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Measuring naturalistic proximity as a window into caregiver–child interaction patterns

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Abstract
The interactions most supportive of positive child development take place in moments of close contact with others. In the earliest years of life, a child's caregivers are the primary partners in these important interactions. Little is known about the patterns of real-life physical interactions between children and their caregivers, in part due to an inability to measure these interactions as they occur in real time. We have developed a wearable, infrastructure-free device (TotTag) used to dynamically and unobtrusively measure physical proximity between children and caregivers in real time. We present a case-study illustration of the TotTag with data collected over two (12-hour) days each from two families: a family of four (30-month-old son, 61-month-old daughter, 37-year-old father, 37-year-old mother), and a family of three (12-month-old daughter, 35-year-old-father, 33-year-old mother). We explored patterns of proximity within each parent–child dyad and whether close proximity would indicate periods in which increased opportunity for developmentally critical interactions occur. Each child also wore a widely used wearable audio recording device (LENA) to collect time-synced linguistic input. Descriptive analyses reveal wide variability in caregiver–child proximity both within and across dyads, and that the amount of time spent in close proximity with a caregiver is associated with the number of adult words and conversational turns to which a child was exposed. This suggests that variations in proximity are linked to—though, critically, not synonymous with—the quantity of a child's exposure to adult language. Potential implications for deepening the understanding of early caregiver–child interactions are discussed.

Keywords Proximity · Parent–child interaction · Ecological · Wearable · TotTag

Introduction

Early environmental experiences have a profound and lasting impact on children's development (Fox et al., 2010; Fraley et al., 2013), setting in motion developmental cascades (Masten & Cicchetti, 2010) that shape functioning and abilities across the life-course. Here, we focus on a critical domain of early experience that has received relatively little attention in the study of human development, given its survival value: children's physical proximity to a caregiver. Much of our understanding of the role of caregiver proximity in promoting healthy development comes from nonhuman animal studies, human species-atypical cases of psychosocial deprivation in children reared in institutions, or laboratory-based microanalysis of caregiver–child interactions. To advance understanding of how variations in early experience shape development, it is essential to study species-typical patterns in children who are exposed to normative variation in these experiences along a continuum ranging from neglect to enrichment (King et al., 2019) and to observe these patterns as they unfold naturally. Herein, we introduce and provide an initial illustration of the TotTag—a novel tool for measuring natural patterns of physical proximity between children and caregivers. We propose that observing patterns of caregiver–child proximity as they unfold in real time and in a family's natural contexts (e.g.,

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outside of the laboratory setting) provides a novel perspective on the early caregiving environment and fills an important gap by addressing the need for more ecologically valid approaches to our understanding of children's early experiences (de Barbaro, 2019; Rogoff et al., 2018).

Caregiver proximity

Across mammalian species, physical proximity to one's caregiver is necessary for survival. In humans, infants are completely dependent on their caregivers for safety and instrumental care needs. Not only do caregivers physically protect their offspring, they are the gatekeepers for the infant's experience with the world. The relationship between caregiver and child serves as the primary source of experience-dependent learning in early development (Bowlby, 1982)—the caregiver is responsible for providing the child with stimulation across domains. The types of interactions that are most supportive of positive socioemotional and cognitive development, those that are responsive and reciprocal such as observing facial expressions and engaging in back-and-forth conversations, take place when caregiver and child are physically close to one another. Insufficient stimulation and nurturance during the critical early years of life disrupts experience-dependent development (De Bellis, 2001; Greenough et al., 1987; McLaughlin et al., 2017), and thus can have far-reaching negative consequences.

There is a large body of research highlighting the association between contact with a parent or caregiver and functioning. In the earliest work on the effects of the early environment using animal models, researchers found that laboratory rodents placed in an enriched environment performed better in terms of spatial processing and memory than rodents in a standard and comparatively deprived laboratory environment (Hebb, 1947). Further, human children who are raised in deprived early environments characterized by low cognitive and social stimulation (e.g., children raised in orphanages) exhibit developmental problems across domains (Nelson et al., 2014).

Addressing a gap in knowledge

Much of what we know about the effects of being *deprived* of close contact with a caregiver comes from either studies of rodents and nonhuman primates (Brett et al., 2015) or extreme cases of psychosocial deprivation in human children (Bakermans-Kranenburg et al., 2011; Nelson et al., 2007; Rutter et al., 2010). Likewise, while laboratory-based microanalysis of parent–child interactions gives insights into potential *mechanisms* for the link between the presence of a caregiver and healthy child development, these studies cannot provide a broad-lens view of the type and amount of interactions a child is likely to encounter over the course of a day, week, or year. Further, these studies are limited to examining variation only at the closest end of the spectrum of caregiver proximity. To advance understanding of how variation in early experience shapes development, it is essential to study children who experience normative variation in these experiences along the full continuum ranging from neglect to enrichment (King et al., 2019).

Current techniques for assessing variability in child–caregiver interactions are limited in their ability to provide insight into *in vivo* proximity patterns. Self-report measures are often susceptible to biases (Bennetts et al., 2016), and rarely can caregivers provide sufficient detail regarding their interactions with their children. Both in-laboratory and in-home observations, either with in-person experimenters or the use of cameras, suffer from "performance effects" or "demand characteristics," wherein caregivers are likely to be on their best behavior while being observed by a third party (Gardner, 2000; Tamis-LeMonda et al., 2017). Observational measures are also incredibly costly in terms of the time required to train raters, code hours of recordings, and assess reliability to obtain data for studies with even relatively small sample sizes. The importance of studying children's behavior and experiences in their natural contexts has often been echoed by scientists over many decades (Bronfenbrenner, 1977; de Barbaro, 2019; Rogoff, 2003; Rogoff et al., 2018; Tamis-LeMonda et al., 2017), and the limitations to current methodologies highlight the importance of identifying novel ways to capture variation in the early environment that may be incorporated into multimodal assessment approaches. With advances in technology, particularly in wearable devices, we can overcome a significant "blind spot" in our understanding of early experience (de Barbaro, 2019).

Ecologically valid measures of real-world interactions between caregivers and children can provide information that is unbiased by the laboratory environment or by performative effects caused by in-person observers at home visits. Two examples which have proven useful include the use of first-person perspective video cameras to record parent–child interactions in the home (Lee et al., 2017) and the LENA (Language Environment Analysis) wearable digital language processor (Ford et al., 2008), which produces all-day recordings of the child's language environment. While both have proven fruitful in capturing variation in parenting behavior not otherwise seen when an observer is present, the former method requires many hours of manual coding and, currently, we have no similar method to measure parent–child proximity, or physical closeness.

