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Validity of contact diaries compared with electronic sensors for measuring household contacts in Mozambique

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Bachelor of Science
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Thesis Committee Chair: Benjamin Lopman, PhD, MSc

An abstract of
A thesis submitted to the Faculty of the
Rollins School of Public Health of Emory University
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Abstract

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Measuring social contacts and their characteristics is an important aspect of infectious disease modeling. Traditionally, a self-kept contact diary was the popular method as it can capture the characteristics of contacts such as age, sex, location of contacts, and the existence of physical contacts. Recently, wearable proximity sensors got more attention in measuring contacts because it does not depend on participants' memory, and they are objective overall. However, there are a limited number of studies that compared the two measurements, especially in low-resource household settings. Therefore, this study aimed to compare and validate the household contacts measured by diaries and sensors in Mozambican households. We compared the number of contacts, age characteristics of contacts, and infant proximity scores by age groups between contact diary and wearable proximity sensor. While cleaning the dataset to suit the analysis, we encountered many losses for the sensor dataset due to loss of sensor and inconsistent data. We also had an issue with identifying the contacted person in the diary dataset which excluded many recorded contacts from our analysis. The overall number of contacts recorded by diary and sensors was similar while the age-specific average number of contacts indicated a higher number of reported contacts in diary measurement. The diary could not capture the difference in the duration of contacts with infants while sensors detected longer duration of contacts of infants with parents' age groups. We concluded that two measurements had specific characteristics they could capture which we need to consider for conducting future studies to measure social contacts. With the data loss in sensor and unidentifiable people in the diary dataset, we aim to conduct further analysis for future study.

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1 Introduction

In infectious disease modeling, contact rates and mixing patterns are important factors in determining parameters for estimating the transmission of diseases that spread through close contact and implementing intervention strategies[1]. When researchers model a specific infectious disease, they are required to estimate the parameter for the contact rates and transmission probability per contact based on the route of transmission, which takes into account of contact patterns of individuals[2]. Especially the diseases that can spread through droplets require a wider definition of contact such as having conversations or some type of skin-to-skin contact to better estimate the transmission of the pathogens[3].

Contact data has been used in modeling various infectious diseases. For example, Marziano et al. incorporated the parameter of contact matrices in their modeling of varicella transmission in France[4]. Two models were tested, one with a contact matrix assuming no change in mixing patterns over time and the other one with a contact matrix accounting for changes in mixing patterns over time. They used the two models to show that the potential explanation for the increase in varicella cases in France is the change in contact patterns among young kids over time. More recently, many studies used contact data in the modeling of COVID-19 dynamics. A study modeled a potential new outbreak of COVID-19 with a contact parameter in differential equations[5]. A prediction of the model in this paper indicated that lowering contacts was the best way to mitigate the transmission of the virus. Another study used a model that included contact components and assessed the potential risk by relaxing the COVID-19 measures[6]. Overall, contact data has been incorporated into math models for various reasons including estimating the number of cases in a community and assessing risks of interventions.

Multiple methods have been employed to measure characteristics of contacts in a population to better understand the nature of contacts and how they can be incorporated into mathematical models of infectious diseases[1]. A self-kept contact diary is one of the most popular methods to collect data on contacts in epidemiological studies and has been used widely around the world[2,7,8]. One of the advantages of the diary is that it is possible to collect many information such as the location of contacts, the existence of physical contacts, and many others that are not included in the sensor data[9]. Researchers can select a set of questions to ask participants so that it can meet their research needs. One of the limitations of collecting contact data by contact diary is that not all the contacts may be reported by the participants, especially when the duration of the contact is short such as less than five minutes of talking[10]. Additionally, some people contact a large number of people in one day due to their occupation such as local bus drivers[11]. For those people, it is impossible to record all the contacts so the contacts could be underreported for some groups of the population.

Another method that has emerged recently is collecting contact data by wearable sensors. Due to the development of technology, wearable sensors are getting more attention as alternative methods for contact information collection and becoming used globally. For example, they were used to measure household contacts in Kenya[12] and hospitals in France[13]. The advantage of the wearable sensors is that the burden for the participants is not big as they only need to wear the sensors but not write down contacts or answer questions[14]. Another advantage could be that it is a more objective measurement overall since it does not depend on the memories of participants[15]. There are several limitations to this method. First, sensors only capture contacts of people who wear the sensors, so if a person who has sensor contacts with a person who does not wear the sensor, it does not count the contact[16]. Secondly, sensors are usually not able to distinguish whether the contact involved physical contacts or any other high-risk contacts associated with infectious disease transmissionn[16]. Overall, both contact diaries and wearable sensors have advantages and disadvantages in contact data collection. Thus, comparing the two methods is crucial to understanding their characteristics and applying the methods in social contact study and its following infectious disease modeling.

To the extent of our knowledge, a few studies have done a comparison of contact diary and wearable sensor data of which two were done in high school and one was done at a scientific conference[10,17,18]. All three studies found that there was underreporting from contact diaries especially when the contact was of short duration, typically less than five minutes[10,17,18]. They also noted that there were a significant number of inconsistencies in reported contact between the two data. Two studies explained that this difference is partly due to the difference in the definition of contacts by contact diary and wearable sensors[10,18]. Sensors seemed to be more sensitive to short-duration contacts which were most likely to be the contacts where people did not talk but were close to each other for a short period of time[17]. When comparing the data from contact diaries and wearable sensors, participants tended to report longer contacts in the diary than the time captured by the wearable sensors[10,17]. The three previously described studies focused on developed countries such as France, Germany, and the U.S. Also, the setting of the data collection is limited only to high schools and a scientific conference.

To accumulate evidence on the comparison of the two methods of contact data collection and identify characteristics of each method, it is important to conduct research in different contexts. It is also important to mention that contact behaviors could be different in different cultures and socioeconomic status. Therefore, our study aimed to focus on contact data measurement in Mozambican households. This sub-analysis was a part of the GlobalMix study conducted in four low and middle-income countries (India, Pakistan, Guatemala, and Mozambique). To account for differences within a country, we collected data from both urban and rural settings in each country. In the present study, we were particularly interested in the contact behaviors among household members, particularly the contact behaviors around infants. Overall, the study aimed to validate how well the data from contact diaries and wearable sensors match to each other and thus, examine to what extent data from the two methods reflect participants' contacts in Mozambican household.

2 Material and methods

2.1 Study population

This study was based on the GlobalMix study which aimed to characterize the social mixing patterns in resource limited settings[19]. The study population were recruited from rural and urban settings in Mozambique. The rural area in this study was in Manhiça Health and Demographic Surveillance Site (Manhiça HDSS) in Maputo province. The urban area in this study was in Polana Caniço Health and Demographic Surveillance Site (Polana Caniço HDSS) in Maputo city. For the contact diary, we recruited participants through quota-random sampling based on age and study site. Within the participants of the contact diary, we randomly sampled children less than 5 years old as an index child to participate in the sensor data collection. For each index child, entire household members were required to wear sensors.

