interaction networks

Students' changing interaction patterns were investigated during the three months of the study. The lunchroom was chosen as the site for network observation because students tend to sit with social intimates at lunchtime. Social interaction patterns were recorded during lunchtime using an unobtrusive proximity-sensing active RFID tag worn in a neck lanyard. In conjunction with small wall-mounted receivers, these devices allow for the identification of who interacts with whom with a 20 s time resolution throughout the approximately 25-min long lunch period. Though 6th-graders ate lunch at the same time as 7th grade students, students self-segregated by grade, and 7th-graders were not involved in this study. There was always a teacher present in the lunchroom, and no aggressive or otherwise negative behavior incidents were observed during the study term.

Each tag recorded a digital signature of another tag only when two individuals were having a face-to-face interaction within a range of approximately 1.5 m, and the sensors were tuned so that the proximity of two individuals wearing them could be assessed with a probability in excess of 99% over an interval of 20 s. Moreover, radio signals from other proximate individuals were of such low power that they would be stopped by the water content of each person's body. Thus, signals would not pass backwards through a student's chest and interact with a tag of another student sitting back-to-back with her at another table. This specific technology has been successfully used to measure person-to-person interactions in settings as diverse as a hospital ward (Isella et al., 2011), elementary school (Stehlé et al., 2011), and conferences (Cattuto et al., 2010). Similar wireless sensor technologies have been used to measure interactions in a high school (Salathe et al., 2010) and college (Eagle et al., 2009), and real-time experiences among adult park visitors (Doherty et al., 2014).

The most basic unit of measurement is the occurrence of a digitally observed interaction between two individuals, which then becomes coded as an undirected social tie. For each day, only those interactions between participants that had a minimum cumulated interaction length of 80 s were retained. First, it was important to reduce the inclusion of transitory or accidental interactions measured at lower scan thresholds (i.e. 20–40 s) as they can represent, at some level, practical and statistical noise and it is doubtful that all of them capture a meaningful interaction. Second, sensitivity analyses of self-report friendship vs. RFID-measured interactions over the three periods of this study suggest that longer-duration face-to-face interactions, especially above the 60-s duration threshold, correspond to more meaningful social relations such as friendship (discussed in Section 1 of Supplementary Data). Social ties from Days 1–3 of the first week were then aggregated to constitute Period 1; days 4–6 comprised Period 2; and days 7–9 comprise Period 3. It is hypothesized that there will be an association between these interaction-derived social ties and mental health indicators, as social relationships have been previously implicated in mental health status in early adolescence.

4.1.4. Dependent variables: self-esteem and depressive symptoms

Two indicators of mental health were assessed as outcomes to be analyzed with interaction-derived measures of social ties. The first is self-esteem, measured using eight questions drawn from the DuBois Self-Esteem Questionnaire (DuBois et al., 1996). These questions tap self-concept, children's perceptions as people, and sense of contentment; students rate statements using a four-point Likert scale. The self-esteem scale has good reliability at all periods (Cronbach's alpha, $P1 = 0.83$, $P2 = 0.86$, $P3 = 0.83$). Summary scores for each measure were constructed using component questions in order to evaluate the stability of the construct over time. The stability of the summary scores is consistent from Period 1 to 2 (Spearman's rho = 0.74) and from Period 2 to 3 ($r = 0.72$). At Period 1, 55% ($n = 21$) of students are in the top two self-esteem quartiles; at Periods 2 and 3, 53% ($n = 20$) are in the upper half of the distribution.

The second indicator is generalized depressive symptoms, assessed using the 10-item short form of Kovacs' Children's Depression Inventory (CDI) (Sitarenios and Kovacs, 1999). It asks questions related to sadness, feeling alone, self-image, and social integration, and for each item participants choose one of three sentences that described their symptoms over the past two weeks (0 = symptom absence; 2 = the most severe symptom expression). This measure has good within-scale reliability at all periods (Cronbach's alpha, $P1 = 0.80$, $P2 = 0.82$, $P3 = 0.89$). Over time, the scale is fairly stable from Period 1 to 2 ($r = 0.74$), and a bit less stable from Period 2 to 3 ($r = 0.68$). There are low rates of depressive symptoms. At Period 1, two males and six females are above the 50th *t*-score percentile for depressive symptoms; the remaining students (80%) are below. During Period 2, one male and three females are above; 93% are below. At Period 3, one male and five females are above; 85% are below.

4.1.5. Statistical analysis

First, bivariate associations are calculated between time-invariant demographic traits with time-varying social status, health behavior, and mental health dimensions at each of the three observation periods. Correlation is used for continuous covariates, and χ^2 associations for categorical covariates. Next, various structural attributes of the student interaction networks are described at each observation period, and associations are assessed between the between socio-demographic traits and network attributes. The [sna] (Butts, 2013) and [igraph] (Csardi, 2013) packages for the *R* programming language were used for descriptive network analysis, and the [RSiena] package for *R* (Ripley et al., 2013) was used for statistical social network analysis.

Because the initial descriptive analysis reveals cross-sectional associations between network characteristics and mental health, the dynamic co-evolution of mental health and social interaction is analyzed as a *joint* dependent outcome. To do so, a stochastic actor-based modeling (SABM) framework is used to treat social ties and either depressive symptoms or self-esteem as inter-related dependent variables. While detailed elaborations of this approach are found elsewhere (Snijders et al., 2010; Steglich et al., 2010), a brief treatment of procedures is appropriate. Relative to traditional regression-based approaches that assume individuals are statistically independent, actor-based models instead treat individuals as interconnected. Models of interpersonal dependencies rely upon simulation methods that treat the observed network structure as a consequence of micro-changes in actors' behavior that proceed according to specified rules in a continuous-time Markov process.