The current project addresses this significant methodological gap by introducing the TotTag (Biri et al., 2020), a wearable device used to dynamically and unobtrusively measure physical proximity between children and caregivers throughout the day. The TotTag uses time-of-flight technology to assess the distance between device wearers in real time, measuring distance based on the time difference between a signal emission and return after being responded to by another device. Critically, the TotTag system is infrastructure-free, allowing for proximity between wearers to be continuously measured regardless of location (i.e., inside or outside of the home throughout the day). There is a growing body of research using wearable sensors designed for infrastructure-free environments to measure physical proximity between individuals—systems built on infrared (Starnini et al., 2017), radio-frequency identification (RFID; Cattuto et al., 2010; Olguín Olguín et al., 2009; Ozella et al., 2018; Stehlé et al., 2013), Bluetooth (Aharony et al., 2011; Montanari et al., 2017) or custom radio signals (Migliano et al., 2017; Min et al., 2014). However, these systems are almost exclusively limited to binary proximity detection and often limited to measuring face-to-face contact, rather than high fidelity ranging of proximity at 360 degrees. Extending beyond face-to-face measurement is an important feature for assessing parent–child proximity, as children and their caregivers may spend time in close proximity that is not face-to-face, yet that physical closeness may still serve an important function in their relationship. Biri et al. (2020) provide detailed information about the comparative benefits of the SociTrack methodology utilized by the TotTag. In short, the TotTag's novel technology allows for the observation of patterns of caregiver–child proximity as they unfold in real time, in a family's natural contexts (e.g., outside of the laboratory setting), with continuous proximity measurement (i.e., how far two devices are from each other as opposed to a binary cutoff of within close-range or not) at all angles.

Ecologically valid assessments of child–caregiver proximity have the potential to obtain information not previously available relevant to a host of questions in developmental science, human ecology, family relationships, developmental psychopathology, and related areas of research. For example, an examination of face-to-face contact patterns in families with infants aimed at understanding disease transmission showed significant variability within and across families, and links between feeding patterns and infant contact with caregivers (Ozella et al., 2018). However, as noted above, the contact-sensing device used in this study was limited to binary detections of face-to-face interactions and only assessed within the home. In the present study we report a descriptive overview of the patterns of caregiver–child proximity as assessed via the TotTags with data collected from two families. Proximity was captured dynamically; recorded as continuous distance measurements at 360 degrees as interactions occurred in real time, both inside and outside of the home. Our primary aim is to provide an initial illustration of this novel measurement technology, setting the foundation for future research to examine patterns across time and development and between families.

Given that ecological assessments of children's experiences may be most rich in the context of multimodal assessments, capturing more than one domain of potential enrichment or stimulation, we compared proximity data from the TotTag devices with simultaneously collected language exposure data recorded using LENA digital language processors (DLPs) worn by the children. Several recent studies have compared LENA recordings with data on children's physical location (Altman et al., 2020; Irvin, Crutchfield, Greenwood, Kearns, & Buzhardt, 2017a; Irvin, Crutchfield, Greenwood, Simpson, et al., 2017b; Little et al., 2019; Little & Irvin, 2018; Sangwan et al., 2015), providing insight into how language exposure varies depending on where children are in their environment and deriving new ways to assess social interactions. However, the location tracking systems utilized in these studies either restrict data collection to a single indoor location due to necessary infrastructure and calibration (e.g., Irvin, Crutchfield, Greenwood, Kearns, & Buzhardt, 2017a), or are limited in the precision of location identification (e.g., Little et al., 2019). The TotTag addresses these limitations by including being infrastructure-free and providing precise continuous ranging. We examined the association between caregiver–child proximity and language exposure, exploring whether measurements corresponding to close proximity between child and caregiver would indicate periods in which increased opportunity for developmentally critical interactions occur (i.e., greater language exposure), whereas measurements corresponding to greater caregiver–child distance would indicate periods with limited to no interaction. A significant association with large effect size would suggest that moments of close proximity are almost always comprised of verbal interactions of some type. In other words, that measurement of physical proximity and language exposure provide redundant information about a child's experiences with their caregiver. Alternatively, a small to medium effect for the link between proximity and language exposure would suggest that while these two modes of caregiving input can operate in concert, they represent unique processes within the caregiver–child relationship. This would support the potential for each to provide complementary information about a child's caregiving experiences. Due to the case-study nature of the data presented, it is important to note that this study is intended primarily as an initial validation and illustration of the TotTag rather than an empirical examination of generalizable patterns in caregiver–child proximity.

Method

Participants

Data were collected from repeated measurement occasions within two families. The first family, hereafter referred to as Family 1, consisted of two caregivers (mother [author KLH] and father, both age 37 years) and two children (one female aged 61 months and one male aged 30 months). The second family, hereafter referred to as Family 2 consisted of two caregivers (mother [author VCS], age 33 years, and father, age 35 years) and one child (female; age 12 months). Both families spoke only English, all individuals were identified as White, non-Hispanic, all four caregivers had graduate degrees, and no child was diagnosed with a developmental disorder. The mothers provided informed consent on behalf of themselves and the children. The fathers provided informed consent for themselves.

Procedures

The participating families were provided with one TotTag for each family member and two LENA DLPs for each child. The TotTags were worn by the caregivers in the pocket of a running belt or pants pocket, while the children wore both the TotTag and LENA DLP in a specialized vest with front pockets fitted for each device (Fig. 1). The vests were custom-made to accommodate both the LENA and TotTag devices, but were modeled after the LENA vests to ensure the LENA DLP was positioned an appropriate distance from the child's mouth. After each day of recording, data were offloaded from each device and they were set to charge overnight. Data collection for each family occurred over two consecutive weekend days. Participants were instructed to turn each family member's devices on and begin wearing and recording as soon as they woke up in the morning and to record continuously until the children were put to bed. To provide further validity checks of the proximity measurements and to provide context for the data, the parents were also asked to report on their activities during recording days in two ways. First, they were provided with an activity log on which to keep track of each family member's activities over the course of the day in 15-minute increments. In addition to the activity logs, each parent was sent text messages throughout each day (an experience sampling method) prompting them to complete a brief questionnaire about their current location and proximity to each family member.

Fig. 1 Custom vests for children to wear both the LENA DLP (top pocket) and the TotTag (bottom pocket). Pockets have snap closures to secure the devices.