2.2 Data collection

Data were collected from August 2020 through July 2021 to be able to measure the seasonal differences in social contact. In our study, social contact involved both physical and non-physical. The protocol defined a physical contact as "a 2-way face-to-face interaction between two or more individuals standing at arm's length with each other that involves touching either skin-to-skin or over clothes"[19]. Non-physical contact was defined as "a 2-way face-to-face conversation between two or more individuals standing at arm's length with each other, with no physical barrier but not touching each other"[19].

2.2.1 Contact diary

Once the participants were enrolled in the study, they were randomly assigned two consecutive days to complete the contact diary. Participants were asked to keep a record on the paper diary for two days, then, fieldworkers filled in the data on REDCap platform for all the participants. Participants filled in the survey at the end of each 24 hour of the two days. Fieldworkers asked participants if they reported all contacts, and if not, prompted participants to remember and these were captured in the data. In addition to the social contact information collected by the survey, demographic data were collected by the fieldworkers.

2.2.2 Wearable sensors

Data collection was done by wearable sensors for seven consecutive days starting from a randomly assigned date. Participants were asked to wear sensors on chest area and asked to keep a record of when they wore sensor in the morning and when they took off the sensor for each day. The sensors detect other sensors in proximity when individuals are face-to-face within 1 – 1.5 meters. A maximum of one data packet that includes the unique ID, timestamp and transmission is exchanged per second when the sensors are in proximity. The sensors do not detect any physical touch between the individuals, but the signals are based on the distance between individuals wearing sensors.

2.3 Statistical analysis

To be able to compare the sensor and diary dataset about the contacts, people who had a record in sensor and had a household contact record in diary were extracted. Then, to grasp the overall idea of participants' characteristics, the demographic information about the participants that met these criteria was summarized.

Next, to see how many contacts were captured in both the diary and sensor, the number of contact events that are recorded in both measurements and one measurement only is reported. The diary dataset did not have the individual ID of the contacted person; thus, the ID of the contacted person was matched by using household ID, age, and sex variables from the participants' information. Those who had missing age and sex were removed from the diary set for this analysis as it would not match to the participants' dataset. As the three variables used for matching could match multiple participants, the contacted persons in the diary who had multiple potential matches were removed from the analysis to prevent matching an incorrect individual. Any households that had a person not identifiable in the contacted person was removed as an entire household to avoid biased data in that household (Figure 1).

All the participants in this study were asked to wear sensors; however, the resulting dataset only included 242 participants out of 562 participants. The loss of participants in the sensor dataset was due to the following reasons: (1) loss of sensors or sensor IDs leading to loss of data itself or non-identifiable data of the participants; (2) sensor data was captured in the electronic form, but the data were not available due to multiple reasons including incorrect household and personal identifiers; (3) there were no data recorded in the sensor data or inconsistent data such as sensors recorded data for 48 hours continuously suggesting the participants not wearing sensors but put them all together at the same place; (4) person living alone so no contacts should be counted as a household contact.

The number of contacts from diary was defined as the number of unique people that a specific person recorded in diary over the two days of our interest. For the sensor contacts, the degree of contacts was defined as the number of unique nodes a sensor is connected to, meaning that this is the same measure for the number of contacts in diary. For both measurements, the number of contacts were summarized by rural/urban in addition to the overall summary statistics. Then, the number of contacts for sensor and diary was compared using Mann-Whitney U test as the distribution of the number of contacts were not normal for the two datasets. Additionally, to assess how the difference in number of contacts are distributed, difference in number of contacts, which we defined as the number of contacts in diary subtracted by the number of contacts in sensor, was calculated for each individual and its distribution was displayed in a density histogram for rural and urban study site.

Next, to compare the nature of contacts in diary and sensor data, contact matrices by age were created. For the diary dataset, three types of contact matrices (all diary contacts, household only contacts, and sensor-matched contacts) were created. All diary contacts were defined as all the contacts that were recorded in the diary dataset including non-household and household contacts. Household only contacts were defined as the contacts that were identified among a participant and a household member, and verified by checking the location of the contacts although contacts with household members may occur outside the house. Sensor-matched contacts were defined as the contacts that were household contacts, and the participants ID were included in the sensor dataset. For the sensor dataset, all the data except one participant who did not have data in the diary were used to create the matrix. Then, a matrix that compared the age-specific average number of contacts was created. The difference in age-specific average number of contacts were calculated as the average number of contacts in diary subtracted by the average number of contacts in sensor in each age group.

Lastly, infant proximity score (IPS), which is an indicator of how much household members are in contact with infants in comparison to the overall contacts in the household, was calculated. The IPS was calculated as the median duration of contacts with infants for each age group and summarized in a bar graph for rural and urban households. The IPS were also calculated by sex to examine the difference in interaction with infants between male and female household members. For the diary dataset, duration of contacts is a categorical variable, so the midpoint of each category, for example, 2.5 hours for 1-4 hours category, was used for the calculation. For the category of more than 4 hours, 8 hours was used assuming that the longest duration would be around 12 hours a day. For the sensor dataset, recorded duration was used. For each age groups stratified by study site or sex, data for the groups that had less than 5 participants were treated as missing because it is too small to show the summarized value for those groups and it could introduce bias in the results. All the analysis in this study was done in R 4.3.1 using RStudio.

