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Feasibility of assessing brain activity using mobile, in-home collection of electroencephalography: methods and analysis

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Abstract

The last decade has seen increased availability of mobile electroencephalography (EEG). These mobile systems enable researchers to conduct data collection "in-context," reducing participant burden and potentially increasing diversity and representation of research samples. Our research team completed in-home data collection from more than 400 twelve-month-old infants from low-income backgrounds using a mobile EEG system. In this paper, we provide methodological and analytic guidance for collecting high-quality, mobile EEG in infants. Specifically, we offer insights and recommendations for equipment selection, data collection, and data analysis, highlighting important considerations for selecting a mobile EEG system. Examples include the size of the recording equipment, electrode type, reference types, and available montages. We also highlight important recommendations surrounding preparing a non-standardized recording environment for EEG collection, obtaining informed consent from parents, instructions for parents during capping and recording, stimuli and task design, training researchers, and monitoring data as it comes in. Additionally, we provide access to the analysis code and demonstrate the robustness of the data from a recent study using this approach, in which 20 artifact-free epochs achieve good internal consistency reliability. Finally, we provide recommendations and publicly available resources for future studies aiming to collect mobile EEG.

KEYWORDS
development, EEG, in-home EEG, mobile EEG, portable EEG

1 | INTRODUCTION

The last decade has seen increased availability and use of mobile electroencephalography (EEG). Mobile EEG data collection is an exciting new frontier for developmental science, as it is likely to allow for the collection of neural activity in novel environments and populations. However, as with most technical advances, there is a learning curve associated with mobile EEG data collection. Additionally, such technical advances need to be piloted and validated for use with developmental populations. As such, standards for data collection and integrity need to be revaluated.

Mobile EEG collection is a rapidly evolving field with a growing number of systems available both to researchers and consumers. The use of mobile EEG both inside and outside the laboratory environment allows electrophysiological research to begin asking new questions and to use novel methods to address old ones. For instance, using mobile systems in the lab allows participants to move more freely and/or interact with lab-based simulations of real-life events (Lau-Zhu et al., 2019).

Outside of the lab, mobile EEG makes it possible to record in a large variety of locations, including classrooms (see Xu & Zhong, 2018 for review), museums (Kontson et al., 2015), and the home (Zich et al., 2015). Finally, the affordability and portability of mobile EEG provide an exciting frontier for research on neurodevelopmental disorders (see Lau-Zhu et al., 2019 for review), including epilepsy (Askamp & van Putten, 2014) and psychiatric disorders (Loo et al., 2016). To date, contemporary studies utilizing mobile or portable EEG systems with pediatric populations are rare. Additionally, to our knowledge, the reliability of mobile EEG signals for infants has yet to be examined. Finally, few recommendations exist for selecting a recording system, standardizing recording environments, and analyzing pediatric mobile EEG data.

The present paper aims to provide insights into and recommendations for mobile EEG data collection for infants and children. This paper is informed by insights obtained following the successful completion of in-home data collection from more than 400 twelve-month-old infants from low-income backgrounds, using a mobile EEG system employed in the nationwide Baby's First Years study (BFY; www.babysfirstyears.com). BFY is the first study in the United States to assess the impact of poverty reduction on family life and infant cognitive, emotional, and brain development (for more information, see Noble et al., under review and babysfirstyears.com).

Given that this effort was the first large-scale study to collect in-home EEG recordings with a sample of low-income mothers, we went through an intensive piloting and training process. Piloting began by conducting recordings using multiple mobile systems on adult volunteers. A subset of systems was next piloted on infants. After selecting our recording system, we piloted multiple electrode types, electrode configurations, and reference locations with adults and infants. Ultimately, we selected to use the Enobio system by Neuroelectrics (Barcelona, Spain) with a 20-dry-electrode configuration.

Following this pilot testing, we conducted in-person focus groups with mothers drawn from similar communities and backgrounds as our participant sample, in order to understand the questions and concerns that participants may have about EEG data collection. Following these focus groups, the data collection protocol was presented to scientific advisory and community engagement boards for comment and further revision. Finally, the field team was trained on collecting data using both adult and infant pilot participants before beginning data collection in the field. This paper aims to summate across these piloting and training endeavors to provide useful insights and recommendations for future research teams.

This paper is split into three sections: Equipment, Data Collection, and Analysis. In each section, we will draw on insights gained from our piloting and provide concrete recommendations for future data collection. We also provide access to many of the resources we created for future studies.

2 | EQUIPMENT

When considering the transition from lab-based to mobile EEG collection equipment, there are many unique issues. Unlike lab-based recording systems, the goal of mobile EEG systems is to collect data in a variety of remote, unstandardized locations. This need for flexibility leads one to reexamine many of the conventions used for selecting lab-based systems, including the size and shape of the recording equipment, electrode type, recording reference, and how electrodes are arranged on the head (also known as the recording montage). This section will examine these considerations, beginning with recording equipment, moving to electrode types, and ending with recording considerations (electrode montages and reference).

2.1 | Recording equipment

EEG systems vary widely in their required equipment. However, most systems include an amplifier, electrodes, and recording computer(s). Given the potential for the home recording environment to be small, noisy, and cluttered, we focused our tests on systems that would easily fit into a space of a few square feet.