One benefit of this approach is the ability to account for both stable and time-varying properties of individuals, as well as changes in network structure that may result from endogenous interpersonal mechanisms like preferential attachment (those with many friends tend to attract more friends) and transitivity (friends of friends tend to become friends). The particular processes of interest can then be parameterized in models. The forward model selection procedure suggested by developers was used to choose a parsimonious set of predictors for model inclusion. Important SABM considerations are that continuously-coded variables need to be transformed into ordinal variables, and there must be adequate change in the outcome behaviors of interest. While there were relatively low rates of depressive symptoms and low self-esteem at baseline, diagnostics indicate models are well-parameterized. Further information on model specification, variable transformations, and behavior changes are found in Supplementary Data (Sections 3 and 4).

5. Results

Table 1 provides information on the baseline demographic composition of the cohort, as well as cross-sectional detail on participants' social environment, health behavior, and mental health characteristics, with bivariate tests for group differences by gender. There was no significant gender distinction in age, race/ethnicity, or parent education. Across all observation periods, boys tend to be higher in subjective social status than girls, during all three periods (the last period only reaches a marginal level of significance). There was no significant gender difference in peer-nominated popularity, or school connectedness. In terms of health behaviors, boys are significantly more physically active during the day, both in duration and intensity ($p < 0.001$). Though boys report eating fewer unhealthy food choices at the first and last period, neither healthy nor unhealthy food varies significantly by gender. As expected in this age group, distributions are skewed towards low depressive symptoms and high self-esteem, and there are few gender differences. Only self-esteem at the first period reaches a marginal threshold for significance ($p = 0.08$), with boys reporting higher self-esteem than girls. Additional correlations between mental health indicators, socio-demographic, social environment, and health behavior covariates are reported in Supplementary Data (Sections 2, Tables A1 and A2).

5.1. Network change and associations with mental health

Though measures of mental health and social status were obtained once per period, three days of lunchtime interaction were observed per period, yielding nine days of network observation. Fig. 1 shows the structure of the daily lunchroom networks, which are then aggregated into three weekly networks to match the periodicity of the self-reported covariates. As expected, gender was the most salient axis of socio-demographic differentiation.

There are several important details to note about daily lunchroom interaction networks. First, with the exception of days 4 and 9, the majority of lunchtime periods contain several disconnected network components, reflecting subgroups that sat at different tables. There appears to be a strong tendency towards gender homophily, though a strict polarization is not observed everyday. Although there are a few students who are unconnected to others, it is erroneous to think of these students as isolates. It is more appropriate to state that these students did not meet the minimum 80-s interaction criterion for tie creation. Additional information on network change (node- and graph-level attributes) as well as change in dependent variables is found in Supplementary Data (Section 3, Table A3).

Table 2 reports on associations between individual-level network attributes and mental health status, and with few exceptions the direction of the association (positive/negative) is described, rather than the strength of association (Pearson correlation, $r = 0.0–1.0$). Three node-level network statistics are

Table 1
Participant characteristics, by student gender.

	Period 1					Period 2					Period 3				
	Male ($n = 15$)		Female ($n = 25$)		p-val	Male ($n = 15$)		Female ($n = 25$)		p-val	Male ($n = 15$)		Female ($n = 25$)		p-val
	Med	IQR	Med	IQR		Med	IQR	Med	IQR		Med	IQR	Med	IQR	
Demographic															
Age	12.2	(0.6)	12.3	(0.3)	0.65	–	–	–	–		–	–	–	–	
Race/ethnicity (Obs, %)					0.42										
Not European-American	3	20%	8	32%		–	–	–	–		–	–	–	–	
European-American	12	80%	17	68%		–	–	–	–		–	–	–	–	
Parent Education (Obs, %)					0.80										
One or both went to college	6	40%	10	40%		–	–	–	–		–	–	–	–	
One or both have adv. Degrees	8	53%	12	48%		–	–	–	–		–	–	–	–	
Don't know	1	7%	3	12%		–	–	–	–		–	–	–	–	
Social environment															
School social status ladder	9.0	(3.0)	8.0	(3.0)	0.012**	8.5	(1.5)	7.5	(1.0)	0.03**	8.5	(1)	8	(2)	0.09*
Peer popularity nominations	2	(12)	1	(6)	0.97	2	(14)	1	(7)	0.81	2	(11)	2	(7)	0.56
School connectedness	19	(2)	19	(4)	0.31	20	(1)	20	(3)	0.45	20	(2)	20	(3)	0.65
Health behaviors															
Steps (average freq./day)	7482	(1663)	5828	(778)	<0.001***	6473	(1514)	4864	(574)	<0.001***	7629	(2740)	6166	(755)	0.002***
Vigorous act. (avg. min/day)	57	(22)	40	(8)	<0.001***	37	(17)	25	(6)	<0.001***	40	(23)	29	(10)	0.003***
Healthier food	7	(3)	7	(3)	0.62	7	(3)	8	(3)	0.86	7.5	(4)	7	(4)	0.68
Unhealthier food	1	(2)	2	(2)	0.24	2	(1)	2	(2)	0.32	1.5	(2)	2	(2)	0.46
Mental health symptoms															
Childhood depression inventory (1–20)	1	(2)	1	(3)	0.18	0	(1)	0	(2)	0.22	0	0	0	(2)	0.12
Self-esteem (1–32)	29.0	(4.5)	27.5	(5.0)	0.08*	28.5	(4.0)	29.0	(6.8)	0.73	30.0	(2.0)	29.0	(6.0)	0.46

Note: Med (Median), IQR (interquartile range). p-value denotes significance level of bivariate association between gender and covariates. Chi-squared test used for categorical covariates (race/ethnicity, parent education). A nonparametric Mann–Whitney U test was used to assess group difference significance between gender and continuous variables with skewed distribution.