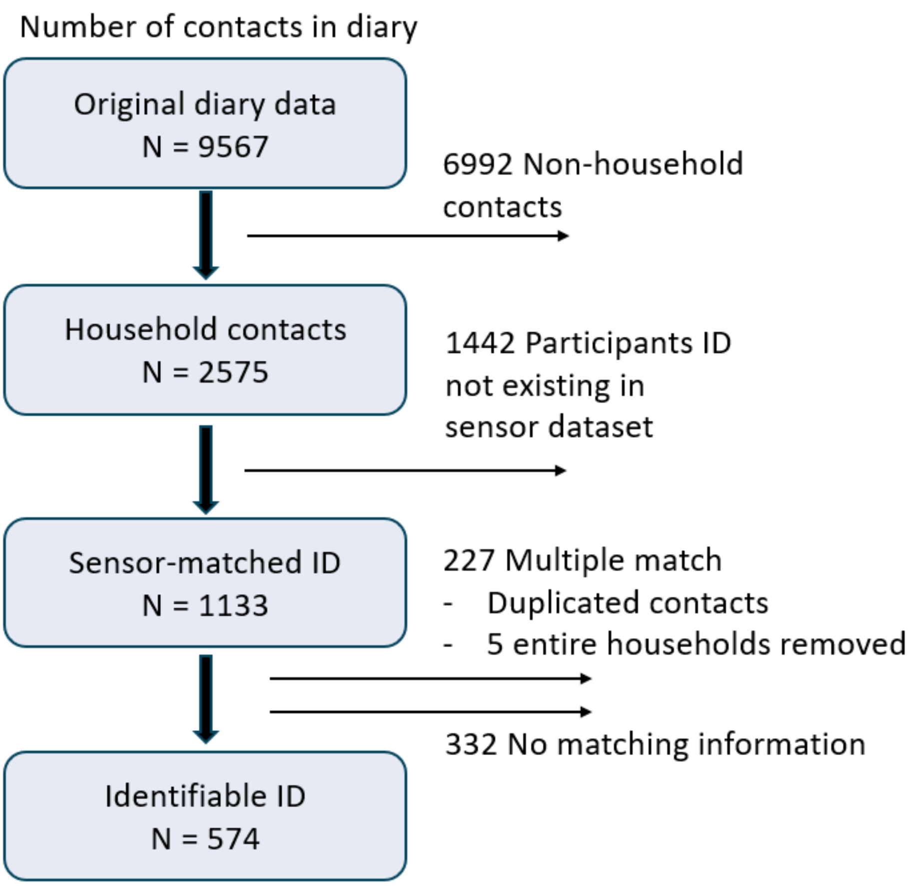

Figure 1: Flow diagram of the data cleaning process of diary dataset

2.4 Ethical considerations

Following the Declaration of Helsinki, written consent was obtained from all the participants with a signature or thumb impression. Participants $\geq$ 18 years provided written informed consent, those aged 13-17 years provided verbal assent and parental written consent, and children <13 years required written parental consent to participate in the study. A detailed explanation of the study, which includes the description of potential risks and the potential usage of the collected data in the research, was provided to the participants before signing the consent. This study was approved by Institutional Review Board of

Emory University (00105630) and the study site Mozambique (CIBS-CISM/012/2021).

3 Results

3.1 Participants' characteristics

Overall, 562 participants recorded data in the diary, and 553 (98.4%) of them had at least one household contacts recorded. Of those 553 participants, 241 participants had sensor data available (Figure 2). Sensor data had 242 participants, and all the participants except 1 had at least one household contact recorded in the diary data. Demographic data of participants who had data in both diary and sensor as well as those who did not are shown in table 1.

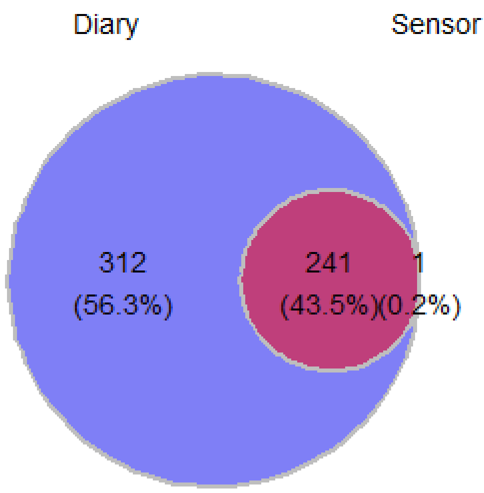

Figure 2: Recorded participants in diary and sensor dataset

Table 1: Characteristics of participants

	Included participants N = 241	Excluded participants N = 321	Included participants by site	
			Rural N = 133	Urban N = 108
Sex				
Female	148 (62%)	182 (57%)	85 (64%)	63 (58%)
Male	92 (38%)	138 (43%)	47 (36%)	45 (42%)
Participant age				
<6mo	21 (9%)	21 (7%)	15 (11%)	6 (6%)
6-11mo	22 (9%)	27 (8%)	9 (7%)	13 (12%)
1-4y	29 (12%)	50 (16%)	16 (12%)	13 (12%)
5-9y	36 (15%)	40 (12%)	23 (17%)	13 (12%)
10-14y	26 (11%)	46 (14%)	19 (14%)	7 (6%)
15-19y	16 (7%)	25 (8%)	10 (8%)	6 (6%)
20-29y	43 (18%)	53 (17%)	19 (14%)	24 (22%)
30-39y	23 (10%)	29 (9%)	12 (9%)	11 (10%)
40-59y	16 (7%)	24 (7%)	7 (5%)	9 (8%)
60+y	9 (4%)	6 (2%)	3 (2%)	6 (6%)
Able to read and write	110 (46%)	160 (50%)	53 (40%)	57 (53%)
Currently enrolled in school	68 (29%)	106 (34%)	45 (35%)	23 (22%)
Occupation				
Child	43 (21%)	48 (19%)	24 (21%)	19 (21%)
Unemployed	50 (25%)	51 (20%)	32 (28%)	18 (20%)
Student	57 (28%)	90 (35%)	35 (31%)	22 (24%)
Homemaker	8 (4%)	7 (3%)	2 (2%)	6 (7%)
Casual laborer	6 (3%)	11 (4%)	3 (3%)	3 (3%)
Farmer	9 (4%)	12 (5%)	9 (8%)	0 (0%)
Business person	11 (5%)	15 (6%)	0 (0%)	11 (12%)
Office worker	15 (7%)	16 (6%)	4 (4%)	11 (12%)
Retired	1 (0%)	0 (0%)	0 (0%)	1 (1%)
Other	41 (17%)	71 (22%)	24 (18%)	17 (16%)
Acute respiratory infection				
>1 symptom	41 (17%)	45 (14%)	35 (26%)	6 (6%)

3.2 Number of contacts

Overall, 9567 contacts were recorded in the diary dataset and 2575 (26.9%) contacts were recorded as household contacts among the 241 participants. Among the 241 participants included in the analysis, there were 1133 contacts recorded. Of those 1133 contacts, we identified the individual ID of 574 (50.7%) contacts (Figure 1). Most of the unidentifiable contacts were those that did not have matching information in the participants database or those that have multiple matching information and were excluded from the analysis. Sensor data recorded 334 contacts and we assumed reciprocity as the sensors exchange the data packet with another sensor and these are bidirectional; thus, we have 668 records in total. Overall, 378 contacts were recorded in both diary and sensor dataset, and this accounted for 66% and 57% of the diary and sensor dataset respectively.

In rural households, the median number of contacts was the same (3 contacts) for the diary and sensor records (Table 2). In urban households, the sensor reported a higher median number of contacts compared to the diary (3 contacts for the sensor and 2 contacts for the diary, Table 2). Rural households recorded a higher median number of contacts for the diary and the same number of contacts for sensor data than urban households. Figure 3 shows the distribution of differences in the number of contacts between the diary and sensor for rural and urban households. Both rural and urban had 0 as a median value. The difference between diary and sensor records seemed to be distributed normally for rural households while that of urban households seemed to be skewed and had multiple outliers.