Equipment and measures

Proximity measurement via the TotTag

TotTags are small (78 mm x 48 mm x 20 mm; 58 g), open-source (https://github.com/lab11/socitrack), wearable devices that aim to provide proximity data using ultra-wideband (UWB) radio signals. The device is entirely wireless and operates in an infrastructure-free fashion whereby all TotTag devices in a similar area (approximately 98 ft [30 m]) form their own ad-hoc network without requiring supporting stationary base stations or other instrumentation of measurement spaces. The enclosure is designed to meet Ingress Protection IP54 standards (i.e., protected against small particles and liquid splashes). The embedded hardware comprises two commercially available microcontroller units, a Bluetooth radio for connectivity, a UWB radio for ranging, and an SD card slot for data storage (Fig. 2). The basic ranging principle is to measure the time-of-flight of radio packets between devices. As radio waves travel at the speed of light (i.e., 1 ns ≈ 30 cm), the accuracy of the distance estimate is almost entirely controlled by the accuracy of the time-of-flight estimate. This is the purpose of the UWB radio, which can estimate signal arrival time with sub-nanosecond precision. For timekeeping, the TotTags include a real-time clock with a dedicated, independent power supply. This device tracks time with approximately 2 ppm accuracy, which allows for a maximum drift below 200 ms/day. The TotTags utilize a 1200 mAh battery.

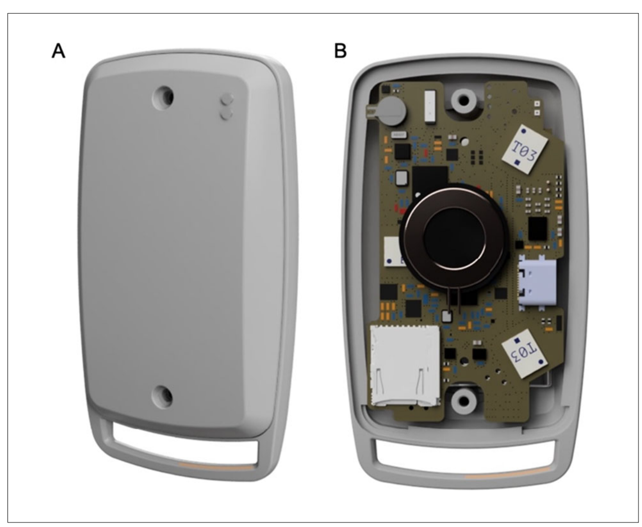

Fig. 2 3D rendering of the TotTag case exterior (A) and interior hardware (B).

Battery life can range from approximately one day to several days, depending, in part, on the number of nodes in a network. For the current study, to ensure full charges for each day of recording, families were instructed to charge the TotTags overnight after each day of recording.

TotTag distance measurement is based on the SociTrack methodology (Biri et al., 2020), which uses multiple UWB radio channels and three distinct antennas to provide significant signal diversity to improve the accuracy of the ranging measurements and to increase the robustness of network communications in real-world environments. The longest ranges recorded to date were ~200 ft (~60 m) in unobstructed scenarios, with more consistent ranging for indoor line-of-sight scenarios within 65–100 ft (20–30 m). The radios exhibit reasonable penetration capacity for obstructions (i.e., through drywall, through one body; not through metal walls or a large crowd). For the purposes of the current study, we censored proximity readings above 20 ft (i.e., all readings > 20 ft were considered "out of range" and removed from analysis). This decision was based on the focus for the current study on the time caregiver–child dyads spent within touching distance of each other (defined as ≤ 3 ft) as compared to time spent in the same location, but not necessarily close or interacting. The specific distance of 20 ft was chosen as a proxy cutoff for members of a dyad being in the same room, based on the average living room size in modern homes in the United States (Emrath, 2013).

The other core operation of TotTag devices is efficient discovery of other TotTags that are nearby. Members of a network (e.g., family members each wearing a TotTag) may come and go throughout the day and may travel together or separately outside of the home environment. To date, UWB-only systems all require the use of wall-powered infrastructure to support discovery and coordination of UWB network members. This is the primary purpose of including the additional Bluetooth radio; it requires 20–30 times less energy to communicate with Bluetooth than with UWB. This allows the Bluetooth radio to handle the mobility of cohort members without sacrificing the battery life of the TotTag device. To deliver proximity measurements, the TotTag system continuously performs "neighbor discovery" to form ad-hoc groups of nearby devices. These groups then perform recurring ranging events, which capture multiple time-of-flight samples between every pair of devices. The statistical median of the resulting data is taken as the most likely "true range" between any two devices. In established groups, ranging events take place once per second, with the results being stored and timestamped on an external SD card for later download and analysis.

After recording, data were processed offline using Python scripts (developed by author DAR, available at https://github.com/lab11/socitrack). First, measurements from each pair in a dyad were synced according to timestamp and averaged. Second, any measurements outside of the specified window of analysis were removed. Next, to mitigate the impacts of random, brief fluctuations in the data, a moving average was calculated using a ±3-second window. During this process, for any gaps in the data which were identified as greater than 3 seconds the window was truncated so as not to span the gap, thus avoiding introducing new errors. Lastly, the proximity measurements were converted from mm to ft to aid in interpretation. This process results in a data set comprised of a single proximity value (ft) for each dyad for every second the devices detected each other.

Prior to data collection with the participating families, a series of "ground-truth" tests were conducted to establish baseline validity. Proximity readings from four TotTags were compared with pre-measured distances of 1-, 3-, and 6-ft squares. Readings were collected at each specified distance for 5 minutes at each of two trials. Table 1 presents the mean and standard deviation of the measurements collected from those device pairs which formed the perimeter of the square at each distance for each trial. These results suggest valid measurement of the physical distance between TotTags at relatively close range. For a more in-depth report of the validity and fidelity of the SociTrack technology which the TotTags deploy, please see Biri et al., 2020.

Activity logs and momentary assessments

Each family was provided with activity logs on which to keep track of each family member's activities over the course of each day in 15-minute increments. The parents were asked specifically to note if family members were engaging in activities together or separately, the type of activity in which they were engaged, and the general location of the activity (i.e., a neighborhood walk, breakfast in the kitchen, playing in the yard). Each parent was also sent 12 text messages throughout each day prompting them to complete a brief questionnaire about their current location and proximity to each family member. The questionnaire asked them to report, at the time of survey completion, where they currently were (e.g., in the kitchen, in the yard, at the grocery store, in the car), who they were within arm's reach—or touching distance—of, and who they were in the same room as but not within arm's reach.

Table 1 Summary statistics from TotTag ground-truth testing

Measured distance	TotTag Trial 1		TotTag Trial 2	
	Mean	*SD*	Mean	*SD*
1 ft	1.03	0.34	0.91	0.35
3 ft	2.73	1.03	2.81	1.01
6 ft	6.52	1.58	6.51	1.03

These questionnaires, collected using REDCap electronic data capture tools (Harris et al., 2009, 2019), were sent at quasi-random intervals (such that they would not occur within less than 30 minutes of the previous time point and that the mother and father would not receive surveys at the same time). Timestamps were logged noting when the questionnaire was completed, down to the minute.