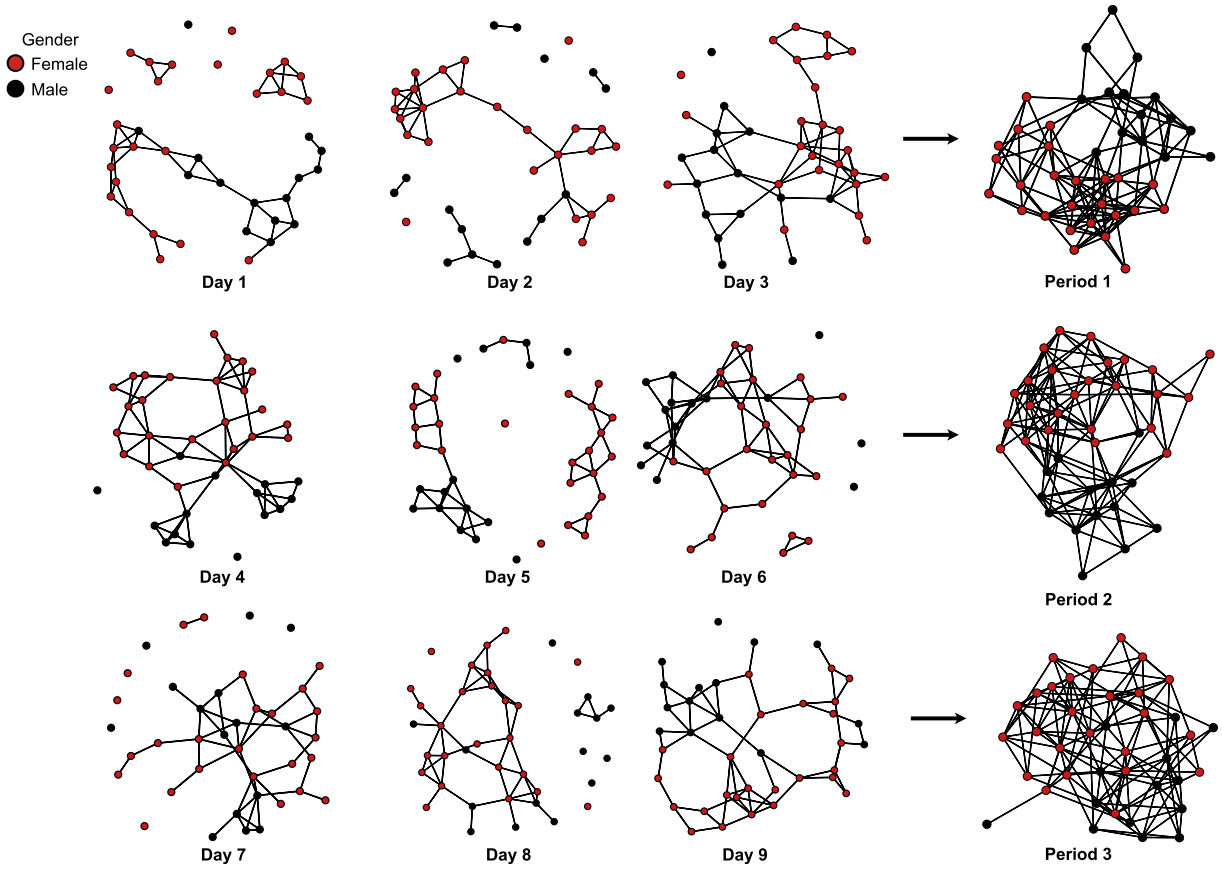

Fig. 1. Gender structure of 6th-grade interaction network during lunch, over nine days in a three-month period.

Table 2
Correlations between network indicators and mental health.

	CDI (*P*1)		SE (*P*1)	
	M ($n = 15$)	*F* ($n = 25$)	*M* ($n = 15$)	*F* ($n = 25$)
Network size (# of alters)	0.15	−0.21	0.06	0.37
Transitivity	0.17	0.03	−0.20	0.32
Closeness centr.	0.18	−0.22	0.06	0.33
	CDI (*P*2)		SE (*P*2)	
	M ($n = 14$)	*F* ($n = 25$)	*M* ($n = 14$)	*F* ($n = 24$)
Network size (# of alters)	0.66*	−0.47*	−0.47	0.19
Transitivity	−0.33	0.65*	0.46	−0.31
Closeness centr.	0.61	−0.56*	−0.42	0.30
	CDI (*P*3)		SE (*P*3)	
	M ($n = 14$)	*F* ($n = 25$)	*M* ($n = 14$)	*F* ($n = 25$)
Network size (# of alters)	0.24	−0.56*	−0.19	0.52*
Transitivity	−0.04	0.22	0.25	−0.19
Closeness centr.	0.30	−0.54*	−0.35	0.51*

Note: CDI (Childhood Depression Inventory); SE (Self-esteem scale). Pairwise correlation significance, *$p < 0.05$.

presented: (a) size of personal networks, indicating the number of alters to whom a given individual is connected; (b) transitivity (local clustering), an indication of how tightly grouped students are (Wasserman and Faust, 1994); (c) closeness centrality, a measure of central or peripheral structural location in one's network (Freeman, 1979). Associations are reported by gender for each mental health outcome, with significant correlations indicated.

