A survey of protocols from 54 infant and toddler neuroimaging research labs

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ABSTRACT

Infant and toddler MRI enables unprecedented insight into the developing brain. However, consensus about optimal data collection practices is lacking, which slows growth of the field and impedes replication efforts. The goal of this study was to collect systematic data across a large number of infant/toddler research laboratories to better understand preferred practices. Survey data addressed MRI acquisition strategies, scan success rates, visit preparations, scanning protocols, accommodations for families, study design, and policies regarding incidental findings. Respondents had on average 8 years' experience in early life neuroimaging and represented more than fifty research laboratories. Areas of consensus across labs included higher success rates among newborns compared to older infants or toddlers, high rates of data loss across age groups, endorsement of multiple layers of hearing protection, and age-specific scan preparation and participant accommodation. Researchers remain divided on decisions in longitudinal study design and practices regarding incidental findings. This study summarizes practices honed over years of work by a large collection of scientists, which may serve as an important resource for those new to the field. The ability to reference data about best practices facilitates future harmonization, data sharing, and reproducibility, all of which advance this important frontier in developmental science.

1. Introduction

Infant and toddler MRI has become an important means of examining neural organization and disease ontogeny. Longitudinal infant MRI studies highlight that birth to age 3 years represents a period of rapid developmental plasticity, making it an optimal time for the administration of preventative interventions (Gao et al., 2017, 2015; Knickmeyer et al., 2008). A number of studies have shown that environmental factors, such as prenatal stress (Humphreys et al., 2020), marijuana (Grewen et al., 2015), and lead (Thomason et al., 2019) leave behind neural signatures that can be detected in fetal and infant MRI brain measures. It has even been shown that intergenerational exposures such as maltreatment from the mother's childhood can be detected using MRI studies of the infant brain (Hendrix et al., 2021; Moog et al., 2018). Moreover, MRI-derived measures of neural development during gestation and infancy are prospectively associated with subsequent preterm birth (Thomason et al., 2017), neurodevelopmental outcomes (Hazlett et al., 2017; Woodward et al., 2006), psychopathology (Rogers et al.,

2016), and individual differences in cognitive ability (Graham et al., 2016). Together, these findings and many others, have deepened our understanding of the early life origins of health and disease and underscore that early life neuroimaging is crucial to these and future clinical and scientific advancements.

1.1. Special considerations in early life neuroimaging

Scanning children within the first few years of life requires adaptations of standard imaging approaches. Both variation in neuroanatomy and constraints in child behavior alter the experimental paradigm. Indeed, rapid developmental changes in brain size, myelination, and microvasculature affect sequence optimization and choices with regard to MRI hardware and image processing (Turesky et al., 2021). Limited language ability, inhibitory control, and understanding additionally restrict compliance, with major implications for study design. Overall, there are unique challenges in infant and toddler MRI, and yet gold standards in imaging approaches remain to be established.

As testament to this, several infant and toddler imaging research groups have published valuable recommendations for optimizing MRI imaging protocols to the early human brain (e.g., Antonov et al., 2017; Dubois et al., 2020; Ellis et al., 2020; Howell et al., 2018; Mongerson, Jennings, Borsook, Becerra, & Bajic, 2017; Raschle et al., 2012) and a recent review compiled MRI acquisition strategies from published MRI studies on children age 0–6 years (Copeland et al., 2021). This review of the field reveals that preferred practices vary across labs and relate to individual experience rather than an external accepted standard. For example, consensus varies regarding the value of mock scanning practice prior to the MRI session (Thieba et al., 2018; Vannest et al., 2014). A needed supplement to the recommendations from individual research groups is a consolidated, data-driven report that pools the collective knowledge of a variety of experts in infant and toddler neuroimaging. This will allow us to differentiate between generalizable and site-specific practices to facilitate more effective and consistent data collection across independent research groups.

1.2. Sharing expertise across labs facilitates open science and community building

Infant and toddler neuroimaging is a time-consuming, expensive, and challenging endeavor with particularly high failure rates; up to 30–40% of infant scan visits result in no usable data (Copeland et al., 2021; Ellis et al., 2020; Raschle et al., 2012). However, these failure rates have high inter-lab variability (Copeland et al., 2021), likely due to differences in data acquisition techniques or institutional support. Sharing information across labs and across institutions regarding successful and unsuccessful strategies as well as honest assessments about costs and failure rates provides leverage for negotiating needed structural support for developmental neuroscience projects. This informational exchange also speeds the optimization of high-quality data collection practices, ultimately resulting in more efficient and affordable acquisition of infant and toddler MRI data. Finally, inter-lab communication contributes to a transparent, supportive environment that is conducive to robust scientific discovery. The informal sharing of learned expertise between researchers is already common practice; yet without formalized avenues for sharing, this important information is not equally available to all scientists. Professional societies, such as the Fetal, Infant, and Toddler Neuroimaging Group, and published, open-access manuscripts that consolidate information gleaned from years of experience in the field are therefore a necessary supplement to the informal exchange of ideas between individuals.