Lastly, the Mann-Whitney U test indicated that there was no significant difference in the median number of contacts between the diary and sensor measurements (Table 2).

Table 2: Summary of the number/degree of household contacts in two measurements

	Diary	**Sensor**
Overall		
Median	2	3
Mean (std)	2.7 (1.6)	2.7 (1.3)
10th percentile	1	1
25th percentile	2	2
75th percentile	3	3
90th percentile	5	4
p-value	0.52	
Rural		
Median	3	3
Mean (std)	2.9 (1.7)	2.7 (1.3)
10th percentile	1	1
25th percentile	2	2
75th percentile	4	3
90th percentile	5	4
p-value	0.50	
Urban		
Median	2	3
Mean (std)	2.5 (1.3)	2.7 (1.3)
10th percentile	1	1
25th percentile	2	2
75th percentile	3	4
90th percentile	4	5
p-value	0.086	

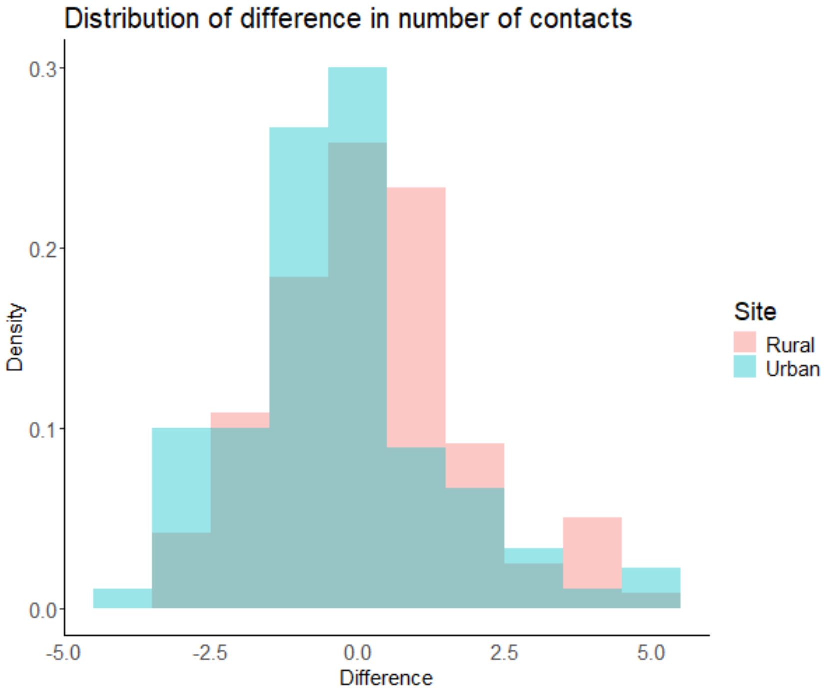

Figure 3: Density plot showing the distribution of difference in number/degree of contacts for individuals in each study site. The positive values indicate more contacts recorded in diary and negative values indicate more contacts in sensors.

3.3 Contact matrices representing average number of contacts

The contact matrix of the diary dataset showed a high average number of contacts with children-children contacts and parents-children contacts. There was especially high average number of contacts for the contacts with 10-14 years old across other age groups. There were also high number of contacts of 60+ years old with 20-39 years old groups. There was notably low average number of contacts with 15-19 years old across all the age groups. When stratifying to rural and urban sites, rural households had a higher average number of contacts, especially for children-children contacts compared to urban households (Figures S1e and S1f). Additionally, the matrix of all the contacts (Figures S1a and S1b) showed age-assortative as the cells in diagonals have higher values. This pattern was especially strong in 10-14 years old and 30-39 years old for both rural and urban settings. There was more assortativity in younger ages for the rural household contacts compared to the urban households. The contact matrix from the sensor dataset showed that there was a pattern of infants (0 – 11 months) contact with older siblings (5 – 9 years) and with parents (20 – 29 years). In rural households, 1 – 14 years olds had a high contacted number compared to other age groups (Figure S2a). On the other hand, in urban households, 20 – 29 years old had a high average contacted number compared to other age groups (Figure S2b). Figure 4c shows the comparison of the diary and sensor contact matrix. The values in most of the cells were positive indicated by the orange color, meaning that the average age-specific number of contacts was higher for the diary dataset than the sensor dataset. However, there was also a pattern that the contacts with less than 6 months and 15-19 years old were more recorded in the sensor dataset indicated by negative values and blue color. When stratified by study sites, rural households showed a similar pattern while urban households showed a higher average number of contacts for the diary dataset among contacts with older generations and higher contacts in sensor dataset with younger generations (Figure S3a and S3b).

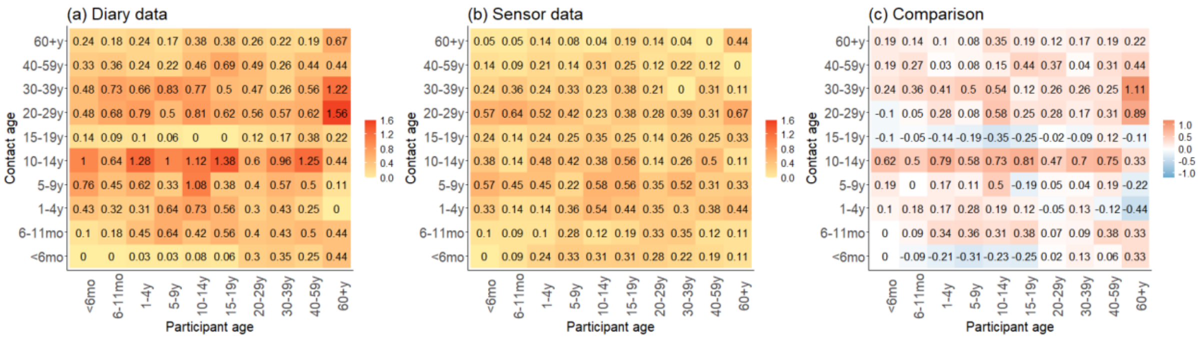

Figure 4: Contact matrix. Panel (a) shows the contact matrix of the diary dataset. Panel (b) shows the contact matrix of the sensor dataset. Panel (c) shows the contact matrix of the comparison of diary and sensor dataset. Red color indicates higher contact number in diary and blue indicates higher contacts number in sensor dataset.

3.4 Infant proximity score (IPS)

IPS of the diary data showed that most of the scores were the same value of about 500 minutes for all the age groups and study sites except the rural 60+ group. As the longest duration category that participants could choose was more than 4 hours and most of the contacts were recorded as more than 4 hours, the IPS from diary dataset resulted in the same values and we could not distinguish the actual duration of contacts and proximity to the infants by the diary measurement. On the other hand, IPS from the sensor dataset showed a pattern of highest values in the parents' age groups which were 20-29 and 30-39 years old. The values of the older siblings were second highest following the parents' age group, which showed the expected contact patterns in a household. Next, the IPS stratified by sex also showed the same issue of having mostly the same score in all the age groups for the diary dataset.years old group, the score for the female was much higher, indicating mothers were spending more time with infants compared to father. For the sensor dataset, there were several groups that had less than 5 participants in that group and resulted in removing from analysis.