At all periods, boys with more depressive symptoms tend to have strong positive coefficients for network size, suggesting greater integration in social networks, though the gender difference is only statistically significant at the second period. Girls are more consistent in the direction of association between depressive symptoms and network indicators at all periods. Girls with more depressive symptoms tend to be significantly less integrated in their networks at two periods (−network size), are significantly more peripheral at two periods (−closeness), and have significantly more transitive relationships at one period (+transitivity), though even non-significant coefficients have the same valence across periods. These patterns are consistent with a greater perceived social stigma related to depressive symptoms for girls, while boys' depressive symptoms appear not to be associated with their propensity to interact. However, while Table 1 reports that the difference in girls and boys' depressive scores is not significant at any of the three periods, the boys' level was consistently lower.

Examination of self-esteem reveals no significant or consistent relationship with boys' network attributes over time. Female students with higher self-esteem tend to have more interaction partners at all periods (+network size), though only one period was statistically significant. In addition, girls with higher self-esteem tend to have greater centrality (+closeness), though again only the last period was significant. These associations suggest that girls with higher self-esteem tend towards greater sociability and social integration, while there is no consistent pattern among boys. This is consistent with depressive symptoms as well.

Taken together, cross-sectional evaluation of associations between indices of network structure and mental health provides evidence of a great deal of variability even within a relatively narrow timespan (three months), indicating fluidity in children's social interactions and mental health status.

5.2. Co-evolution of social interaction behavior and mental health

Next, the extent to which individual attributes and aspects of network structure predict the joint formation of ties and change in mental health status is assessed (first for depressive symptoms, then for self-esteem). It should be noted here that not every measured health behavior (physical activity and eating behaviors) was significant in the forward model-selection process for each mental health outcome. Results from alternative analyses that included all health behaviors did not differ significantly. See Supplementary Data (Section 4) for additional detail on model specification.

Table 3 reports on the joint outcome of network formation and self-esteem change, and indicates a highly significant rate of change in lunchtime interaction, with network change from *P*2 to *P*3 greater than from *P*1 to *P*2. The degree parameter indicates that students are selective in their choice of interaction partners, and a positive transitive triad parameter indicates a tendency towards children's interaction partners being connected as in three-person groups. Demographically, there is a negative tendency for girls to contribute to network tie formation, suggesting that boys are doing more tie initiation, even after adjusting for their relatively fewer numbers in the gender distribution. We also observe a strong positive tendency towards gender homophily in tie formation, suggesting that boys tend towards interactions with boys, and girls towards girls (Stehlé et al., 2013). Last, there is a strong significant relationship between perceived popularity similarity and subsequent tie formation, suggesting that students perceived as popular by others tend to form ties with each another.

Changes in self-esteem were predicted by two actor attributes: student report of school connectedness, and race/ethnicity. For the former, feeling connected to the school is predictive of subsequent self-esteem. However, the latter term indicates a racial disparity, insofar as European-American students shift towards higher self-esteem. Also of note is a significant negative quadratic shape effect. This type of negative feedback is known to indicate a self-correcting behavior and suggests that as individuals approach either very high or very low self-esteem values, there is proportionally less change.

Tie-formation findings for depressive symptoms/social interaction co-evolution (Table 4) are similar to the self-esteem model,

Table 3
Social interaction and self-esteem co-evolution.

	Self-esteem (final model)		*p*
	PE	SE	
Network dynamics			
Rate of network change *P*1 to *P*2	15.33	(2.51)	(na)
Rate of network change *P*2 to *P*3	19.78	(5.41)	(na)
Structural effects			
Degree (density)	−1.09	(0.13)	***
Transitive triads	0.13	(0.03)	***
Transitive ties	0.27	(0.14)	*
Demographic & social environment			
Gender (ego's)	−0.20	(0.09)	**
Gender (same)	0.49	(0.07)	***
Perceived popularity (ego's)	−0.01	(0.05)	
Perceived popularity similarity	0.24	(0.09)	***
Self-esteem (ego's)	0.01	(0.05)	
Self-esteem similarity	−0.03	(0.21)	
Behavior dynamics			
Rate of behavior change *P*1 to *P*2	3.09	(1.30)	(na)
Rate of behavior change *P*2 to *P*3	1.58	(0.58)	(na)
Behavior linear shape	−0.24	(0.15)	
Behavior quadratic shape	−0.30	(0.12)	**
Attribute effects on behavior			
Race/ethnicity	1.07	(0.46)	**
School connectedness	0.97	(0.41)	**

Note: Parameter Estimate (PE), Standard Error (SE). Parameter estimates divided by standard errors yield t-values for each parameter; *t*-values greater than 1.65 ($p < 0.1$*), greater than 1.96 ($p < 0.05$**), greater than 2.58 ($p < 0.01$***).

Table 4
Social interaction and depressive symptom co-evolution.

	Dep. symp. (Final model)		
	PE	SE	*p*
Network dynamics			
Rate of network change *P*1 to *P*2	15.28	(2.92)	(na)
Rate of network change *P*2 to *P*3	19.48	(3.22)	(na)
Structural effects			
Degree (density)	−1.07	(0.13)	***
Transitive triads	0.13	(0.03)	***
Transitive ties	0.25	(0.14)	*
Demographic & social environment			
Gender (ego's)	−0.20	(0.09)	**
Gender (same)	0.49	(0.08)	***
Perceived popularity (ego's)	−0.01	(0.06)	
Perceived popularity similarity	0.23	(0.09)	**
Depressive symptoms (ego's)	0.03	(0.06)	
Depressive symptom similarity	0.23	(0.44)	
Behavior dynamics			
Rate of behavior change *P*1 to *P*2	3.51	(1.94)	(na)
Rate of behavior change *P*2 to *P*3	4.57	(2.12)	(na)
Behavior linear shape	−2.80	(2.05)	
Behavior quadratic shape	−0.01	(0.08)	
Average depressive similarity	−32.29	(31.49)	
Attribute effects on behavior			
Perceived popularity	−0.41	(0.34)	
Steps	0.21	(0.19)	
Vigorous activity	0.23	(0.19)	

Note: Parameter Estimate (PE), Standard Error (SE). Parameter estimates divided by standard errors yield *t*-values for each parameter; *t*-values greater than 1.65 ($p < 0.1^{*}$), greater than 1.96 ($p < 0.05^{**}$), greater than 2.58 ($p < 0.01^{***}$).

having the same significant parameters for degree, transitivity, ego gender, same-gender, and popularity similarity. However, the behavior dynamics part of the model reveals that none of the actor attributes shape depressive symptoms, and the lack of significance in average depression similarity suggests that early adolescents do not shape one another's depressive symptoms through a social influence process. Additional sensitivity analyses used "average alter" and "total similarity" as alternative social influence effects, with no difference in findings.