Amplifier size and form factor vary widely across mobile systems. Most mobile EEG systems were created for adults, for whom the size and weight of the system are not as important. However, for developmental work, amplifier weight and location are especially critical considerations. Many amplifiers for mobile systems are attached to the infant's head either directly or tethered to the electrodes by a corded connection. For amplifiers connected to the head, the weight and size of the amplifier are significant issues. In our initial pilot testing, amplifier weights of 2–3 ounces worked well for 12-month-olds, while heavier amplifiers led to changes in infant behavior (e.g., head tipping back and altered head movement). In contrast, corded connections between the amplifier and the electrodes do not have issues with the amplifier's weight, but they are much more cumbersome for remote recording. For instance, it can be complicated to arrange placement of the amplifier during recording in nonstandardized environments; longer electrode cords can limit placement in the home. Also, lengthy exposed cords between the electrodes and the amplifier increase the risk for participants and siblings to potentially interfere with the system (e.g., tripping over cords, pulling amplifier to the ground). Given these issues, we did not pilot test these systems with infants.

In addition to the connection between the electrodes and amplifier, many systems offer a variety of solutions to connect the amplifier to the recording hardware (e.g., computer). Options include corded connections, Bluetooth, and Wi-Fi. In our initial piloting stages, we attempted Wi-Fi and Bluetooth connections with varying success. Occasionally, wireless connections worked perfectly. However, at other times, we experienced a variety of issues including connection loss and intermittent dropping of the signal. This potential loss of signal ultimately led us to select a corded connection between the amplifier and recording computer. While initially, this solution seemed optimal, we later learned, for the system we chose, this corded connection was prone to breakdown. Thus, if a corded connection is selected, precautions should be taken to minimize damage to the ports and cable. Solutions may include reinforcing the port and/or clipping the cord to the mother or infant to reduce the weight on the amplifier port.

TABLE 1 Quality of different types of mobile electrodes as observed through in-lab and in-home piloting with adults and infants

Electrode type	Signal quality	Data cleanliness	Ease of capping	Use with different hair types
Liquid gel	↑	↓	↓	→
Saline	↑	→	↑	↓
Solid gel	↓	↑	→	↓
Dry–flat electrodes	↓	↑	↑	↓
Dry–comb electrodes	→	↑	↑	↑

Legend: ↑ Superior → Acceptable ↓ Inferior

Recording systems vary widely in their space requirements. The smallest systems require just two electrodes attached to the head and have virtually no footprint, while larger systems require multicomputer configurations and can require a space of 10 or more square feet. When considering space requirements for home recordings, a few things need to be taken into account. First, the ability to monitor data quality in real-time necessitates at least one screen. In our pilot testing, we had little success collecting good, usable data on multielectrode systems without real-time data monitoring (see more about the number of electrodes in the Section 2.3). For some systems, a second screen is needed for stimulus presentation (this is particularly true for event-related potentials (ERPs). Based on our pilot testing, finding sufficient space in the home for a two-computer configuration proved difficult. Therefore, we opted for a one-screen EEG system, which allowed for real-time data quality monitoring. We additionally used system-independent, lightweight tablets for stimulus presentation during the resting state recording (for more information on stimuli, see the Section 3).

2.2 | Electrode type

The last decade has seen a steep increase in available electrode types, including the relatively common liquid gel and saline-based electrodes, as well as more novel solid gel and dry electrodes. When considering what electrode type to use for in-home recording (which also limits what amplifiers are available for data collection), a number of factors should be taken into account, including equipment needed, time to put the cap on the participant, clean-up, and sample inclusiveness (e.g., ages and hair types accommodated). Here we will review some of these considerations as well as other pros and cons of each of these electrode types (see Table 1 for a summary).

Saline-based sensors are commonly used in lab-based systems for developmental research. Saline electrodes tend to have higher impedances than gel electrodes, but still have good recording quality. For in-home recordings, saline-based electrodes become somewhat cumbersome, as the bucket of saline solution needed to soak the nets can be easy to spill or splash. For some electrodes, it is possible to deposit the saline in each electrode from a smaller vessel instead of soaking, but this is difficult and time consuming when doing so in a home with active children. In addition, as water content varies from home to home, the saline (and associated materials such as towels) should be brought into the home, which makes the system heavier and less portable. Additionally, while not essential, it is common practice to warm the saline solution before soaking the sensors, so that the cap is not cold when it is placed on a child's head. However, this process is challenging for in-home recordings, requiring the use of a microwave. Disposing of the saline solution can also be problematic if there is not easy access to a drain in the testing location. Finally, while not specific to mobile EEG, most saline-based systems are more challenging to use with denser hair types, as the sponges that hold the saline solution commonly end up lying on top of the hair after application. This can be especially challenging with younger children and infants. Adding too much saline when dealing with thick or coarse hair can cause electrode bridging—an artifact where electrodes are joined together by a low-impedance electrical connection, losing their unique information (e.g., spatial localization).

One of the oldest electrode types for EEG recording systems is the liquid gel-based electrode. Liquid gel-based electrodes generally provide the lowest impedances for recording as well as one of the cleanest signals. However, liquid gel electrodes can be difficult to use with young children, given that these systems commonly recommend or require abrading the scalp, which can be very uncomfortable. Additionally, such systems commonly require filling each electrode individually with conductive gel—a process that can be time consuming and therefore challenging when working with pediatric populations. For in-home recordings, liquid gel-based systems can also be very messy. We found it very difficult to avoid accidentally dripping gel on chairs, couches, and carpets during capping as well as when we removed the cap. Additionally, access to water and materials to clean the gel off of the head after recording proved difficult in some locations. Finally, in pilot testing, we had some difficulty obtaining a good signal with more dense and curly hair types with liquid gel, though with compliant adult participants, good impedances could be achieved by skillfully moving hair.