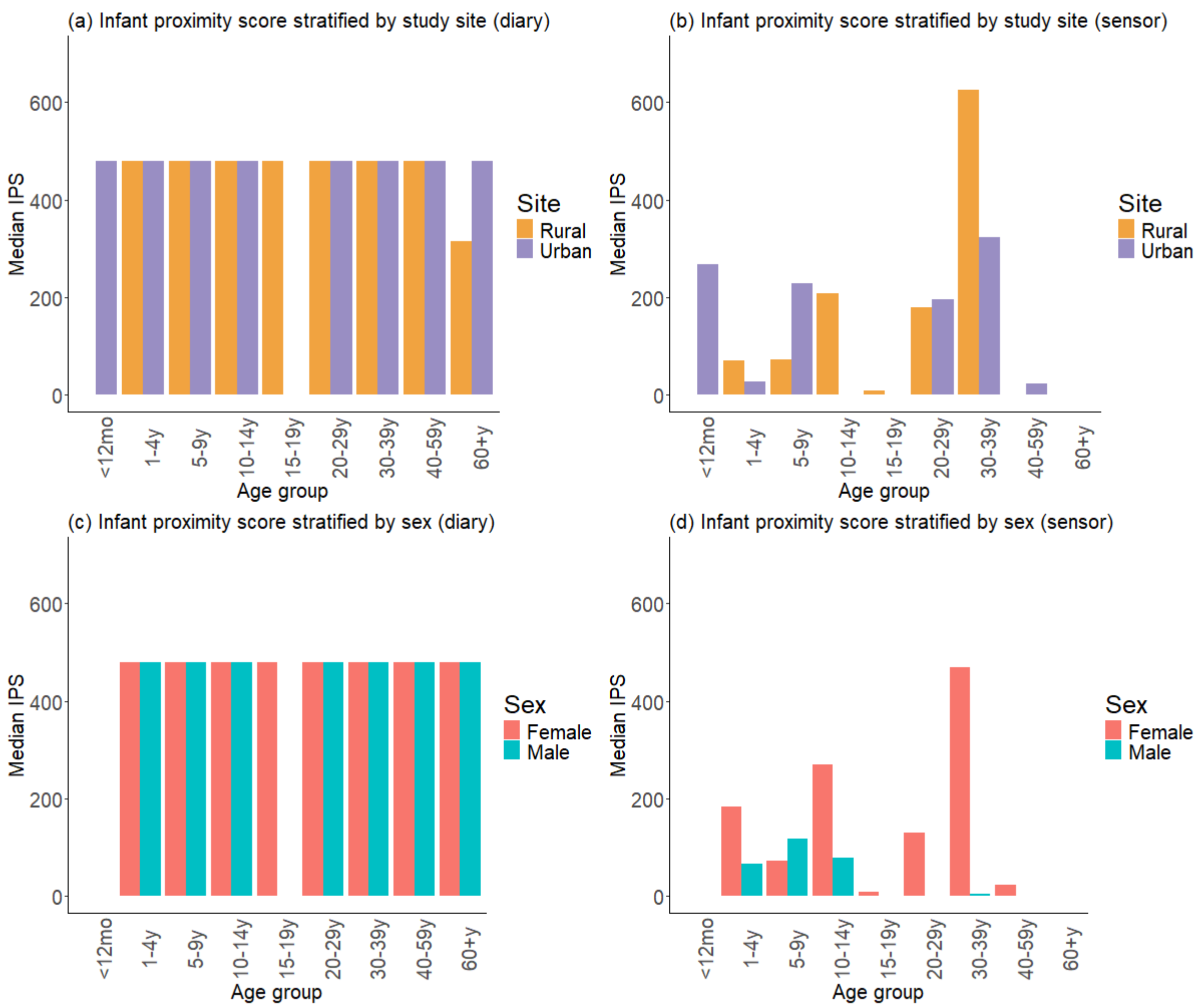

Figure 7: Infant proximity scores (IPS) by age group and sex. Panel (a) shows the IPS of diary dataset. The IPS were calculated as median duration of contacts that involved infants in each age group. Panel (b) shows the IPS of sensor dataset. The IPS were calculated as the median duration of contacts involving infants in each age group. Panel (c) shows the IPS of diary dataset stratified by sex. Panel (d) shows the IPS of sensor dataset stratified by sex.

4 Discussion

4.1 Key findings

This study aimed to validate the diary and sensor in measuring contact behavior in household settings in Mozambique. To do so, the number of contacts, average number of contacts stratified by age groups, and duration of contacts with infants in each age group for each measurement were analyzed. Before the analysis, we found that more than half of the participants were lost for the sensor data due to loss of sensor or data, and inconsistent data. Additionally, about half of the contacted people in the diary were not identifiable. These unidentifiable people could be either due to incorrectly recorded information in the diary or misclassification of household contacts. Some contacts could not be identified to a unique individual because multiple people had exactly same household ID, age groups, and sex. We found that the median number of contacts recorded in the diary and sensors was the same for rural households and diary had one less median number of contacts for urban households. Additionally, on the individual level difference in the number of contacts, both rural and urban households had the highest density at 0, suggesting that the two measures were likely to report the same median number of contacts. The contact matrices from both diary and sensor showed relatively high number of contacts between 10-14 years olds and other age groups especially children and parents' age groups. The comparison matrix suggested that most of the age groups had higher average number of contacts in diary compared to sensor. Contacts with less than 6 months old and 15-19 years old for rural households had a higher average number of contacts reported in sensor compared to diary dataset. Additionally, IPS showed a longer duration of contacts between infants and parents compared to other age groups by the sensor dataset. We also observed that females in the parents' age group had longer duration of contacts with infants compared to males by the sensor dataset. On the other hand, diary measurements could not distinguish difference in duration of contacts in different age groups. IPS, in other words, duration of contacts with infants, was generally higher in diary compared to sensors. This could be due to the difference in what is considered as contact duration in diary and sensors. For example, if two members were talking for 15 minutes but walking around the room while talking or one of them going out of the room for some minutes and come back, sensors would not count those time as duration. On the other hand, it would most likely counted as contacts with 15 minutes in diary even though some minutes within the 15 minutes were not face-to-face contacts within 1-1.5 meters.