6. Discussion

Although prior research has established a relationship between depression and peer group structure among older adolescents, the present study is novel in its objective enumeration of dynamic social interaction networks in a middle school setting to examine the development of both self-esteem and depression during early adolescence. While this was a new application of this approach, we believe that reliance upon social interaction data to construct network data, that reflects who students actually interact with, has great potential to clarify how socialization processes unfold. In addition, this sociocentric focus on short-term changes in children's networks reveals substantial social fluidity even within three months. While some prior work (Chan and Poulin, 2007) suggests that approximately one-third of 6th-graders' self-reported friendship ties are unstable from month to month, examination of who children *actually interact with* reveals that nearly two thirds of 6th-graders' ties change. This is similar to findings by Cairns and colleagues among 4th and 7th-graders (Cairns et al., 1995).

These longitudinal analyses of changes in mutually dependent tie-formation and mental health confirm the important role that gender and popularity play in shaping social interaction during early adolescent years (Stehlé et al., 2013). There is also an observed propensity towards transitive closure at this age – friends of an individual tend to be friends as well. A further notable finding is that similarity in peer-perceived popularity has a key role in determining interactions. The role of health behaviors such as eating and exercise are often emphasized as key determinants in physical and mental health improvement. However, these health behaviors – even when physical activity is measured objectively rather than via self-report – do not seem to be as relevant to distressed mental health among this age group.

Findings on the co-evolution of self-esteem and social interaction suggest that the development of self-esteem in a network setting is socially moderated such that individuals' self-esteem neither becomes too inflated, nor dips too low. Rather, the quadratic behavior shape parameter provides some evidence that self-esteem development is self-correcting in an interconnected social system. Change in self-esteem is not dependent upon just the individual, but upon those to whom the individual is socially connected. The observation that increased sentiments of feeling connected to the school predict greater self-esteem suggests that fostering a welcoming environment for students may pay dividends in terms of their self-esteem and resilience. However, there is also evidence that a racial disparity in self-esteem improvement has roots, in part, in a network mechanism. This highlights a phenomenon that may be proactively addressed through attention to student interaction experiences, rather than simply attempting to address self-esteem on an individual basis.

Consistent with prior research, there are cross-sectional associations between mental health status and school-based peer social network attributes. However, the stringent causal methods employed here did not provide evidence of peer mental health status similarity over time, either from social selection or from peer social influence. This stands in contrast to the small number of adolescent studies of peer mental health that find peer influence or social selection mechanisms for depressive symptoms or positive affect in later adolescence (Kiuru et al., 2012; Prinstein, 2007; van Workum et al., 2013; van Zalk et al., 2010). While present findings do not necessarily comport with prior studies, neither do they contradict them, as this research was conducted with adolescents at an earlier stage of social development. The present objectively-assessed findings do harmonize in part with those of Chan and Poulin (2009), who did not find that changes in self-reported network ties affected subsequent depressive symptoms among 6th-graders.

There are several possible interpretations as to why study participants did not demonstrate similarity in depressive symptoms nor self-esteem over time, despite evidence in cross-sectional associations. First, children may not be fully aware of the mental health status of others at so young an age. This is consistent with a developmental explanation that early in adolescence children are less influenced by peer sentiment, and that one's perceptions of others' opinions begin to play a stronger role in shaping mental health beyond early adolescence. This explanation is also consistent with neurological development in that the youth in this study are at the cusp of shifts in social-affective processing but not yet in the thick of these changes (Crone and Dahl, 2012). Second, it may be that socialization shapes mental health status in ways unobservable from outward manifestations of social interactions. Third, features of the specific school studied may have played a role in influencing the observed patterns. During the study collaboration, school administrators and staff expressed that care for others was a key concern of the teaching staff and a core value of the school culture. This care was clearly reflected in students' interactions with one another; students may thus have been socialized to interact with others regardless of perceived mental health disposition. Despite this possibility, these data indicate that students nonetheless clearly discriminate in their social interaction patterns and do make affiliation choices, largely on the basis of gender and popularity. Fourth, it may be that out-of-school interactions and other forms of

school interaction not captured by sensor network technology may also shape mental health.

Another possible explanation for a lack of social influence effects is that there was a relatively low baseline level of distressed mental health in this population to begin with, and less change over time in depressive symptoms than in self-esteem. However, model specifications followed the process advocated by developers, and diagnostics suggested the models were well-fit. Though we strove for complete participation, four of the 44 students approached declined to participate. Sensitivity analyses were conducted that indicate non-participating students are no different in terms of age or gender than their included peers. However, it may be that the connections those four students had with other 6th-grade peers were, in fact, relevant to the processes being examined here. These data do not allow us to evaluate this possibility.