1.3. Current study

We conducted a study of international pediatric MRI researchers to ascertain current practices and observations drawn from years of work in this field. We compared scan success rates, visit preparations, scanning protocols, opinions about developmental study design, and policies regarding incidental findings. We additionally report on the impact of the COVID-19 pandemic on infant and toddler scanning. Finally, we convey recommendations regarding areas that still require consensus within the field.

2. Material & methods

2.1. Recruitment

We recruited experts in infant and toddler MRI acquisition using three primary approaches. First, experts were identified by iteratively searching for articles using Clarivate Analytics EndNote X9's built in PubMED (NLM) online search tool. Peer-reviewed abstracts were searched based on a combination of five conditions, and the tool returned a result only when all five conditions were met:

(1) Abstract contains a relevant developmental keyword, i.e.: "neonate", "neonates", "newborn", "newborns", "infant", "infants", "toddler", "toddlers", "baby", or "babies"
(2) Abstract contains a relevant methodological keyword, i.e.: "functional connectivity", "cortical thickness", "fMRI", "resting state fMRI", or "structural connectivity"
(3) Abstract contains the word "brain"
(4) Abstract contains the word "MRI"
(5) Article publication date range 2017 through 2020

The list of resultant articles was exported from EndNote X9 as a RIS file and imported into R for processing. Custom R scripts were used to extract the article DOI as well as the corresponding author's name, institution, and email address from the RIS file. In the case of multiple corresponding authors, all corresponding author information was noted. Duplicate emails were removed from the corresponding author contact list and the remaining abstracts were manually checked to ensure the study met inclusion criteria. Articles were removed if the focus of the study was non-human animal MRI ($n = 11$), post-mortem MRI ($n = 1$), participants > age 5 years ($n = 35$), or non-MRI measures of brain functioning (e.g., EEG or fNIRS; $n = 6$). Three additional articles were excluded either because MRI was not the focus of the manuscript ($n = 1$), or the corresponding author was one of the investigators of the present study ($n = 2$).

This objective method of recruitment was supplemented with direct referral. Specifically, investigators who received the survey link were encouraged to share it with colleagues performing infant and/or toddler MRI studies. Finally, a link to the survey was distributed via the Fetal, Infant, and Toddler Neuroimaging Group (FIT'NG) listserv. This listserv was founded in 2018 by Drs. Marisa Spann, Dustin Scheinost, Alice Graham, and Lilla Zollei for interdisciplinary scientists with an interest in early brain development. The FIT'NG listserv had 120 members at the time the survey was circulated. Through these efforts, at least 288 experts were invited to participate in the study.

2.2. Participants

Our multi-pronged recruitment efforts resulted in 62 investigators enrolling in the study. Enrolled participants were excluded if they indicated they do not use MRI to scan infants or toddlers for research ($n = 4$) or if they had not attended any infant/toddler MRI scan visits ($n = 2$). Additionally, participants were excluded if they indicated predominantly scanning sedated infants or toddlers given significant differences in data acquisition from children in this state ($n = 2$). The final sample for analyses was 54 experts comprising regions of the United States, Canada, South Africa, the Netherlands, France, and the United Kingdom. The sample was highly educated and predominantly comprised of professors. Experts had a median of 8 years of experience in early life neuroimaging and had personally attended a median of 50 infant or toddler scans. See Table 1 for additional sample demographics. Experts represent 38 unique institutions, and no institution had more than 3 respondents representing it, meaning that every institution accounted for less than 6% of the final sample. We did not exclude individuals representing the same institution because these individuals may be part of independent research labs that scan different age groups and/or use different techniques.

2.3. Procedures

Potential participants were contacted via email and asked to complete a 20-minute online survey administered in Qualtrics. The survey link directed respondents to the study consent form. After providing signed electronic consent, participants indicated their experience with fetal, infant, and/or toddler age groups, which served as branching logic for question selection. Participants were not compensated for their time, but participants who completed the entire survey are included in the

Table 1

Sample demographics.