Language environment measurement via the LENA DLP

LENA DLPs were used to assess the home language environment. Similar to the TotTag, the LENA DLP contains a real-time clock with a dedicated power supply, although information on potential drift in the clock is not provided in the technical reports. Using the LENA software (Xu et al., 2009), we extracted the number of adult words spoken near the child as well as the number of conversational turns each child engaged in summed over 5-minute segments throughout each day. Conversational turns are defined as the number of speaker alternations that take place between the child wearing the LENA DLP and an adult speaker, wherein each speaker's vocalizations are separated by no more than 5 seconds of silence. To match the adult word values with the dyadic proximity measurements, this was calculated separately for adult words spoken by a female (i.e., mother) and adult words spoken by a male (i.e., father). To distinguish between male and female voices, the LENA software employs a series of iterative modeling algorithms to separate the audio stream into short segments. These segments are then preliminarily classified into one of eight categories (including adult male and adult female) by identifying the model with which the acoustic features of the segment have the best statistical fit (Gray et al., 2007). Further, while the LENA software separately segments and categorizes speech that is near and clear to the child and that which is overheard farther away from the child, the counts of adult words used herein comprise only near and clear speech. Speech that is far away from the child is much less likely to be directed at, or intended to be heard by, the child and therefore would not constitute stimulating and supportive input. Recent validations of the LENA software against manually coded speech segments indicate the accuracy of the software-generated categorizations (Bulgarelli & Bergelson, 2020; VanDam & Silbert, 2016); however, there is evidence that the automated measure of adult word count is more reliable than conversational turn counts (Cristia et al., 2020).

Data analysis

We conducted analyses in R and RStudio (Version 4.0.2; R Core Team, 2020). Analysis scripts and data are available at https://github.com/vanderbiltsealab/tottag_methods. The recordings took place over approximately 12- to 13-hour days. For the purpose of comparison across the two recording days within each family and across the two families and to ensure each dyad had complete data, recordings were trimmed to 12 hours, shortly following the latest individual wake-up time and shortly following the children's bedtime (8:00 AM to 8:00 PM each day for Family 1 and 7:00 AM to 7:00 PM each day for Family 2). To illustrate the variability in proximity, we first plotted the continuous second-by-second proximity readings recorded by the TotTags for each caregiver–child dyad on each day of recording. To quantify this variability, several summary statistics were calculated for each dyad. The amount of time spent within touching distance was operationalized as the sum of 1-second readings within 3 ft. Given the standard deviation of measurements observed in the ground-truth testing, this may be a conservative estimate of the true amount of time spent within touching distance. We then calculated the proportion of the 12-hour day that each dyad spent within touching distance (proximity $\leq$ 3 ft) as well as the proportion of the day that a dyad was within touching distance out of the total time they spent "in range" of each other, the amount of time the devices were close enough to detect one another. The distance detected to be "in range" can vary widely depending on whether the devices are in line of sight or are obstructed by obstacles (distance and obstacle type both affect ability for devices to be "in range"). As noted above, for the current study all readings > 20 ft were considered "out of range" and removed from analysis, as a proxy for being in the same room. Detecting the amount of time in close contact out of the amount of time "in range" provides a metric (i.e., proportion) that can be interpreted as how much time a dyad spent in close contact out of the total time spent together. The primary focus for this illustration was on the six caregiver–child dyads across the two families; see the supplementary materials for results from the remaining dyads.

To examine "real-world" validity of the proximity measurements, we compared these with the activity logs and the momentary assessments completed by the caregivers. Specifically, for comparison with the momentary assessments, the average proximity for each relevant dyad was calculated within the 1-minute window preceding the completion of each questionnaire. In preliminary testing, a very slight delay was noticed in sending and logging a questionnaire as complete. Averaging proximity over the preceding minute was thus selected given that the questionnaire timestamps were only specified to the minute and not the second, and to account for this slight delay. If the window was based on the mother's report, this was calculated for mother–child and mother–father dyads; and if the window was based on the father's report, this was calculated for father–child and father–mother dyads. These values were then grouped and averaged based on whether the caregiver had categorized that paired family member as being within touching distance or not within touching distance but in the same room. This analysis was conducted on data combined across families.

Lastly, to explore the association between proximity and language exposure, proximity measurements were aggregated in three ways into 5-minute segments and time-locked with the matching 5-minute segments derived from the LENA recordings. Within each 5-minute segment, we calculated (1) average proximity between dyads, (2) the proportion of time that each dyad was within touching distance (≤ 3 ft), and (3) for each child, the proportion of time within each segment that at least one parent was within touching distance. As missing data points, or observations when two TotTags were out of range of each other, would attenuate the estimate of average proximity between a dyad, before calculating average proximity we replaced all "out of range" observations with our a priori maximum value of 20 ft. Five-minute segments for which average proximity was near or at 20 ft can thus be interpreted as periods in which members of a dyad spent most or all of the time apart from or "out of range" of each other. If the TotTags were out of range and provided no proximity data during a segment, the proportion of time a dyad was within touching distance was zero. Correlations between average proximity and adult word count and between proportion of time within touching distance and adult word count were calculated with aggregated data from the two families, but separately for mother–child dyads and female adult words, and father–child dyads and male adult words. Because conversational turn count does not distinguish the gender of the adult speaker, we calculated the correlation between the proportion of time at least one parent (either mother or father, or both) was within touching distance of a child and the number of conversational turns that the child was engaged in. This was also calculated on aggregated data from the two families. All measures derived from the TotTags and LENA DLPs were skewed, either positively due to the preponderance of 0s (proportion of time within touching distance, adult word count, conversational turns) or negatively due to the preponderance of ceiling values (average proximity). As such, we calculated Spearman's correlations. See the supplementary materials for the results of these correlation analyses broken down within each family. Given the limited nature of the data collected, it is important to note the exploratory nature of these analyses.

Results

Observed proximity patterns

Figure 3 illustrates the observed proximity measurements from each caregiver–child dyad on each day of recording. Summary statistics for each day of recording by dyad can be seen in Table 2. On Day 1, of the six caregiver–child dyads, the father–daughter dyad from Family 1 spent the greatest amount of time within touching distance of each other and the father–daughter dyad from Family 2 spent the least amount of time within touching distance of each other. However, out of the time they spent in range with one another, indicating the opportunity to spend time in closer contact, the mother–daughter dyad from Family 2 spent the greatest proportion of that time within touching distance. This value was roughly equal across all dyads on Day 2 except for the mother-daughter dyad from Family 2 who again spent the greatest proportion of time within range also within touching distance; approximately twice that of any other dyad. No dyad spent more than 16% of the full day within touching distance of each other.