4.2 Limitations

There were several limitations in the study. First, the overall adherence to study instructions may have been low, particularly regarding sensor measurements, as more than half of the participants failed to contribute data to the sensor dataset. Some participants appeared to have not worn the sensors at all during the study period. This could be attributed to simply forgetting to wear them, as they were not accustomed to wearing such devices in their daily lives; practical difficulties in movement or completing daily tasks while wearing the sensors; or privacy concerns, despite the sensors only capturing data signals from other sensors without collecting personal information. In low-resource settings, the adoption of new technologies like proximity sensors can be challenging due to budget constraints. For instance, we reused the same sensors for multiple households, which resulted in the loss of previous data if a sensor was misplaced by one household.

Secondly, there were multiple issues with data cleaning for both diary and sensor. There was a limited amount of data available for the sensor dataset. All the 562 participants who filled in the diary also had access to sensors; however, the sensor data that had reasonable data for analysis only included 242 participants. This could bias our results if the participants who had available sensor data had certain characteristics compared to those who did not. Additionally, about half of the household contacts in the diary were not identifiable, and thus, could not be used for our analysis as explained in the results section. Over half of the unidentified contacts (332/559) were because the contacted person's information did not match any participants. This indicates that there was a potential misclassification of household contacts in the diary dataset, meaning that the participants reported contacts as household contacts, but the contacted person was not a household member as defined in our study. Another potential reason is the incorrect information of age and sex of the contacted person, making the person unmatched to any of the participants' information. The other 227 unidentified contacts were due to the multiple matching information, meaning that there were multiple people in our participants who had the same household ID, age category, and sex and it was not possible to distinguish which person was the actual contacted person. This could be avoided if we had more demographic information about the contacted person as the more variables we have, the better we can distinguish the person.

This leads to the third limitation in the study which was the definition of IPS based on the age groups. A better way of computing the IPS would be based on the relationship between the infant and a household member as previous study defined[20]. However, there were substantial missing data on the household member relationship in the dataset (979/1133), requiring us to define IPS differently. In future, we will explore re-establishing the relationships between household members to calculate the IPS as in previous studies. Additionally, we aim to convert units for the IPS to be the same for diary and sensor measurements for future studies so that we can compare them more accurately.

Lastly, the contact duration of the sensor dataset was not available for this study, making some analysis potentially biased. As the duration of contact is an important component of social contact, specifically in the context of transmissibility of infectious disease, the lack of comparison between diary and sensor measurements on contact duration is a limitation that needs to be addressed. The sensor dataset had data only on the count of at least one data packet exchange within a 20-second window but not the exact duration of the contacts. In this study, to calculate IPS and match the unit to the diary, we assumed that the at least one data packet exchange indicates the 20-second contacts. However, this might not be accurate for some cases. For example, if the data packet exchange only occurs in 1 second within a 20-second window because they only passed by each other, this will still be counted as 20-second contacts. In addition to the sensor dataset, the diary dataset had contact duration data in a categorical format which the longest category was more than 4 hours. As household members spent a long time together, many participants reported contact duration as more than 4 hours; which in reality, could be substantially different duration such as 5 hours and 14 hours, and could be introducing bias in the current analysis.

4.3 Strengths

As the wearable sensors are relatively new technology to measure social contacts, there are not many studies done to compare and validate the measurement especially in the household settings. Therefore, this study adds an insight into how the sensor measurement performs in comparison with the diary measurement. Previous literature focused on the settings outside of household and in developed countries, thus, this study is novel in terms of comparing the diary and sensor in a household in resource-limited settings. As infants spend large amounts of time with household members, it is critical that this study examined the contact pattern using two measurements and compared them. This study can contribute to expanding our understanding of how to measure infants' contact patterns.

4.4 Comparison with literature

The number of contacts reported in the diary and sensor were similar overall as the median values were mostly the same and individual level difference in number of contacts also showed the highest density at 0. A previous study conducted at middle school reported higher number of contacts in sensor compared to survey which does not align completely with our results[21]. This could be due to the previous study looked at lunch time and class time which have a much higher number of contacts than household contacts. Another previous study found that nodal degree distribution was one higher for the sensor for the raw dataset, but after removing the short duration contacts, the degree distribution was similar to the survey measurements[18]. As the household contacts recorded in this study tended to be long duration mostly, we can say that our results that showed the similarity in number of contacts between two measurements aligns with the previous study.

Comparison contact matrix revealed that diary generally reported higher number of contacts compared to the sensor, especially for adults age groups. This is contradictory to the previous study which found a much higher number of contacts reported by sensors compared to diary[17]. The higher number in diary measurements could be due to either participants not wearing sensors or diary overreporting such as counting same people multiple times. Diary measurements tended to capture higher age-specific mean number of contacts for the children-children and children-parents contacts which tended to have longer duration of contacts. This suggests that although the two measurements reported similar number of contacts, diary tended to capture the contacts that had longer duration which was most likely easy for the participants to remember the contact events compared to short duration. This follows the results from a previous study which raised a point that diary tended to miss contacts with short duration[10,17].

Our study found that 48.8% of the contacts were reported in both measurements, which is higher than the previous study that reported 191 concordant report, 407 reports by sensor only, and 104 reports by diary only[10]. However, 87% of the contacts that were recorded only by sensor in the previous study had a duration of one minute or less, indicating that it was not considered as a contact by the diary definition. After stratifying the contacts by the duration, the congruency of the contacts of 15-60 minutes reported by both measurements was 93.8% in the previous study. Our study focused on the household contacts that tended to be longer than 15 minutes, but the congruency was only about 66%. This could be due to participants not wearing sensors at certain times, not wearing them correctly, or any other reasons that could potentially miss the contacts in the sensor measurement.

4.5 Public health implications

By comparing the characteristics of the contacts in the two measurements, we can suggest which measurements most likely report certain types of contacts and thus, know the advantages of each measurement. By understanding the advantages and disadvantages of each measurement, we would be able to correctly employ the suitable measurement depending on the study aim and settings in the future study. For example, this study highlighted that the contact diary was not useful in measuring the duration of contact with infants because most of the contacts were more than 4 hours and could not report how many hours they actually contacted with infants. On the other hand, sensors captured the different duration of contacts in each age group with the infants, which seemed to represent the actual household contact patterns. As each contact in household settings tends to be longer, this study opens up the potential of sensors in capturing the actual duration of contacts which could not be captured in the diary. However, this study also showed that sensors missed many data that had inconsistent data or no data, and this could result in bias if future study only use the sensor measurements.

For the future study, we would like to check the original data for any misclassification of household contacts, to better identify the contacted person in the diary. Then, comparing the characteristics of the contacts that were reported in both diary and sensors, and the contacts that were reported only in one of the measurements would add value to this study by providing more insights for the characteristics of contacts that were more likely to be reported in certain measurement. Currently, as we could not identify half of the contacts in the diary and lost large amount of data from sensors as well, conducting this type of analysis might not capture the accurate characteristics of the contacts. Therefore, we presented a preliminary result as a supplemental material showing the age distribution of the contacts reported in both measurements, only in diary, and only in sensor that showed the potential future study direction (Figure S4). Additional characteristics such as household member relationships and contact duration are also suggested to be analyzed.