Solid gel systems are a more recent innovation and are less common than liquid-gel and saline-based systems in the broader mobile EEG marketplace. These electrodes use a solid block of conductive gel (similar to a gummy bear consistency). These gel blocks are preloaded into the cap before it is placed onto the head. In our pilot testing, the capping procedure was quick and easy, but getting the gel gummies to stay in place posed a challenge, as they commonly rotated or slipped out of the electrode housing. Solid gel electrodes are light and mostly dry, which means they are much cleaner and more portable than saline and liquid gel. We found the solid gel electrodes were one of the most comfortable options for young infants. However, in our experience, data quality was often poor at the beginning of the session and improved over recording time—possibly as the electrode warmed up and increased conductivity. Additionally, we found that solid gel electrodes were easily impeded by even the thinnest hair types and were essentially unusable on thick or curly hair types without significant amounts of manual electrode placement and the use of additional glycerin.

The final type of sensor we review is the dry electrode. New research has emerged showing that dry electrodes can deliver a usable EEG signal (Lopez-Gordo et al., 2014; Mathewson et al., 2017) However, both prior research (Mathewson et al., 2017) and our piloting found that the signal for dry electrodes appears good, though more susceptible to environmental noise than gel electrodes. Nonetheless, dry electrodes offer the cleanest and easiest solution for in-home capping since they require no wet materials or disposable pieces. Like the solid gel electrode, our pilot tests revealed that these electrodes reached peak conductivity after they warmed up a bit and settled on the head. Dry electrodes tend to come in one of two form factors—a flat metal disk or combs. The flat disks, while ideal for lower forehead use, were not ideal where any hair was present. In contrast, the comb electrodes performed the best for thick and curly hair types, which enables broader research participation and more racially and ethnically diverse participants. At first glance, comb electrodes, which have the appearance of a "Bristle Block" or small comb, appear to be somewhat sharp. However, when many combs are used for recording and the weight of the cap is distributed across them, adults find them comfortable, and infants do not seem discomforted.

Indeed, we piloted several different electrode types for the electrodes that were on the forehead (Fp1 and Fp2), including solid gel, flat disks, and the comb electrodes. Unexpectedly, we found that comb electrodes worked best at these locations for infants despite less hair being present for many children (as a note, adults tended to prefer the flat disk electrodes). Comb electrodes worked better for infants for two reasons. First, while hair was not uniformly present, many participants did have hair pushed from the top of the head onto the forehead during the capping process, and this hair commonly impeded the signal for flat disk and solid gel electrodes. When hair is pushed forward for adults, it was easy to move the hair out of the way with subsequent adjustments (e.g., lifting the cap and pushing hair out of the way), but infants did not tolerate these subsequent adjustments well. Second, when flatter-profile electrodes (e.g., flat disk) were used, infants seemed bothered by more pressure being placed on the surrounding comb electrodes due to the constriction of the elastic cap. By using comb electrodes at the forehead sites (Fp1 and Fp2), we found more recording success owing to the decreased post-capping cap adjustments and increased distribution in cap pressure. As a cautionary note, however, because the comb electrodes are rigid, they could cause discomfort or even pain if an infant or child were to hit their head while wearing the cap. Thus, without intense piloting for safety, we would hesitate to recommend these electrodes for paradigms during which infants or children are freely mobile (e.g., crawling or walking).

2.3 | Montages

There are many montages available for recording EEG in the home. Mobile systems range from just a few activeelectrodes to region-specific (e.g., frontal) to extended montages of 32 channels or more. Montage selection is very important, as it has implications for the questions that can be asked as well as processing techniques that can be used. In particular, for mobile systems, it is important to consider that extended montages are likely to add weight to the amplifier and time to capping. Additionally, extended montages tend to drain the amplifier battery, constrain the range of recording durations, and typically requiring real-time monitoring. However, extended montages also allow for more sophisticated processing approaches compared to smaller montages (see Section 4 for more information). For the present project, we selected a low-density, 20-electrode montage. This montage was selected because it only took about a minute to make sure the electrodes had a good signal, but still afforded a whole-brain estimate of functional brain activity.

2.4 | Online reference

Online reference types and locations vary both within and across systems. Major reference types include active electrode and driven right leg/common mode sense (DRL/CMS) configurations. Both of these configurations allow for a variety of locations on the head to serve as a reference. In piloting, we tried wet and dry electrodes, stickers, and ear clips as possible references with infants. We found that infants did not tolerate ear clips—even when the pressure was very light. We also found that on-head references with dry electrodes were highly problematic, as the slightest movements led to substantial artifacts across all channels. The best reference configuration we observed (taking into account both infant comfort and signal quality) was a mastoid application of a DRL/CMS reference using sticker electrodes. This reference configuration allowed a relatively stable signal across all electrodes with minimal noise when placed properly. However,