Additional dyads

We also examined patterns of proximity between the sibling dyad from Family 1 and the caregiver (mother–father) dyads from both families. Figure S1 illustrates the observed proximity measurements from each additional dyad on each day of recording. As can be seen in Table S1, across both days the sibling dyad in Family 1 spent more time within touching distance of each other than either child did with either caregiver, and as compared to any other dyad across both families. Conversely, the mother–father dyads, in both families, spent the least amount of time within touching distance of each other as compared to any other dyad, except for the Family 2 father–daughter dyad on Day 1.

Validation against activity logs and ecological momentary assessment reports

To provide validation and context for the patterns seen, we compared the continuous data to the activity logs completed by the caregivers. Overall, each recording day for each family included a range of activities both inside and outside of the house and involving different iterations of family members. For Family 1, there is a marked lack of proximity between the son and either caregiver on Day 1 during the period between 12:00 PM and 3:30 PM. During that time the son was reported to be taking a nap and was checked in on by each parent after failing to fall asleep. Also during that time, the mother noted working in her office, and the daughter had a brief nap/quiet time in her bedroom and then was noted to have visited the mother in her office a few times and to have spent time with the father. The greatest proportion of either day that a dyad in Family 1 spent within touching distance of each other was between the father and daughter on Day 1, and they were reported to engage in several longer activities together (a reading lesson and practicing balancing on a bike). For Family 2, there is also a large gap in proximity with either caregiver on both days during the daughter's midday nap, although both caregivers "checked in" on her during her nap on Day 1. There were also several instances where the caregivers traded off primary caretaking duty, as indicated by alternating gaps in

Table 2 Summary statistics of the proximity measurements within each day and caregiver–child dyad

	Caregiver–child dyad					
	Family 1				Family 2	
	Mother–daughter	Mother–son	Father–daughter	Father–son	Mother–daughter	Father–daughter
Day 1						
Time within touching distance (min)	71.27	90.17	115.53	59.60	77.10	25.35
Proportion of day within touching distance	.10	.13	.16	.08	.11	.04
Proportion of time within touching distance over time in range	.39	.44	.36	.26	.60	.33
Day 2						
Time within touching distance (min)	62.02	57.75	43.65	47.58	117.23	40.78
Proportion of day within touching distance	.09	.08	.06	.07	.16	.06
Proportion of time within touching distance over time in range	.21	.26	.25	.25	.57	.28

proximity with their daughter. In the afternoon of Day 1, Family 2 reported time spent at a park during which the daughter repeatedly wandered away from and then circled back to her caregivers.

Of the 96 momentary assessment invitations that were sent to the four caregivers over the 2 days each family recorded (12 invitations each day per caregiver), 92 were completed (each caregiver skipped one report). Seven of these were dropped for being completed outside of the analyzed time window, resulting in 85 usable reports. For each category in each report, there is a possibility of up to six data points for Family 1 and up to four data points for Family 2, as each caregiver reports on each of the other family members' relative location. For all reports when both a caregiver report and proximity data were available (i.e., caregiver responded about the location of a specific other family member and that member's TotTag was detected as in range with the caregiver) the mean and standard deviation of the associated proximity measurements were calculated. These results are presented in Table 3 and may suggest that a wider range may be seen by the parents as being in touching distance than was defined by our a priori calculations (i.e., 3 ft). Alternatively, this may also reflect a change in actual proximity from the time a parent selected a response and the time their response was submitted and received.

Comparing proximity patterns with language exposure

The results of the correlation analyses between proximity measures and language exposure are displayed in Table 4 and scatterplots of the associations can be seen in Figs. 4, 5 and 6. Average proximity during a 5-minute segment was associated with the number of adult words heard for both parent genders, such that closer proximity to their child was associated with their child hearing more adult words. Also for both parent genders, the proportion of time dyads spent within touching distance was significantly and positively associated with the number of adult words heard. The proportion of time at least one parent was within touching distance was also significantly positively correlated with the number of conversational turns, $r(862) = .30$, 95% CI [0.24, 0.36], $p < .001$.

Discussion

The impact of caregiver proximity on children's development is believed to be broad and significant, with effects ranging across various developmental domains and impacting long-term trajectories. However, much of what we know about caregiver proximity comes from research on severe deprivation, using either nonhuman animals or children raised in institutions, or fine-grained analysis of relatively brief laboratory-based interactions. This project introduces a novel method for capturing patterns of caregiver–child proximity as they unfold naturally, filling the need for ecologically valid approaches to our understanding of children's early experiences (de Barbaro, 2019; Rogoff et al., 2018).

Here we present data illustrating three young children's experience of caregiver proximity using TotTag proximity measurement devices. On average, a small proportion of each child's day was spent within touching distance of a caregiver. However, the plots of the continuous data suggest that caregiver–child dyads spent a large portion of each day within 10 ft or so of each other. A qualitative comparison of the proximity data with activity logs provided by the families provided context and validation for the patterns observed. Further validation was provided by a