	Final Sample (n=54)
Number of infant/toddler scans attended, *Median(IQR)*	50 (20–150) scans
Number of infant/toddler scans supervised as PI/Co-I, *Median (IQR)*	60 (15–200) scans
Years of infant/toddler MRI experience, *Median(IQR)*	8 (5–10) years
Ages scanned, *N(%)*	
Fetus	12 (22%)
Newborn (birth-2 months)	41 (76%)
Infant (3–18 months)	43 (80%)
Toddler (19–59 months)	24 (44%)
State of infant/toddler during scan, *N(%)*	
Natural sleep	38 (84%)
Awake	7 (16%)
Primary study developmental study designs, *N(%)*	
One age only	11 (26%)
Cross sectional	11 (26%)
Longitudinal	24 (57%)
Combination (e.g., accelerated longitudinal)	16 (36%)
Gender, *N(%)*	
Male	14 (38%)
Female	23 (62%)
Education, *N(%)*	
BA, BS, or BSN	2 (5%)
MA, MS, or MPH	1 (3%)
MBChB	1 (3%)
MD	4 (11%)
PhD	26 (70%)
MD/PhD	3 (8%)
Current academic position, *N(%)*	
Graduate student	4 (11%)
Resident	1 (3%)
Postdoctoral fellow	3 (8%)
Research scientist or engineer	2 (5%)
Assistant professor	11 (30%)
Associate professor	6 (16%)
Full professor	10 (27%)
Number of people in research group, *Median(IQR)*	14 (9–18)
Researcher location	
North America	44 (81%)
Europe	9 (17%)
Africa	1 (2%)

Note. Sample demographics are displayed in the above table. Researchers could indicate scanning more than one age group and could indicate using more than one study design so these percentages do not add up to 100. Due to skew in our variables, median and interquartile range (IQR) is reported instead of mean and standard deviation.

2.4. Measures

The 80-item investigator survey was developed with input from experts at four independent research institutions. The survey was administered on-line using the Qualtrics data capture platform. Three primary sections comprise the survey: (1) questions about infant/toddler MRI data acquisition, (2) questions pertaining to COVID-related adjustments to MRI visits, and (3) questions about expert demographics. Based on indicated experience with newborns (birth-2 months), infants (3 months-1.5 years), or toddlers (1.5–4 years), survey logic directs respondents to complete only those sections applicable to areas in which respondents had core expertise. The 80-item survey is provided as accompanying supplementary material.

2.5. Data analysis

Analyses were conducted using the Pandas library (version 0.25.1) in Python. Skew and kurtosis values for most variables in our analyses were $> |1|$, indicating non-normal distributions. Descriptive statistics and measures of variability are therefore reported in median and interquartile range (IQR), even for normally distributed variables to facilitate easier comparisons across variables in the study and to account for potential outliers. We report descriptive statistics and measures of variability pooled for the entire sample ($n = 54$), as well as grouped by participant age and participant state during the scan as appropriate. Not all researchers in the final sample answered every question, so estimates are based on the available data for that question (*range*=37–54 responses per question).

3. Results

3.1. Basics of data collection: who & what?

In early life neuroimaging, most polled experts scan multiple age groups (see Fig. 1A), with nearly 69% ($n = 37$) of experts scanning more than one age group in their lab. The majority of experts report their study designs are primarily longitudinal, cross-sectional, or a combination of the two rather than exclusively scanning a single age group (see Table 1). This suggests that many of the survey respondents were able to provide perspective on both general and age-specific aspects of developmental MRI acquisition. Across all participant ages, the most

(A)

Number of Researchers Scanning each Age Group

(B)