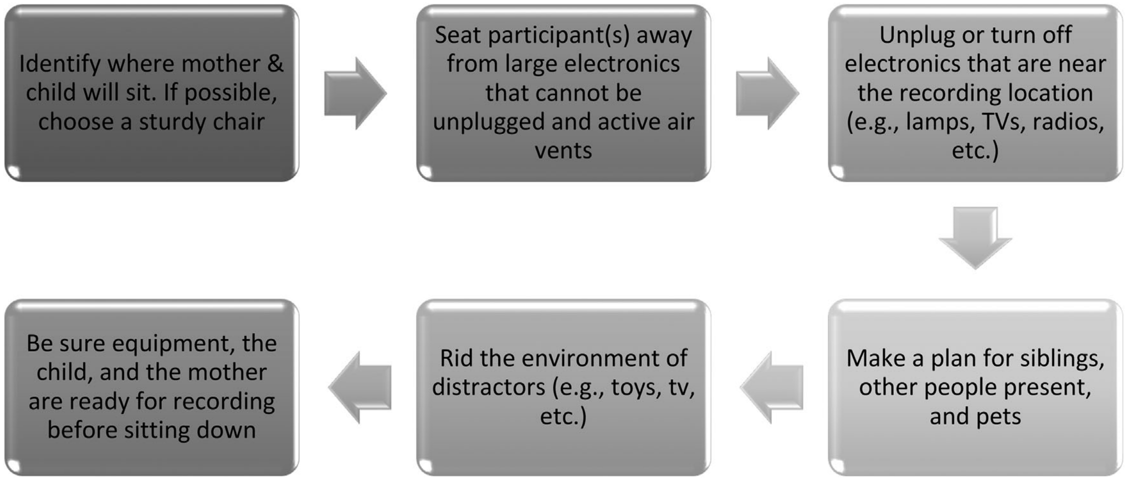

FIGURE 1 How to minimize environmental contaminants during recording

this reference choice was not without complications. First, given that the mastoid of the infant is quite small, it was difficult to fit both electrodes (DRL and CMS) between the ear and hairline. As a result, researchers had to be trained to carefully move hair when placing the reference electrodes to ensure good contact and remove hair from the sticker electrode after capping to prevent upsetting the infant. Additionally, a common experimenter issue was placing the reference electrodes too low (below the ear and onto the neck), resulting in heart rate artifact propagating across all electrodes. We combated this issue through intensive training of researchers in both placement and online monitoring, as well as rapid data review and feedback (see the next section for more information on data monitoring and training).

3 | DATA COLLECTION METHODS

3.1 | Obtaining informed consent

By bringing EEG recording equipment into the home, researchers have the potential to reach new populations of participants who may not have otherwise participated in EEG research. In our case with the Baby's First Years project, we aimed to collect data from a racially and ethnically diverse population of low-income mothers. In focus groups and piloting, we determined that our participants were likely to have never heard of EEG. As such, we found that obtaining informed consent involved introducing new technology and terminology to mothers—in English or Spanish as necessary—as well as carefully describing the EEG recording process. For our project, additional complexity involved the need to standardize the information given to parents by multiple researchers who were not experts in EEG data collection (more details on this in Section 3.5). Through piloting, we found that common questions from mothers during the consent process surrounded what the equipment looked like, what it measured, and what capping would entail. As such, we created a short informative video using footage from pilot families to be sure all mothers experienced the same informed consent process. The consent video was available in English, Spanish, and with subtitles and it is available upon request for training purposes. We also included FAQs for researchers to help answer less common questions (see Supplemental Material 1 in the Supporting Information). The strategy of using a consent video worked incredibly well as we had over 95% of mothers consenting to the EEG recording.

3.2 | Reducing environmental noise

One of the most significant difficulties with in-home EEG data collection is the degree to which recording environments vary. Unlike laboratory environments where recording suites are commonly shielded and have consistent environmental features (e.g., furniture, water properties, air ventilation) from one participant to the next within a given study, home recording environments vary widely (. While increased electrical and artifactual noise is inherent with in-home recordings, we did find that implementing a standardized approach to reducing environmental noise made a substantial difference (see Figure 1 for flowchart).

When choosing an in-home recording location, the first consideration should be what the mother and infant will sit on. In our piloting, rigid seats led to better recording quality. While sitting on sofas and beds are enticing for comfort reasons, the poor back support and room for the infant to roam led to unwanted motor artifacts. If possible, ideal seating is on a wooden or plastic chair. If given a choice between a soft seat (e.g., sofa) or the floor, our piloting showed that sitting on the floor with back support yielded cleaner data. Next, the proximity of the seat to large electronics that cannot be powered down (e.g., refrigerators, furnaces, air conditioners, power boxes, elevators, etc.) and active air vents should be considered. If possible, place the chair or choose a location as far away as possible from these environmental contaminants. Next, nearby smaller plugged-in electronics should be managed. If possible, unplug or turn off electronics that are near the recording location (e.g., lamps, TVs, radios, etc.).

After addressing seating, electrical, and climate control contaminants, other possible environmental contaminants and distractions should be considered. First, and sometimes most difficult, the presence of siblings should be addressed. If possible, siblings should go into another room (supervised as necessary). However, not all dwellings have a second room and/or adult supervision may not be possible. If a sibling is remaining in the room, it is important that they either remain occupied by an activity or they feel like they are part of the capping process. While this may sound counterintuitive at first glance, sibling distress should be avoided at all costs since it commonly leads to infant distress or maternal requests to stop the recording. In piloting, it was not uncommon for siblings to either feel (a) left out due to all of the adult attention being focused on the child being capped or (b) upset by the strangeness of the cap or participant fussiness. Ways to include siblings in the capping process vary by age but can include watching the informed consent video, putting on their own (non-EEG) cap, being a part of the "science crew" by blowing bubbles (see Section 3.4), and/or watching the stimuli alongside their sibling. Next, pets, if present, should be put in other rooms, outside, or in a crate if possible. Finally, in order to get the target child to pay attention to the stimuli of interest, the environment should be rid of other distractions, including TV, music, alluring toys, snacks, and even other adults (if the latter is not possible, they should be asked to be as "unexciting" as possible).

All of the aforementioned steps should be completed before the mother and target child sit down and prepare for recording. The goal should be for the mother and target child to spend as little time as possible constrained to sitting in the recording location.