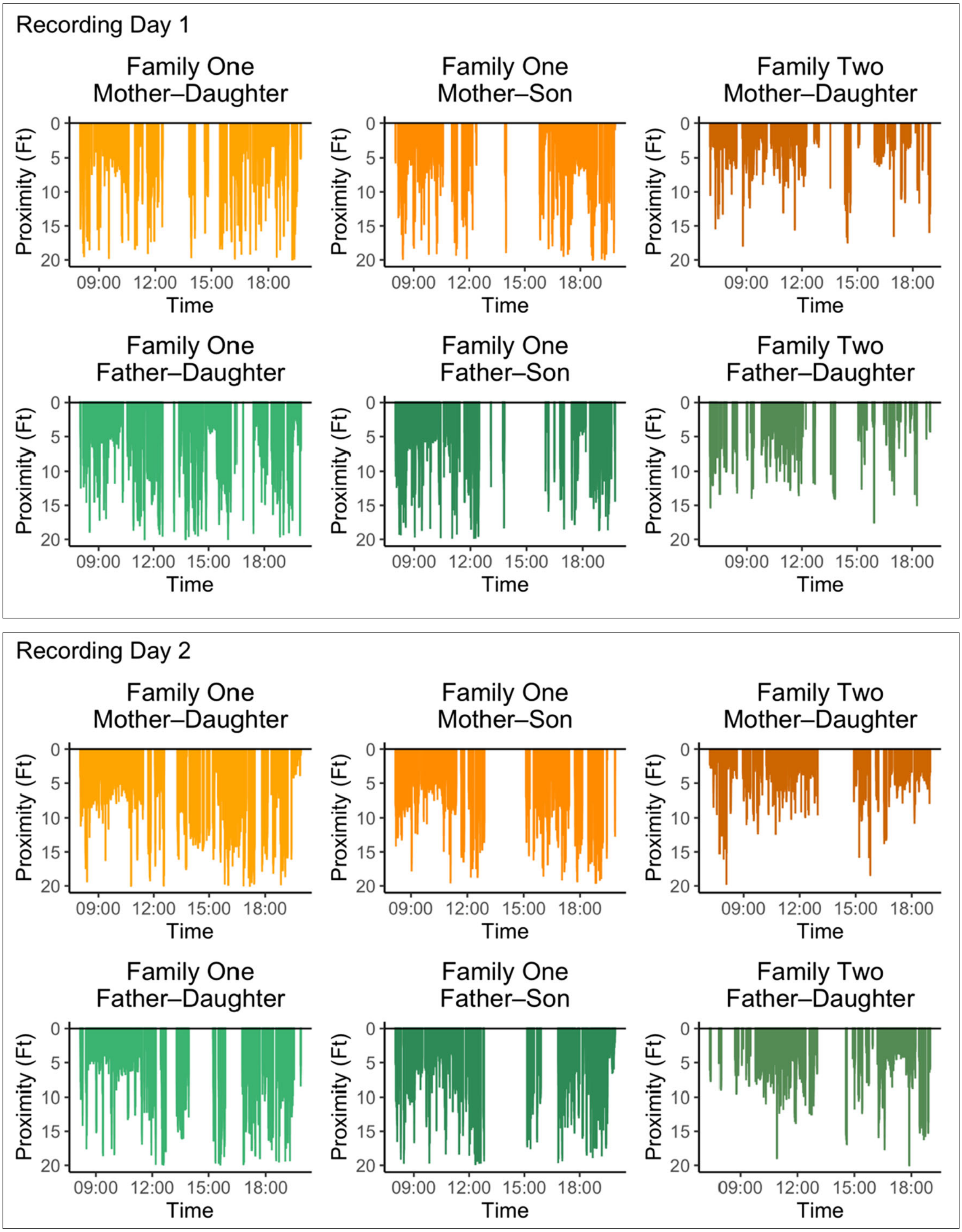

Fig. 3 Observed proximity between caregiver–child dyads on each family's first (top box) and second (bottom box) recording days. Colored bars represent observed proximity (ft) between dyad members at a given point in time (1-second observations), with closest proximity at the top of the *y*-axis and distance between the dyad increasing down the *y*-axis. Plots in orange depict mother–child dyads and plots in green depict father–child dyads. Periods with no data plotted (white space) indicate moments when the dyad was "out of range" of each other.

quantitative comparison with momentary assessments. Parents reported at random intervals which other family members were either within arm's reach or within the same room. Average proximity readings for the matching dyads suggest that the TotTag readings were reliably quantifying proximity between dyad members.

In comparing the TotTag proximity data to the LENA measures of the language environment, we present evidence that

Table 3 Proximity measurements binned and averaged according to caregiver momentary assessments

	N	Mean	*SD*
Within touching distance	54	5.24	3.49
In the same room, not within touching distance	19	6.41	3.95

Note. Mean reflects average proximity measurement corresponding to reports in each category.

closer proximity is indeed indicative of the types of interactions shown to be important for developmental outcomes—in this case, exposure to adult speech and engagement in conversational turns. Should these initial patterns generalize, it would provide evidence that a greater amount of close proximity with caregivers is associated with experiencing higher levels of adult language input. While proximity to a caregiver was, on average, associated with greater linguistic input, this relation was far from interchangeable, as evidenced by a small to medium effect size. Thus, while they may often operate in concert, these two modes of stimulation also seem to operate separately and likely represent unique sources of caregiving input (and unique processes within the caregiver–child relationship). That is, proximity to a caregiver is not equivalent to nor simply a proxy measure of linguistic input. Linguistic input is most likely to occur in instances of close proximity; however, instances of close proximity do not always contain linguistic input. Indeed, one can imagine many scenarios in which a caregiver and child may be proximal to one another, but the child is not receiving linguistic input, such as while both parent and child are separately occupied on tablets or smartphones. An important next step, therefore, is to explore how these two ways of quantifying a child's early experiences are associated in other families and contexts, and to compare predictors and sequelae of each set of measures.

Two limitations of the LENA data should be noted. First, adult word and conversational turn counts are only provided when the algorithm passes a certain threshold of confidence regarding the categorization of a segment as adult speech. As such, adult speech heard from a greater distance is less clear to the recorder and therefore may not be included in the final counts. It is thus possible that the observed association between language exposure and proximity was attenuated, compared to ground truth, at the farther end of the proximity spectrum. Second, while the strength of the associations between proximity and language exposure measured as adult word counts and between proximity and language exposure measured as conversational turns was similar, conversational turns have a documented lower reliability than the measure of adult word count (Cristia et al., 2020). It will thus be important to explore how these different operationalizations of linguistic input compare with proximity in a broader sample. Further, the observed correlations between proximity and language exposure might be impacted by measurement error in either automated measure. Continued work with the TotTag and other *in vivo*-type assessments of children's experiences in their natural environments should aim to triangulate and provide further confidence in our understanding of what is occurring when children are close to and farther apart from their caregivers.

While there is much work indicating that quantity and diversity of adult linguistic input is important for child language development (Bornstein et al., 2020; d'Apice et al., 2019; Hoff, 2003; Huttenlocher, 1998; Huttenlocher et al., 1991, 2007; Pan et al., 2005; Rowe, 2012; Topping et al., 2013). A recent study found that *consistency* of adult linguistic input was a better predictor of psychopathology symptoms in young children (King et al., 2021). Thus, having a caregiver consistently close by may serve a different and uniquely important function than linguistic input in supporting a child's development. It is important to identify methods that comprehensively capture the daily experiences that occur in children's natural environments and to integrate these assessments into a fuller picture of how children's environments vary across families and across periods of development (de Barbaro, 2019). In turn, a vital next step will be to pair ecologically valid measurements of children's natural environments (or lived experience)—such as the TotTag—with reliable assessments of child development across domains. Such work will allow us to better elucidate how children's daily experiences in early life shape developmental outcomes.