Most Frequently Collected Scan Sequences
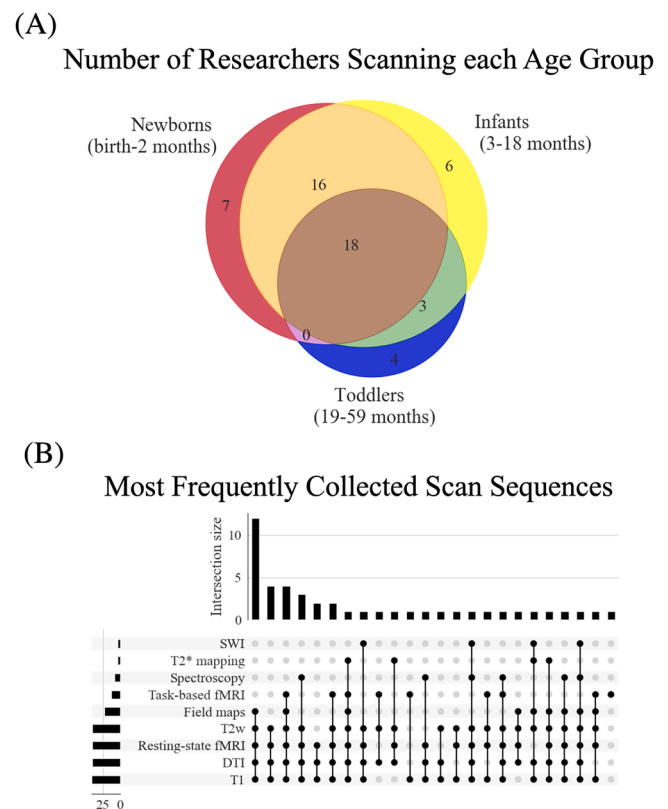
Fig. 1. Most common participant ages and scanning sequences in early life neuroimaging. (A) The number of researchers scanning a particular, or combination of, age group(s) is displayed in Fig. 1A. Most researchers in our sample scan at least 2 early life age groups. (B) The number of researchers who report collecting each MRI scan type is displayed on the y-axis of Fig. 1B. Along the x-axis is the number of researchers who report collecting each *combination* of scans. The most common scan protocol includes field maps, T2w, rsfMRI, DTI, and T1 scans.

common MRI protocol collects multiple types of anatomical images (T1 and T2w), resting-state functional MRI (rsfMRI), and diffusion tensor imaging (DTI; see Fig. 1B). However, a number of researchers additionally collect task-based fMRI in sleeping ($n = 8$) or in awake ($n = 5$) infants and toddlers.

3.2. Scan success and failure rates

Successful scanning is dependent upon the infant or toddler's ability to remain still during image acquisition. The predominant approaches for achieving behavioral compliance in infants and toddlers are to induce sleep, provide mock scanning practice, and/or to use other motivational techniques, such as prizes or enticing stimulus exposure. Once an infant or toddler is in the scanner, researchers report they make it 37.5 minutes into their sequence before needing the end the session, but there is significant variability across labs (*range*=10–80 min, *IQR*=30–45). Generally, researchers report that most infants and toddlers make it through all of a researcher's high priority scans (*median*=77%, *IQR*=70–85% across labs), and 60% (*IQR*=50–70%) make it through the entire scan sequence, including aspirational scans. Consistent with these numbers, researchers report that across labs, a median of 15% of infants do not fall asleep or otherwise do not get into the right state to start scanning (*IQR*=10–30). Even when data is successfully collected at the scan visit, up to 51% of the data may be censored in analyses secondary to high motion (*median*=19%, *IQR*=13–23).

Scans resulting in usable MRI data (i.e., "successful scans") differ significantly by type of scan, age being scanned, and state of the infant or toddler. Experts tend to report the highest success rates for anatomical scans, potentially because these are generally positioned at the beginning of an MRI sequence. Newborn participants consistently have the highest success rates across anatomical, DTI, rsfMRI, and task-based fMRI scans (see Fig. 2). In comparing experts who predominantly scan sleeping infants and toddlers ($n = 32$) to experts who predominantly scan infants and toddlers while awake ($n = 7$), sleeping infants tend to tolerate slightly longer scan times (group medians 37.5 versus 30 min, respectively). There is also slight variability in scan success rates amongst researchers who scan infants while awake versus while the infant is asleep. Specifically, sleep protocols appear to have slightly higher success rates, with 80% (IQR=70–85) of sleeping infants/toddlers making it through a researcher's high priority scans, compared to 70% of awake, behaving infants/toddlers completing high priority scans (IQR=55–77.5).

Consistent with aforementioned success rates, experts generally agree that infants under the age of 3 months are the easiest to scan (see Fig. 3A). In a qualitative language analysis of experts' responses to the question "What makes this age group the easiest to scan?", sleep emerged as a common theme (see Fig. 3B). More specifically, experts report that newborn infants are more easily soothed to sleep in novel environments following feeding and swaddling procedures, and that newborns are more likely to stay asleep amidst fluctuating scanner sounds. This qualitative analysis is further supported by experts across the board reporting that newborns are the most likely age group to stay asleep once in the scanner ($n = 29$, 64%).