It would be fruitful for the field to pursue objectively-based social network enumeration approaches in community-based health research settings, not just among children, but also in adult populations. RFID technologies are currently in their early stages of development, and more research is needed to cross-validate findings across social settings, and types of devices. Additionally, the field would benefit from more research that compares student self-reported networks with whom individuals actually socialize, and that explores reasons for differences (Eagle et al., 2009; Smieszek et al., 2012). Given the rapid growth of computer-mediated lives, face-to-face encounters are but one form of interaction that adolescents engage in on a daily basis. Future studies should examine the overlap between offline and online forms of interaction and their relevance for child health. Children also likely have a variety of other social circles, including neighborhood and other extracurricular activity friendships that would benefit from scrutiny. As with other studies that involve sensitive health information, detail about social interaction may represent a special type of identifying information, and care should be taken that participant privacy receives the highest priority.

We submit that the present study's approach extends research on network dynamics. For the questions investigated here involving the joint development of social interaction and mental health, a SABM framework offers advantages over regression-based techniques in terms of explicitly modeling the dependence of individuals. As a recent discussion of statistical social network methods makes clear (Christakis and Fowler, 2013), any choice of network modeling strategy makes its own assumptions, and this area is in its infancy and enjoying a rapid burst of innovation. We have confidence that both regression and actor-based models will continue to develop with greater precision.

The present finding that one child's mental health distress symptoms do not shape another child's subsequent symptoms may be of particular interest for parents and teachers of early adolescents. This study suggests that the onset of peer influence on mental health is not especially strong in 6th grade, though signs of a social mechanism are starting to emerge. While students are keenly aware of each other's activities, fashions, social status, and gossip of their everyday lives, early adolescent mental health does not yet appear to be affected by the mental health condition of socially-connected peers.

Contributions

MCP and EJO designed the study, MCP conducted fieldwork, conducted all data analysis. AB and CC provided the wearable RFID sensors infrastructure for monitoring the proximity networks. MCP drafted the manuscript and EJO, AB, and CC contributed to manuscript revision.

Funding/conflicts of interest

This work was conducted while MCP was in the Robert Wood Johnson Foundation (RWJF) Health & Society Scholars program, and the project benefited from an RWJF pilot grant. There are no reported conflicts of interest. The Committee on Human Subjects at UC Berkeley approved the original study protocol.

Acknowledgments

We would like to thank the students of Cal School for their participation in this project, and to the Cal School faculty and staff for their assistance and facilitation. Nancy Adler, Ray Catalano, Wendi Gosliner, Bonnie Halpern-Felsher, Barbara Laraia, Kris Madsen, Janet Tomiyama, Nicki Bush, Laura Gottlieb, Aric Prather, Emily Jacobs, Chris Myer, and Shannon Iaffaldano provided valuable feedback on project design. We are grateful for the expert research assistance of Vanessa Davis, the statistical modeling advice of Kevin Lewis, and colleagues in the Behavior Change Research Network at University of California, Berkeley and the Human Nature Lab at Yale University (formerly Harvard Medical School).

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.socscimed.2014.04.015.

References

Andersen, S.L., Teicher, M.H., 2008. Stress, sensitive periods and maturational events in adolescent depression. Trends in Neurosciences 31, 183–191.
Bearman, P.S., Moody, J., 2004. Suicide and friendships among American adolescents. American Journal of Public Health 94, 89–95.
Blakemore, S.J., Choudhury, S., 2006. Development of the adolescent brain: implications for executive function and social cognition. Journal of Child Psychology and Psychiatry, and Allied Disciplines 47, 296–312.
Brooks-Gunn, J., Petersen, A.C., 1991. Studying the emergence of depression and depressive symptoms during adolescence. Journal of Youth and Adolescence 20, 115–119.
Brown, B.B., 1990. Peer groups and peer cultures. In: Feldman, S.S., Elliott, G.R. (Eds.), At the Threshold: the Developing Adolescent. Harvard University Press, pp. 171–196.
Bruening, M., Eisenberg, M., MacLehose, R., Nanney, M.S., Story, M., Neumark-Sztainer, D., 2012. Relationship between adolescents' and their friends' eating behaviors: breakfast, fruit, vegetable, whole-grain, and dairy intake. Journal of the Academy of Nutrition and Dietetics 112, 1608–1613.
Butts, C., 2013. sna: Tools for Social Network Analysis, Version 2.3-1.
Cairns, R.B., Leung, M.C., Buchanan, L., Cairns, B.D., 1995. Friendships and social networks in childhood and adolescence: fluidity, reliability, and interrelations. Child Development 66, 1330–1345.
Cattuto, C., Van den Broeck, W., Barrat, A., Colizza, V., Pinton, J.F., Vespignani, A., 2010. Dynamics of person-to-person interactions from distributed RFID sensor networks. PLoS One 5.
Chan, A., Poulin, F., 2007. Monthly changes in the composition of friendship networks in early adolescence. Merrill–Palmer Quarterly – Journal of Developmental Psychology 53, 578–602.
Chan, A., Poulin, F., 2009. Monthly instability in early adolescent friendship networks and depressive symptoms. Social Development 18, 1–23.
Choudhury, S., McKinney, K.A., Merten, M., 2012. Rebelling against the brain: public engagement with the 'neurological adolescent'. Social Science & Medicine 74, 565–573.
Christakis, N.A., Fowler, J.H., 2013. Social contagion theory: examining dynamic social networks and human behavior. Statistics in Medicine 32, 556–577.
Clack, B., Dixon, J., Tredoux, C., 2005. Eating together apart: patterns of segregation in a multi-ethnic cafeteria. Journal of Community & Applied Social Psychology 15, 1–16.
Collins, R., 2004. Interaction Ritual Chains. Princeton University Press, Princeton, N.J.
Crone, E.A., Dahl, R.E., 2012. Understanding adolescence as a period of social-affective engagement and goal flexibility. Nature Reviews Neuroscience 13, 636–650.
Csardi, G., 2013. igraph, Version 0.6.5-2.
Dahl, R.E., 2004. Adolescent brain development: a period of vulnerabilities and opportunities. Keynote address. Annals of the New York Academy of Sciences 1021, 1–22.