Table 4 Spearman correlations between proximity measurements and female or male adult words

	Mother–child dyads			Father–child dyads		
	Female adult words			Male adult words		
	r	95% CI	*p*	*r*	95% CI	*p*
Average proximity	−.23	−.30, −.17	<.001	−.34	−.39, −.28	<.001
Proportion within touching distance	.26	.19, .32	<.001	.33	.27, .39	<.001

Note. *N* = 864 (144 5-minute segments per dyad per day).

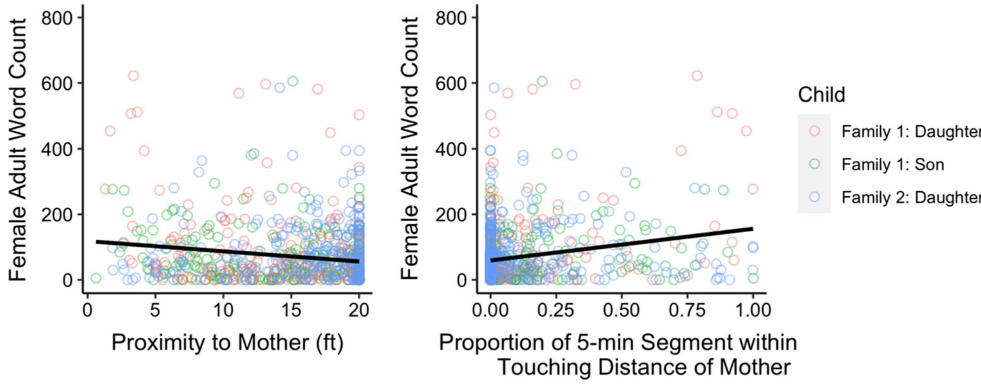

Fig. 4 Associations between proximity and language exposure within mother–child dyads. The *x*-axis in the left plot represents the average mother–child proximity (ft) within each 5-minute segment. The *x*-axis in the right plot represents the proportion of the 5-minute segment the child was within touching distance (3 ft) of their mother. The *y*-axes in both plots represent the sum of estimated female adult words a child heard within each 5-minute segment. Each circle represents one 5-minute segment, and circle color represents the specific child whose data is being illustrated. Black lines represent the slope of the bivariate association.

In addition to a novel insight into caregiver–child interactions, the observed patterns of proximity between the dyads which did not include both a caregiver and a child (i.e., the sibling dyad from Family 1 and the caregiver [mother–father] dyads from both families) provide additional insight into the experiences and dynamics of the family as a whole. For example, we found that the sibling dyad in Family 1 spent the greatest amount of time within touching distance of each other as compared to all other dyads across both families. While many theories of child development focus on the parents and other caregivers as driving forces in shaping the environment and influencing child outcomes (e.g., Attachment Theory: Bowlby, 1982), families can also be thought of as cohesive and dynamic systems (e.g., Belsky et al., 1989). When viewed in this way, each member is seen as playing an important role in shaping the experiences and behavior of each other member, and relationships between other members can impact individuals and other relationships within the family. An important future direction is to examine how sibling relationships, caregiver relationships, and other relationship partners outside of the family context uniquely and collectively shape a child's experiences and development.

In extracting the specific measures of proximity from the raw TotTag recordings, we made several decisions which were driven largely by the intended focus of the current study. Specifically, these were the decisions (1) to censor proximity observations > 20 ft; (2) to bin observations ≤ 3 ft as being within touching distance; and, in matching proximity with language exposure data, (3) to calculate both average proximity for a dyad (per 5-minute segment) and proportion of time a dyad spent within touching distance of each other. Importantly, the continuous proximity measurements captured by the TotTags allow for different analytic decisions to be made which best suit individual project data collection parameters and study goals. The decisions to consider measurements > 20 ft as out of range and measurements ≤ 3 ft as within "touching distance" were intended to allow us to illustrate and compare time dyads spent in the same location, but

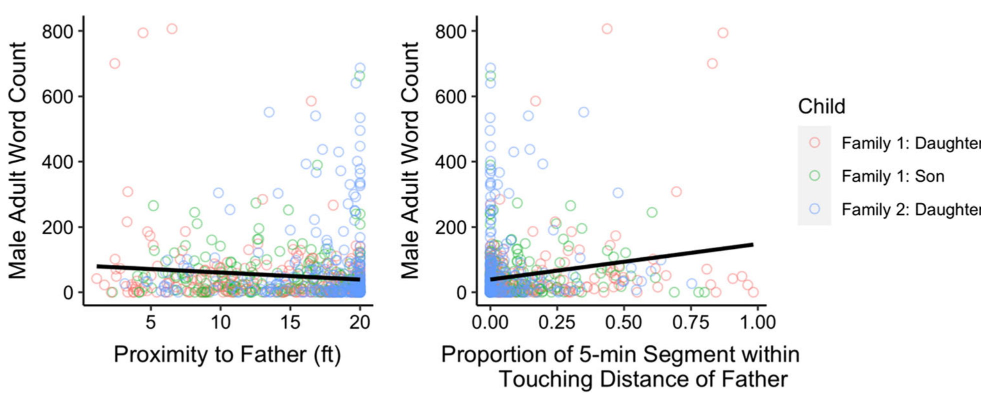

Fig. 5 Associations between proximity and language exposure within father–child dyads. The *x*-axis in the left plot represents the average father–child proximity (ft) within each 5-minute segment. The *x*-axis in the right panel represents the proportion of the 5-minute segment the child was within touching distance (3 ft) of their father. Both *x*-axes represent the sum of estimated male adult words a child heard within each 5-minute segment. Each circle represents one 5-minute segment, and circle color represents the specific child whose data is being illustrated. Black lines represent the slope of the bivariate association.