Conversely, infants between the ages of 1 and 3 years were consistently reported as being the most difficult age to scan (Fig. 2B). Again, themes related to sleep emerged in the open-ended responses from experts. One- to three-year-old children were described as less likely to fall asleep, more aware of the novel scanning environment, and more mobile than younger age groups. From 3 years of age and older, researchers described fewer difficulties because developmental increases in cognitive and behavioral control permitted increased success with awake scanning.

3.3. Expert approaches to a successful scan

Experts generally agree that the most important factors for predicting scan success are (1) experience of the scan team, (2) infant disposition on the day of the scan, and (3) the infant's general sleep habits. Experts who predominantly scan awake infants also rank these factors as
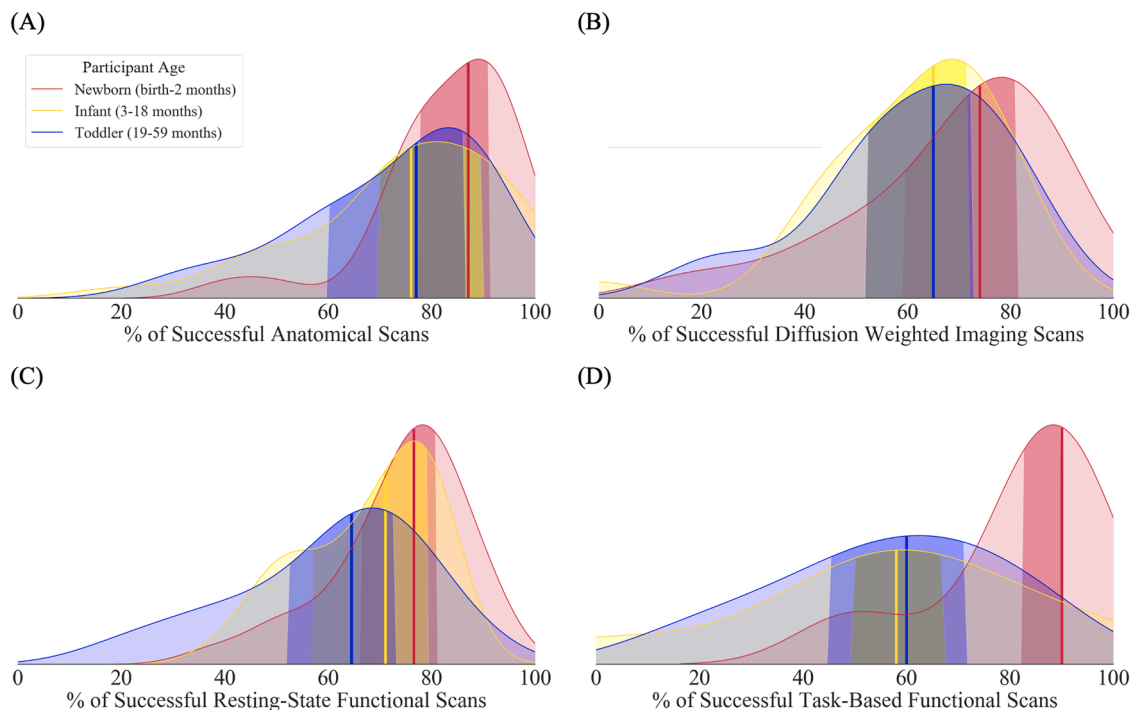

Fig. 2. Scan success rates by participant age and type of scan. Researchers were asked to estimate the percent of scans that result in usable data for each participant age group and type of scan they examine. Across (A) anatomical (i.e., T1 and T2w), (B) diffusion weighted imaging (DWI), (C) rsfMRI, and (D) task-based fMRI scans, researchers consistently reported the highest success rates for newborn participants. The group median for each participant age bracket is displayed by the bolded line, and the group interquartile range is displayed as darker shading within the distribution.