3.3 | Instructions for parents during capping and recording

While parents should have a good idea of what is about to happen from the informed consent process, it is crucial to revisit the most important points from informed consent before capping. First, we recommend reminding parents that their child may become upset during cap application and asking if there is anything they can think of that may help calm their child (e.g., pacifier or a special toy). Next, during capping, parents should be reminded that they should feel free to interact, entertain, and comfort their child as they usually would. We also recommend instructing parents to hold their child's hands (or have their child grab their fingers) during capping in order to keep their child's hands from interfering with cap application. Finally, it is important for parents to understand that they may ask for the capping to be stopped at any time without question.

Instructions for the time during the recording itself include reminding parents to interact with their child as little as possible as long as their child is content. In addition, parents should be reminded to try to keep talking to a minimum. Parents should also be reminded to keep both feet on the ground during the recording, stay as still as possible, and not bounce or rock their child if possible. Finally, if using dry, comb electrodes, parents should be reminded that their child should not walk or crawl, in order to make sure they do not bump their head, which could be uncomfortable with the comb electrodes.

Finally, parents should be reminded that the electrodes may leave mild skin redness and/or marks after the cap is removed, and that these will fade over the next half hour. If older siblings are present and interested, we recommend giving them this information as well, since skin irritation can be alarming if not expected.

After instructing parents on all of the instructions outlined above, we recommend monitoring parents for signs of anxiety and/or discomfort throughout the capping and recording process. While it may seem counterintuitive to split attention between the parent and infant, our team and others have found that having a calm parent is a key factor to recording success. Indeed, a calm parent usually calms the child, leading to better recording quality. In addition, parents provide valuable cues as to when a fussy baby may or may not be able calmed to continue data collection.

3.4 | Stimuli and task design

While capping, we find that a standardized video distractor is very successful. In piloting, we found that exciting singing/dancing stimuli in the native language of the infant were the most successful. In particular, we found the video *Baby Shark* (available in English and Spanish) presented on a tablet held by a researcher or the parent was the most effective for keeping the infant happy and distracted from the cap application procedure, more so than enticing toys and/or nursery rhymes.

Through our piloting, we found traditional lab-based stimuli for the resting recording were not very effective for home environments. The reason for this stems from the fact that the home environment tends to be much more interesting than lab-based stimuli. In our initial piloting, we tried to use silent videos of infant toys as our resting EEG stimuli, which have been used successfully in laboratory-based studies with similar age infants (e.g., Troller-Renfree et al., 2020). However, in an environment much more exciting than a laboratory testing suite, these videos were not interesting enough to hold an infant's attention for the required duration. In an attempt to make the home environment less exciting, we tried turning off lights, but many infants found this abnormal change in their home environment distressing and, even if they were unfazed by the darker atmosphere, the video still commonly did not hold the infant's attention. Given these issues, we created a new standardized video stimulus. This video was comprised of 30-second clips of wordless (but not soundless) infant-friendly videos interspersed with infant-friendly attention getters. This rapid-changing visual stimulus (available upon request) was much more successful in maintaining infant attention throughout the recording.

While our video stimulus was successful for most infants, not all were entertained. As such, we provided two other standardized stimuli as backups. These included bubbles and a nonmechanical spinning toy. Finally, in the rare instances where infants went through these options and started to fuss, favorite nonmechanical and nonword-based toys from the home were used to entertain the participant.

3.5 | Training a large, multisite staff of researchers

Given the time-consuming nature of traveling to participant's homes, in-home EEG studies are likely to have multiple researchers/experimenters/students conducting recordings. As such, standardized training and data monitoring (addressed in Section 3.6) are essential. For the Baby's First Years study, we specifically were tasked with training over 15 novice interviewers to collect infant EEG data. As such, we developed a four-step training sequence to ensure the necessary expertise was gained by interviewers before beginning data collection in the field.

First, interviewers completed a two-day in-person training on EEG. This training session began with presentations detailing what EEG is, why we were collecting it, and introductions to the hardware. Next, each interviewer learned to cap adult volunteers and obtain high-quality data. Finally, interviewers were trained to carry out the infant protocol. Once the infant protocol was understood, interviewers watched and discussed numerous videos of infants being capped by experts in EEG data collection. Topics of conversation included how to deal with siblings, how to calm anxious participants and fussy babies, and how to determine when the cap should or should not be removed.

Second, after in-person training was completed, interviewers completed a formal certification exam to demonstrate a mastery of the capping and data collection process on adults before moving to infants. Interviewers were independently certified by experts in in-home and EEG data collection. The certification was a formal process, and forms with grades were developed and are available for use (see Supplemental Material 2 in the Supporting Information).

Third, interviewers had hands-on practice with capping infants in the home alongside experts in infant EEG data collection. To accomplish this, we had a team of four expert trainers in lab- and home-based EEG collection travel to each data collection site (four in total) for a week. During this period, interviewers had independent, in-home practice capping pilot participants. Interviewers capped infants until they were able to record EEG successfully without the help of the expert trainer.

Finally, quality control was continually ensured by implementing four mechanisms. First, weekly calls took place between an expert in mobile EEG data collection and the entire interviewing team. These calls allowed for the EEG expert to give general updates, observations, and feedback to the interviewers. In turn, interviewers could ask questions that may have come up in the field or follow-up about specific data collection issues. Second, data were monitored and processed on a near-daily basis, and feedback was given to interviewers in monthly one-on-one meetings (see more details in the next section). Third, a calling tree was established for in-the-field troubleshooting and questions. This calling tree included survey collection staff, IT, and a postdoctoral expert in mobile infant EEG data collection and was available to all interviewers during all visits. Finally, booster trainings with the expert trainers were scheduled at each site. These trainings allowed for addressing ongoing interviewer performance issues (if applicable) and allowed for continued training and improvement as the interview staff got more comfortable with EEG data collection.