5 Supplementary materials

Table S1: Characteristics of all diary participants

	Overall, N = 553	**Site**	
		Rural, N = 298	**Urban**, N = 255
Sex			
Female	324 (59%)	173 (58%)	151 (59%)
Male	227 (41%)	124 (42%)	103 (41%)
Unknown	2	1	1
Participant age			
<6mo	41 (7%)	27 (9%)	14 (5%)
6-11mo	48 (9%)	23 (8%)	25 (10%)
1-4y	78 (14%)	39 (13%)	39 (15%)
5-9y	76 (14%)	50 (17%)	26 (10%)
10-14y	69 (12%)	40 (13%)	29 (11%)
15-19y	40 (7%)	24 (8%)	16 (6%)

20-29y	95 (17%)	44 (15%)	51 (20%)
30-39y	51 (9%)	26 (9%)	25 (10%)
40-59y	40 (7%)	18 (6%)	22 (9%)
60+y	15 (3%)	7 (2%)	8 (3%)
Able to read and write	265 (48%)	122 (41%)	143 (56%)
Currently enrolled in school	170 (32%)	104 (36%)	66 (27%)
Unknown	23	13	10
Occupation			
Child	89 (20%)	50 (20%)	39 (19%)
Unemployed	99 (22%)	66 (27%)	33 (16%)
Student	143 (31%)	81 (33%)	62 (30%)
Homemaker	15 (3%)	3 (1%)	12 (6%)
Casual laborer	17 (4%)	8 (3%)	9 (4%)
Farmer	21 (5%)	21 (9%)	0 (0%)
Business person	26 (6%)	3 (1%)	23 (11%)
Office worker	31 (7%)	5 (2%)	26 (13%)
Retired	1 (0%)	0 (0%)	1 (0%)
Other	12 (3%)	10 (4%)	2 (1%)
Unknown	99	51	48
Acute gastroenteritis (diarrhea)	4 (1%)	1 (0%)	3 (1%)
Acute respiratory infection			
No symptom	468 (85%)	241 (81%)	227 (89%)
>1 symptom	85 (15%)	57 (19%)	28 (11%)

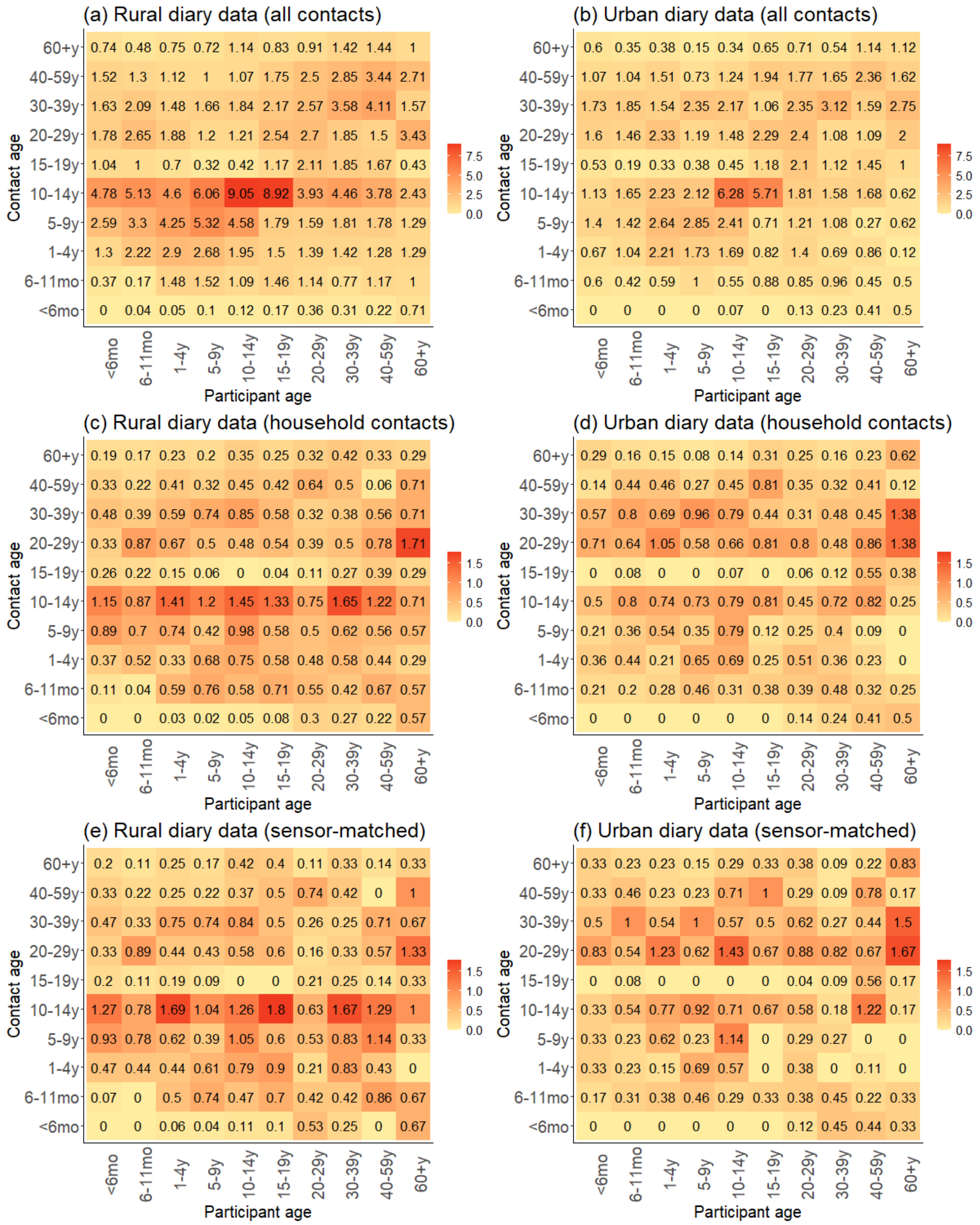

Figure S1: Contact matrix of diary dataset. Panel (a) shows the contact matrix of all the contacts in rural settings, including non-household and household contacts. Panel (b) shows the contact matrix of all the contacts in urban settings, including non-household and household contacts. Panel (c) shows the contact matrix of all the household contacts in rural settings. Panel (d) shows the contact matrix of all the household contacts in urban settings. Panel (e) shows the contact matrix of all the sensor-matched household contacts in rural settings. Panel (f) shows the contact matrix of all the sensor-matched household contacts in urban settings.