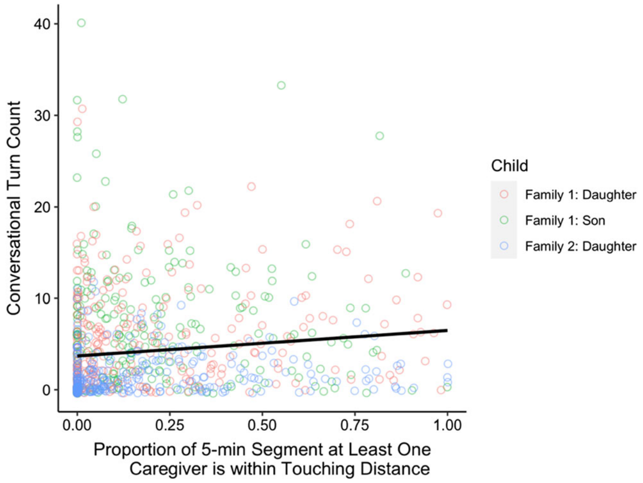

Fig. 6 Association between the proportion of time at least one caregiver was within touching distance and conversational turns. The *x*-axis represents the proportion of the 5-min segment the child was within touching distance of at least one parent. The *y*-axis represents the estimated number of conversational turns the child was engaged in within each 5-minute segment. Each circle represents one 5-minute segment, and circle color represents the specific child whose data is being illustrated. The black line represents the slope of the bivariate association.

not necessarily close or interacting, with time spent in close contact. A cutoff of approximately 3 ft has often been applied in previous proximity-sensing work as indicating meaningful "contact" between individuals (Cattuto et al., 2010; Ozella et al., 2018). However, previous technology is limited by needing to apply that cutoff prior to data collection, whereas the TotTag technology offers the flexibility of applying this cutoff post hoc. Indeed, the results from the momentary assessment analysis suggest that caregivers may view a further distance from their child as being "within touching distance." An important next step for further developing the utility of the TotTag would be to explore how different cutoffs might reflect different kinds of interactions and opportunities for stimulation and input from caregivers for their children, and how these values might differ based on individual (e.g., child's age; developmental needs) and family-level (e.g., cultural background; socioeconomic status) characteristics. The farther range of 20 ft was intended to approximate members of a dyad being in the same room together and was estimated based on the average living room size in modern American homes (Emrath, 2013). The ranging accuracy of the TotTag does decrease with increased distanced and with obstructions to line of sight (Biri et al., 2020); researchers should thus consider where the expected parameters of the space(s) interactions may be taking place and consider whether adjustments should be made to potential censoring values. In the case that the research questions hinge on knowing exact distances greater than the size of a typical room, data collection should be conducted in a space free of obstacles (i.e., outside).

As for our operationalization of proximity within the 5-minute segments (i.e., average proximity and proportion of time within touching distance), we made no a priori assumptions about whether these measures would be independently meaningful. Indeed, in this limited sample, these two measures appeared to operate similarly in terms of their association with linguistic input. When compared at the 5-minute level across all dyads, they are significantly correlated, $r(1203) = -.76$, 95% CI [−.78, −.74], $p < .001$, although not perfectly. Future empirical work is needed to determine the relative utility of one measure over the other. The ability to assess a continuous measure of proximity as opposed to the dichotomized within/outside of touching distance is a significant contribution the TotTag makes to the body of work on mobile proximity sensing. In addition to being limited by binary assessment of proximity, previous work using mobile proximity sensing often only considers contact to have occurred if individuals are "in range" for at least 20 seconds. The time it takes for a young child to, for example, receive a comforting hug from their caregiver and return to independent exploration can take only a few seconds. The TotTag is able to detect changes in proximity on a second-by-second basis. This kind of data supports the application of more complex time series analytic techniques which could make use of the dynamic nature of proximity over time. This will be an important step forward and will lend far greater nuance to our understanding of caregiver–child interactions.

It is important to note that, at this time, there is no clear documentation of what might be considered normative patterns in caregiver–child proximity. Indeed, the "extra" activities asked of the caregivers in the current sample (i.e., keeping an activity diary and responding to periodic surveys via text message) may have distracted the caregivers, altering the natural pattern of interaction with their children (Reed et al., 2017). Further, the data were collected from only two families, both containing unblinded coauthors [KLH and VCS] and are intended primarily as an illustration of the utility of this novel measurement tool. Thus, these findings should provide potential insight into relevant questions for future use with the TotTag rather than making generalizations about patterns to be found across development or between families. Cross-sectional and longitudinal work is needed to develop an understanding of the spectrum of experiences children have in terms of proximity to a caregiver, how these patterns might change over time, and how these trends may help us predict child outcomes. Further, large samples representing families from various socioeconomic and cultural backgrounds, with different constraints on and beliefs shaping caregiver–child interactions, are needed to establish reliable evidence for the existence of, as well as an understanding of variation from, species-typical patterns in caregiver–child proximity. For example, the value placed on the amount of kind of cognitive stimulation perhaps captured by the current measure of language exposure may be a uniquely Western, educated, industrialized, rich, democratic (WEIRD) sentiment (Han, 2020). Also, in non-Western populations, there is evidence for significant cultural differences in parents' beliefs about and practices for providing a stimulating environment for their child, with important implications for child development (Wang et al., 2020; Yue et al., 2019). Thus, it will be imperative to couch our growing understanding of proximity norms within the cultural context in which they are observed and measured. Being infrastructure-free and generating automated measurements (as opposed to requiring human coding of the data), the TotTag is uniquely poised to be usefully deployed in a wide range of settings and to generate the kind of large data sets necessary to identify broad patterns.

The amount of psychosocial stimulation infants and young children receive from their caregivers is linked to their cognitive, linguistic, and socioemotional functioning (Humphreys et al., 2018; McLaughlin et al., 2017; Nelson et al., 2014); as such, time spent in proximity to caregivers in early life is likely to be associated with a broad range of outcomes, including cognition, language, and socioemotional functioning. However, just as positive interactions can occur in close proximity, so too can those characterized as negative interactions (e.g., corporal punishment, physical abuse). Thus, it is important that future studies include characterization of the quality of interactions that occur in close proximity. While the current data are largely descriptive, the TotTag has the potential to inform important ongoing theoretical debates, including (a) identifying both universal and culture-specific aspects of the caregiver–child relationship, (b) which parent/family characteristics explain variance in children's ecologies, (c) how caregiving behaviors change across children's development, and (d) whether different aspects of the caregiving environment (e.g., language input, close proximity) are uniquely linked to different outcomes (e.g., social, emotional, and cognitive).

Conclusion

The TotTag is a novel tool for the ecologically valid assessment of caregiver–child proximity. Observing patterns of caregiver–child proximity as they unfold in real time and in a family's natural contexts (i.e., not in a laboratory setting) provides a novel perspective on the early caregiving environment, filling an important gap in our understanding of children's early experiences. The TotTag is one example where leveraging technological advances in other fields can provide a new window into the continuum of early environments, allowing us to visualize and analyze early life in a new way and advance the study of child development.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.3758/s13428-021-01681-8.

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Declarations

Conflicts of interest/Competing interests No conflicting financial interests exist.

Ethics approval The methodology for this study was approved by the Institutional Review Board at Vanderbilt University #190037.

Consent to participate Informed consent was obtained from both parents.

Open practices statement Analysis scripts and data are available at https://github.com/vanderbiltsealab/tottag_methods; none of the analyses were preregistered.

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