de la Haye, K., Robins, G., Mohr, P., Wilson, C., 2013. Adolescents' intake of junk food: processes and mechanisms driving consumption similarities among friends. Journal of Research on adolescence 23, 524–536.
Dishion, T.J., Tipsord, J.M., 2011. Peer contagion in child and adolescent social and emotional development. Annual Review of Psychology 62, 189–214.
Doherty, S.T., Lemieux, C.J., Canally, C., 2014. Tracking human activity and well-being in natural environments using wearable sensors and experience sampling. Social Science & Medicine 62, 83–92.
DuBois, D.L., Felner, R.D., Brand, S., Phillips, R.S., 1996. Early adolescent self-esteem: a developmental – ecological framework and assessment strategy. Journal of Research on Adolescence 6, 543–579.
Dumont, M., Provost, M.A., 1999. Resilience in adolescents: protective role of social support, coping strategies, self-esteem, and social activities on experience of stress and depression. Journal of Youth and Adolescence 28, 343–363.
Eagle, N., Pentland, A.S., Lazer, D., 2009. Inferring friendship network structure by using mobile phone data. Proceedings of the National Academy of Sciences of the United States of America 106, 15274–15278.
Eccles, J.S., Midgley, C., Wigfield, A., Buchanan, C.M., Reuman, D., Flanagan, C., et al., 1993. Development during adolescence: the impact of stage-environment fit on young adolescents' experiences in schools and in families. American psychologist 48, 90.
Falci, C., McNeely, C., 2009. Too many friends: social integration, network cohesion and adolescent depressive symptoms. Social Forces 87, 2031–2061.
Fergus, S., Zimmerman, M.A., 2005. Adolescent resilience: a framework for understanding healthy development in the face of risk. Annual Review of Public Health 26, 399–419.
Fitzgerald, A., Fitzgerald, N., Aherne, C., 2012. Do peers matter? A review of peer and/or friends' influence on physical activity among American adolescents. Journal of Adolescence 35, 941–958.
Forbes, E.E., Dahl, R.E., 2010. Pubertal development and behavior: hormonal activation of social and motivational tendencies. Brain and Cognition 72, 66–72.
Freeman, L.C., 1979. Centrality in social networks conceptual clarification. Social Networks 1, 215–239.
Gesell, S.B., Tesdahl, E., Ruchman, E., 2012. The distribution of physical activity in an after-school friendship network. Pediatrics 129, 1064–1071.
Gifford-Smith, M., Dodge, K.A., Dishion, T.J., McCord, J., 2005. Peer influence in children and adolescents: crossing the bridge from developmental to intervention science. Journal of Abnormal Child Psychology 33, 255–265.
Goodman, E., Adler, N.E., Kawachi, I., Frazier, A.L., Huang, B., Colditz, G.A., 2001. Adolescents' perceptions of social status: development and evaluation of a new indicator. Pediatrics 108, E31.
Gosliner, W., Madsen, K.A., Woodward-Lopez, G., Crawford, P.B., 2011. Would students prefer to eat healthier foods at school? Journal of School Health 81, 146–151.
Grosbras, M.H., Jansen, M., Leonard, G., McIntosh, A., Osswald, K., Poulsen, C., et al., 2007. Neural mechanisms of resistance to peer influence in early adolescence. The Journal of Neuroscience: the Official Journal of the Society for Neuroscience 27, 8040–8045.
Hatzenbuehler, M.L., McLaughlin, K.A., Xuan, Z., 2012. Social networks and risk for depressive symptoms in a national sample of sexual minority youth. Social Science & Medicine 75, 1184–1191.
Hergovich, A., Sirsch, U., Felinger, M., 2002. Self-appraisals, actual appraisals and reflected appraisals of preadolescent children. Social Behavior and Personality: An International Journal 30, 603–611.
Hertzman, C., Boyce, T., 2010. How experience gets under the skin to create gradients in developmental health. Annual Review of Public Health 31, 329–347, 323pp. following 347.
Hinde, R.A., 1976. Interactions, relationships and social structure. Man, 1–17.
Hirsch, B.J., Rapkin, B.D., 1987. The transition to junior high school: a longitudinal study of self-esteem, psychological symptomatology, school life, and social support. Child Development 58, 1235–1243.
Isella, L., Romano, M., Barrat, A., Cattuto, C., Colizza, V., Van den Broeck, W., et al., 2011. Close encounters in a Pediatric Ward: measuring face-to-face proximity and mixing patterns with wearable sensors. PLoS One 6.
Kingery, J.N., Erdley, C.A., 2007. Peer experience as predictors of adjustment across the middle school transition. Education and Treatment of Children 30, 73–88.
Kiuru, N., Burk, W.J., Laursen, B., Nurmi, J.E., Salmela-Aro, K., 2012. Is depression contagious? A test of alternative peer socialization mechanisms of depressive symptoms in adolescent peer networks. The Journal of Adolescent Health: Official Publication of the Society for Adolescent Medicine 50, 250–255.
McCarroll, E.M., Lindsey, E.W., MacKinnon-Lewis, C., Chambers, J.C., Frabutt, J.M., 2009. Health status and peer relationships in early adolescence: the role of peer contact, self-esteem, and social anxiety. Journal of Child and Family Studies 18, 473–485.
McFarland, D.A., 2001. Student resistance: how the formal and informal organization of classrooms facilitate everyday forms of student defiance1. American Journal of Sociology 107, 612–678.