3.6 | Data monitoring

As data are collected, it is essential that data are monitored in real time to avoid deteriorations in data quality. In particular, for data collection with multiple researchers, we tracked a variety of metrics (detailed below) to ensure in-home EEG data collection success. Each of these metrics had a target benchmark that data collectors were asked to meet. Metrics and benchmarks included:

Consent rate. This is the percentage of mothers who consented to the EEG recording. The target benchmark was 95%.

Capping rate. This is the percentage of visits where a cap was successfully placed on the child and EEG was recorded. In order for a child to count as "capped," at least 1 s of data needed to be successfully recorded. The target benchmark was 80%.

Recording Length. This is the total number of seconds of EEG data recorded per child. The target benchmark was 300 s (5 min). There was no target benchmark for this metric.

Number of bad and flat channels. This is the total number of globally bad and flat channels. The target benchmark was 20% of the montage or less (four electrodes or fewer in our case). Globally bad electrodes were identified as crossing a $\pm$250 mV threshold on 80% or more of the recording. Globally flat electrodes were identified as an electrode that had a range of less than 1 mV for 80% or more of the recording.

Flat midline channels. This is the total number of electrodes along the midline that were identified as globally flat. This metric was used to identify when the cap was not pulled on all of the way, which produced a bubble along the midline of the cap, resulting in flat electrodes. While this was unavoidable on some participants due to head shape, generally, it was possible to have all electrodes make scalp contact on the majority of participants. The target benchmark was one or zero flat midline electrodes, with an understanding that an occasional flat midline electrode was not problematic. Flat midline channels were reviewed on a case-by-case basis with researchers.

Percent usable files. This is the total number of files that were deemed usable out of the total number of files recorded. A file was deemed usable if it had at least 60 artifact-free epochs (see the next section for processing parameters). The target benchmark was 90% of the files being usable.

Each of these metrics was compiled on a weekly basis in order to track interviewer progress. Each month, researchers were informed of their performance and feedback was provided. When numbers were below the designated benchmarks, booster trainings were arranged and goals were set for the following month. This iterative process ensured continued high-quality data collection. A template data tracking spreadsheet is available in Supplemental Material 3 in the Supporting Information.

4 | ANALYSIS

It was our goal to utilize a standardized, reproducible, and publicly available data-processing stream to analyze the mobile, infant EEG data collected. However, given the novelty and low-density montage of our mobile data, off-the-shelf developmental EEG processing pipelines such as the Maryland Analysis of Developmental EEG (MADE) pipeline (Debnath et al., 2020) and Harvard Automated Processing Pipeline for Electroencephalography (HAPPE; Gabard-Durnam et al., 2018) were not optimally suited for our data. Consequently, code was adapted from the standardized MADE preprocessing pipeline to optimize data processing for low-density and mobile systems, which is called miniMADE and is available on GitHub (https://github.com/ChildDevLab). In this section, we discuss how miniMADE deviates from the MADE pipeline, make recommendations for processing parameters of mobile data, and demonstrate the utility of the miniMADE pipeline for mobile, infant EEG.

Development of miniMADE. The goal for optimizing the miniMADE pipeline to process mobile data was to adapt the existing MADE pipeline to work well with low-density mobile EEG data collected in the BFY study. The changes made to the MADE pipeline are detailed below and a flowchart is provided (Figure 2) detailing the steps in the miniMADE-processing pipeline that we recommend for mobile EEG processing.

Replacement of "FASTER " plugin with channel-based artifact identification. The MADE pipeline uses the "channel_properties.m" function from the FASTER EEGLAB plugin (Nolan et al., 2010) to identify bad channels. However, when creating a pipeline for mobile and low-density EEG data, we found that the "channel_properties.m" function from the FASTER EEGLAB plugin (Delorme & Makeig, 2004) commonly identified more globally bad channels than appropriate. This overidentification in mobile data likely stems from the increased environmental noise in in-home recordings. Consequently, for mobile data, we opted to identify bad channels on an epoch-by-epoch basis in hopes of having a more accurate identification of bad channels and retaining more channel-level data.

To identify bad channels in mobile EEG data, we found an epoch-level 3-criterion check worked best: a threshold check, a flat channel check, and a jump channel check. The check examined whether the trace exceeded a defined threshold. For 12-month resting EEG data, we found a threshold of ± 250 mV worked well. The flat channel check examined whether the trace had a range of less than 1 mV for at least half of the epoch. Finally, the jump channel check examined whether the trace had any increases greater than 50 mV from sample to sample. Altogether, we found this three-criterion check resulted in