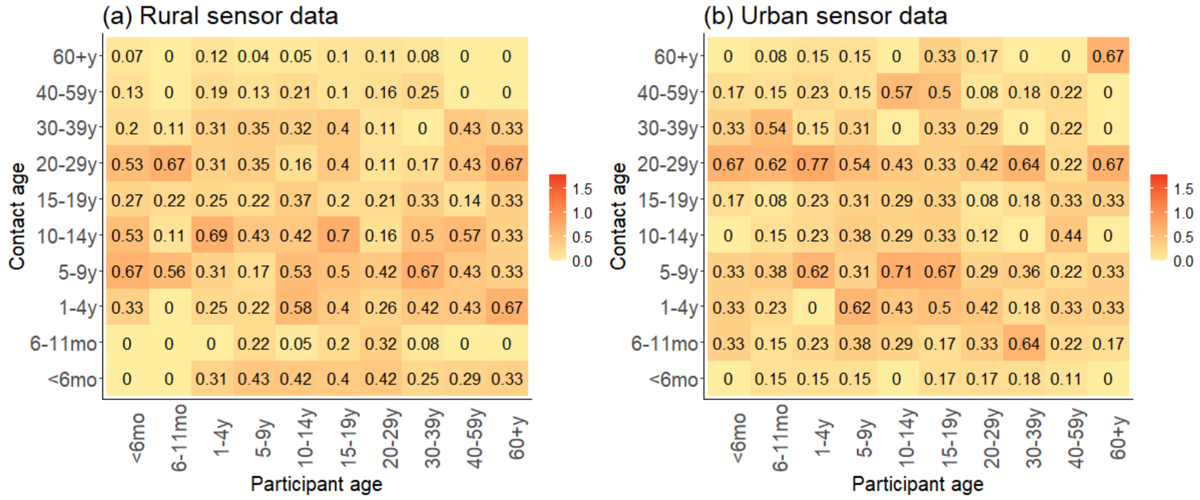

Figure S2: Contact matrix of sensor dataset. Panel (a) shows the contact matrix of sensor dataset in rural settings. Panel (b) shows the contact matrix of sensor dataset in urban settings.

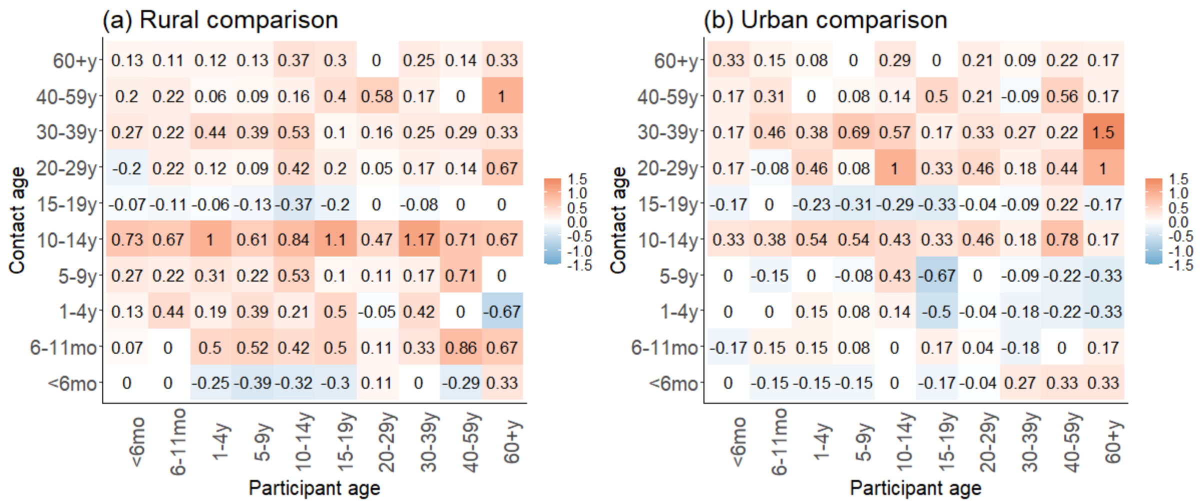

Figure S3: Contact matrix of comparison between diary and sensor dataset. Red color indicates higher age-specific average number of contacts in diary and blue indicates higher age-specific number of contacts in sensor and white color indicates no difference. Panel (a) shows the contact matrix of the difference in age-specific average number of contacts in rural settings. Panel (b) shows the contact matrix of the difference in age-specific average number of contacts in urban settings.

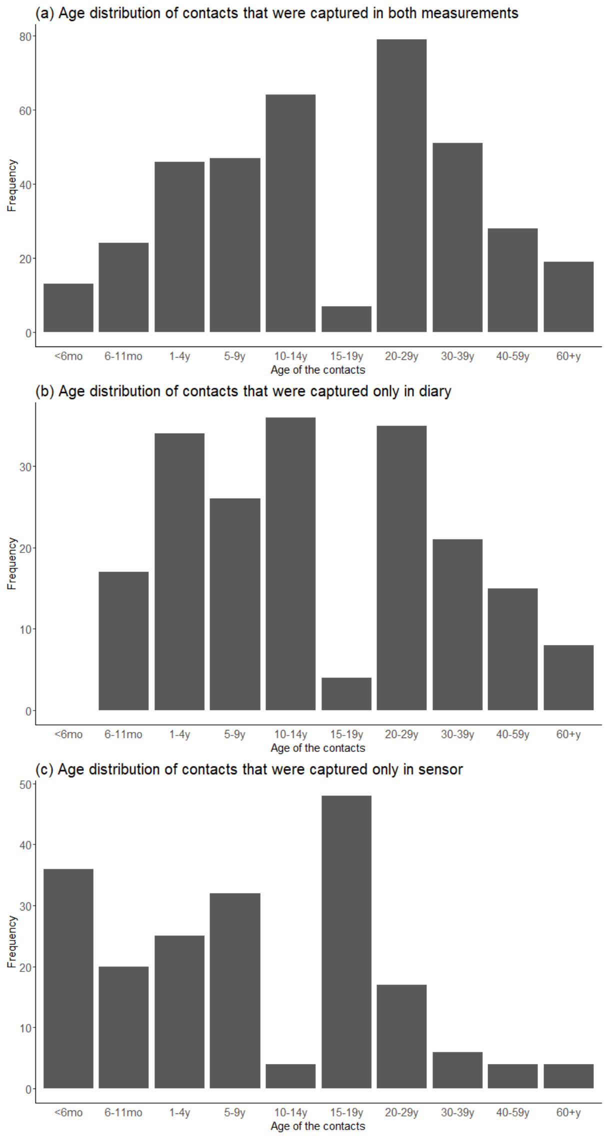

Figure S4: Comparison of the age distribution among the contacts reported in both measurements, only in diary, and only in sensor

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