Parker, J.G., Rubin, K.H., Erath, S.A., Wojslawowicz, J.C., Buskirk, A.A., 2006. Peer relationships, child development, and adjustment: a developmental psychopathology perspective. In: Cohen, D.J. (Ed.), Developmental Psychopathology, Theory and Method, pp. 419–493.
Poulin, F., Chan, A., 2010. Friendship stability and change in childhood and adolescence. Developmental Review 30, 257–272.
Prinstein, M.J., 2007. Moderators of peer contagion: a longitudinal examination of depression socialization between adolescents and their best friends. Journal of Clinical Child and Adolescent Psychology: The Official Journal for the Society of Clinical Child and Adolescent Psychology, American Psychological Association, Division 53 36, 159–170.
Prinstein, M.J., Heilbron, N., Guerry, J.D., Franklin, J.C., Rancourt, D., Simon, V., et al., 2010. Peer influence and nonsuicidal self injury: longitudinal results in community and clinically-referred adolescent samples. Journal of Abnormal Child Psychology 38, 669–682.
Resnick, M.D., Bearman, P.S., Blum, R.W., Bauman, K.E., Harris, K.M., Jones, J., et al., 1997. Protecting adolescents from harm. Findings from the National Longitudinal Study on Adolescent Health. Jama: The Journal of the American Medical Association 278, 823–832.
Ripley, R., Boitmanis, K., Snijders, T.A., 2013. RSiena: Siena – Simulation Investigation for Empirical Network Analysis, Version 1.1, p. 241.
Salathe, M., Kazandjieva, M., Lee, J.W., Levis, P., Feldman, M.W., Jones, J.H., 2010. A high-resolution human contact network for infectious disease transmission. Proceedings of the National Academy of Sciences of the United States of America 107, 22020–22025.
Salvy, S.J., de la Haye, K., Bowker, J.C., Hermans, R.C., 2012. Influence of peers and friends on children's and adolescents' eating and activity behaviors. Physiology & Behavior 106, 369–378.
Samuels, S.E., Craypo, L., Boyle, M., Crawford, P.B., Yancey, A., Flores, G., 2010. The California endowment's healthy eating, active communities program: a midpoint review. American Journal of Public Health 100, 2114–2123.
Schaefer, D.R., Kornienko, O., Fox, A.M., 2011. Misery does not love company network selection mechanisms and depression homophily. American Sociological Review 76, 764–785.
Sitarenios, G., Kovacs, M., 1999. Use of the Children's Depression Inventory. The Use of Psychological Testing for Treatment Planning and Outcome Assessment. Lawrence Erlbaum Associates Publishers, Mahwah, NJ, pp. 267–298.
Smieszek, T., Burri, E., Scherzinger, R., Scholz, R.W., 2012. Collecting close-contact social mixing data with contact diaries: reporting errors and biases. Epidemiology and Infection 140, 744–752.
Smith, K., Christakis, N., 2008. Social networks and health. Annual Review of Sociology 34, 405–429.
Snijders, T.A., Van de Bunt, G.G., Steglich, C.E., 2010. Introduction to stochastic actor-based models for network dynamics. Social Networks 32, 44–60.
Steglich, C., Snijders, T.A., Pearson, M., 2010. Dynamic networks and behavior: separating selection from influence. Sociological Methodology 40, 329–393.
Stehlé, J., Charbonnier, F., Picard, T., Cattuto, C., Barrat, A., 2013. Gender homophily from spatial behavior in a primary school: a sociometric study. Social Networks 35, 604–613.
Stehlé, J., Voirin, N., Barrat, A., Cattuto, C., Isella, L., Pinton, J.F., et al., 2011. High-resolution measurements of face-to-face contact patterns in a primary school. PLoS One 6.
Steinberg, L., 2005. Cognitive and affective development in adolescence. Trends in Cognitive Sciences 9, 69–74.
Steinberg, L., Monahan, K.C., 2007. Age differences in resistance to peer influence. Developmental Psychology 43, 1531–1543.
Steinberg, L., Morris, A.S., 2001. Adolescent development. Annual Review of Psychology 52, 83–110.
Ueno, K., 2005. The effects of friendship networks on adolescent depressive symptoms. Social Science Research 34, 484–510.
Umberson, D., Crosnoe, R., Reczek, C., 2010. Social relationships and health behavior across the life course. Annual Review of Sociology 36, 139–157.
Vahdatpour, A., Amini, N., Xu, W., Sarrafzadeh, M., 2011. Accelerometer-based on-body sensor localization for health and medical monitoring applications. Pervasive and Mobile Computing 7, 746–760.
van Workum, N., Scholte, R.H., Cillessen, A.H., Lodder, G.M., Giletta, M., 2013. Selection, deselection, and socialization processes of happiness in adolescent friendship networks. Journal of Research on adolescence 23, 563–573.
van Zalk, M.H., Kerr, M., Branje, S.J., Stattin, H., Meeus, W.H., 2010. Peer contagion and adolescent depression: the role of failure anticipation. Journal of Clinical Child and Adolescent Psychology: the Official Journal for the Society of Clinical Child and Adolescent Psychology, American Psychological Association, Division 53 39, 837–848.
Wasserman, S., Faust, K., 1994. Social Network Analysis: Methods and Applications. Cambridge University Press, Cambridge; New York.
Welk, G.J., McClain, J., Ainsworth, B.E., 2012. Protocols for evaluating equivalency of accelerometry-based activity monitors. Medicine and Science in Sports and Exercise 44, S39–S49.
Woodward-Lopez, G., Gosliner, W., Samuels, S.E., Craypo, L., Kao, J., Crawford, P.B., 2010. Lessons learned from evaluations of California's statewide school nutrition standards. American Journal of Public Health 100, 2137–2145.