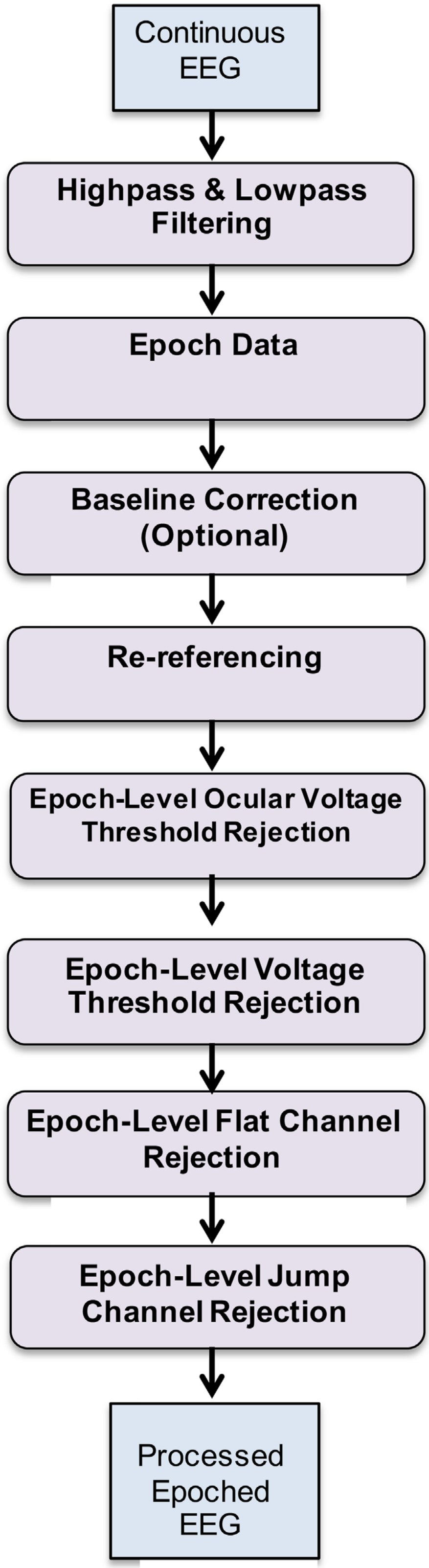

FIGURE 2 Recommended miniMADE processing stream for mobile, infant EEG

generally clean data without too many channels being identified as globally bad.

Removal of ICA and addition of epoch-level ocular artifact rejection. In the MADE pipeline, Independent Components Analysis (ICA) is used to remove artifactual data. However, in the development of the mini-MADE low-density processing pipeline, we found we could not reliably use ICA to identify artifactual data. In particular, we found that mobile EEG data from a low-density montage without eye electrodes gave a poor ICA decomposition, which made it very difficult for automated ICA identification algorithms (e.g., Leach et al., 2020) as well as coders who were experts in infant ICA categorization to identify bad components. In particular, it was highly difficult to disentangle eye blinks from frontal activity. Given this issue, we elected to remove ICA and replace it with a threshold-based approach to identify eye blinks.

Without ICA, we were faced with the problem of how to ensure epochs containing eye blinks and other large ocular artifacts did not make it through to later spectral decomposition. Ocular artifacts, in particular, were of great interest as they are likely to add spectral noise across the scalp with more noise in the frontal region. As such, for mobile data, we created a threshold-based rejection that inspects frontal channels for large amplitude artifacts and subsequently removes eye-blink contaminated epochs from further analysis. In our piloting with our 20-electrode system, we found that if both frontal electrodes (Fp1 and Fp2) crossed a threshold of ±250 mV, it was highly likely that the epoch contained a large frontal artifact; subsequently, that epoch was removed from all analyses. This approach does not perfectly remove ocular artifacts, but the resulting data and topographic heat maps showed that frontal artifacts were largely removed by this procedure.

Removal of electrode interpolation. In processing streams for higher density EEG data (including MADE), it is rather common to use interpolation to replace data for electrodes identified as bad. Doing so allows for complete data across electrodes in each epoch. However, electrode interpolation for low-density data may be problematic because of the sparse spatial coverage of these montages. In line with this, when we tested electrode interpolation with mobile infant EEG data, we found that the interpolation resulted in systematic and problematic patterns in the data. Specifically, a greater number of globally flat electrodes interpolated for a participant was significantly related to overall lower absolute whole brain power in all power bands ($rs = -.108$ to $-.371$, $ps = .035$ to $<.001$), while a greater number of globally bad channels interpolated for a participant (crossing voltage threshold) was significantly related to overall higher whole brain power ($rs = .110$ to $.193$; $ps = .031$ to $< .001$). Given that interpolation introduces systematic biases in whole-brain power, we recommend that bad channels are not interpolated for infant low-density, mobile EEG data.

Split-half reliability of mobile infant EEG data. Given the novelty of collecting mobile infant EEG data, little is known concerning signal reliability. Therefore, we conducted a rigorous examination of split-half reliability for both absolute and relative power in four frequency bands (Theta, Alpha, Beta, Gamma) for 1-s epochs. Frequency band boundaries were selected based on prior studies with similar sample characteristics (Tomalski et al., 2013; Troller-Renfree et al., 2020). Methods for calculating split-half reliability were also consistent with prior research (Leach et al., 2020) and used the Spearman–Brown split-half correlation method with increasing numbers of trials. This method allowed examination of the reliability of the different frequency bands and helped to understand the amount of data necessary to get a reliable signal. Correlation coefficients were calculated from five through 100 trials in steps of five trials. In order to diminish the variability introduced by subsampling trials and randomly splitting the data into halves, for each number of trials, 1000 iterations of split-half correlations were calculated and the average across iterations was used as the estimate (for more information on this approach, see Leach et al., 2020). These analyses provide a measure of whether split-half reliability meets or exceeds good (0.8) and excellent (0.9) reliability for each frequency band. Code to compute split-half reliability is available in Supplemental Material 4 in the Supporting Information or at https://github.com/SMoralesPhD/SplitHalf_Reliability).

Results of this investigation showed that mobile infant EEG generally had good reliability for resting EEG recordings (see Figure 3). In general, lower frequencies had lower reliability than higher frequencies for both absolute and relative power. For absolute power, good reliability was achieved in all bands by 20 1-s trials and excellent reliability (.9) was achieved in all bands by 40 trials. For relative power, good reliability was achieved in all bands by 15 trials and excellent reliability (.9) was achieved in all bands by 35 trials. These findings are in line with the reliability observed in data collected in the laboratory, in which less than 30 s of data are needed to obtain a reliable measure of EEG power across all frequencies (Leach et al., 2020). Given these results, future studies using a similar recording system with infants can plan to acquire at least 20 artifact-free 1-s epochs per participant for analyses of spectral power. However, because reliability estimates are a property of the scores rather than the measure, they should ideally be examined and reported in each study. To this end, we provide the code used in our study to estimate reliability and the minimum number of epochs required to obtain a reliable power measure.

5 | SUMMARY

In summary, we found that the in-home collection of mobile EEG in infants is an achievable, exciting innovation for developmental research. However, as with all new technologies, there is a learning curve for adapting lab-based data collection protocols to mobile data collection. The present paper has provided both editorial and empirical insights into equipment selection, data acquisition, and data analysis. We have also provided numerous resources for future research teams, including videos for informed consent, FAQs for parents, instructions on reducing environmental noise, an interviewer certification form, a data tracking template, code for split-half reliability calculation, and code for EEG processing using miniMADE. It is important to note that the recommendations presented in this paper are the observations and recommendations of the current research team, but may not apply in all situations. Additionally, as mobile EEG is still rather novel, recommendations may change over time. This novel methodological

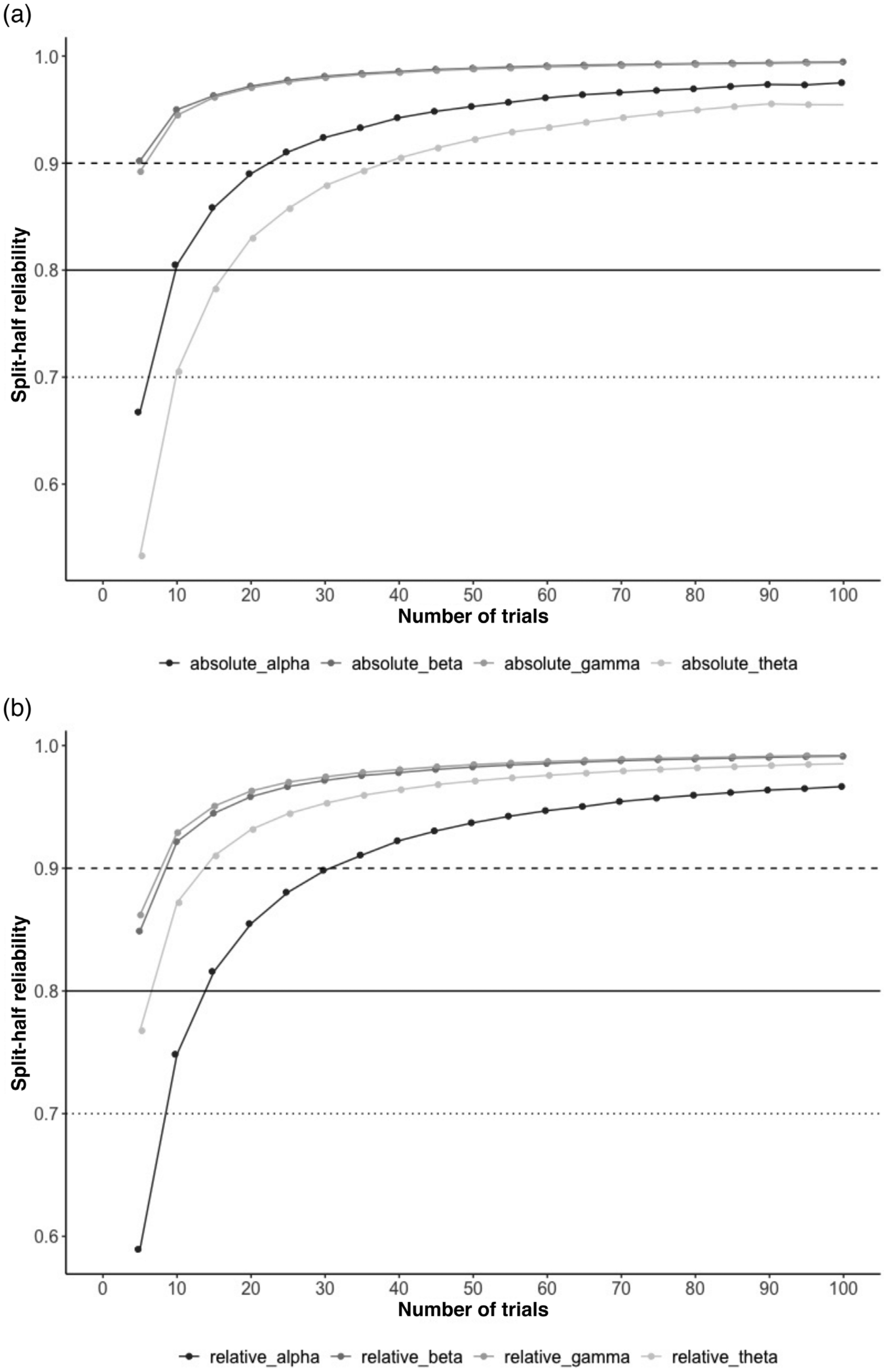

FIGURE 3 Split-half reliability for mobile, infant EEG absolute (a) and relative power (b) during a resting EEG data collection

approach, a new frontier for developmental research, is not only feasible, but is also a promising avenue for increasing the diversity of research questions and participants.

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CONFLICTS OF INTEREST

All authors have no conflicts of interest to declare.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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