(A) Easiest Age to Scan
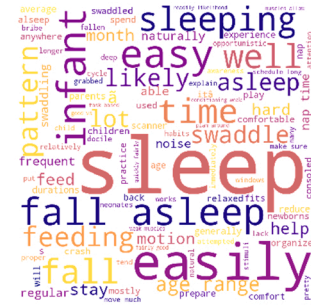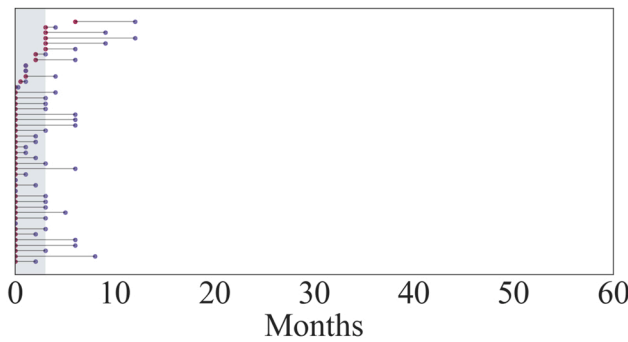
(B) Most Difficult Age to Scan
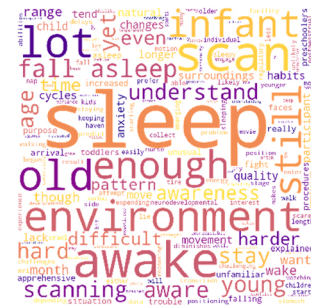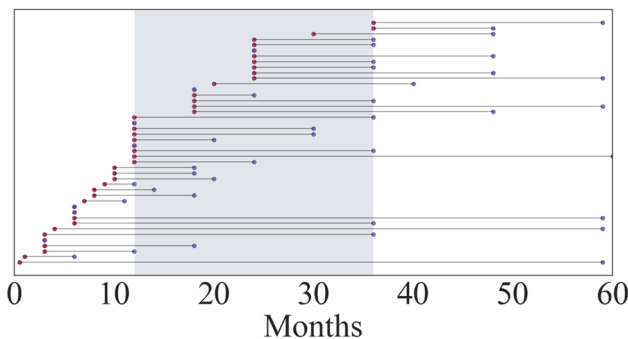
Fig. 3. Easiest and most difficult ages to scan. Experts were asked "What is the easiest age range to scan?" and "What is the most difficult age range to scan?" in a free response format. Each line represents a single researcher's response, with dots indicating the lower and upper ranges of their response to each question. The gray shading represents the modal responses for each question. The text block to the right of the chart is a word cloud created from the researcher's free response answers to questions asking them to explain why the age range they indicated was easy or difficult, respectively. (A) Experts consistently reported that 0–3 months is the easiest age range to scan, largely because they are most likely to fall asleep at the visit. (B) 12–36 months was consistently described as the most difficult age range to scan, secondary to increased child awareness of novelty and difficulty falling sleep in the scanning environment.

being most important for predicting scan success, but unsurprisingly report that rapport with the family is more important than the infant's general sleep habits. These factors were all indicated as being more important for scan success than timing of the scan, preparation of the family in advance of the scan, family experience with scanning, and random chance. We also asked experts to estimate the amount of variance in scan success that is under the researcher's control. The median estimate across experts is that only 60% of the variance in scan success is controlled by the researcher (*IQR*=50–71*)*. Unsuccessful scans are therefore to be expected, and do not necessarily reflect poor preparation on the part of the scan team. However, there are common practices that contribute to the 60% of estimated variance that researchers *can* control, and these practices vary based on age and state of the child being scanned.

3.3.1. Materials

One of the first steps towards having a successful scan visit is obtaining the correct materials. Across ages, experts generally have materials on hand that serve the purpose of monitoring the child's state, soothing the child to sleep, or enhancing family comfort (see Table 2). Baby blankets are generally used across age groups, and if scanning newborns, having a vacuum pillow or papoose to assist with swaddling is endorsed by all experts. This item becomes less commonly purchased as infants age and begin to sleep outside of a swaddle from 6 months onward (Van Sleuwen et al., 2007). For the few researchers who only scan toddlers, the commonly used materials predominantly serve the purpose of motivating the child to comply with the protocol (e.g., toys/prizes) and/or enhancing family comfort during the scan. Multiple

research groups also report adding bedside railings or other modifications to the scanner bed to allow parents to lie on the bed with their toddler prior to or during the scan.

3.3.2. Preparation

Prior to the scan visit, most researchers engage in preparatory tasks (e.g., mock scanning, MRI sound exposure) with families to enhance scan success, with toddlers requiring the most advance preparation. From 3 months through toddlerhood, it is also common to ask families to induce mild sleep deprivation prior to the visit, such as by skipping naps on the day of the scan. If scanning infants or toddlers during natural sleep, another area of consensus among researchers is the importance of a sleep interview during the screening and scheduling process (see Box 1).

3.3.3. At the scan visit

After a family arrives at the scan center, it is most common to feed, weigh, and take other measurements from the infant or toddler. For scans conducted in natural sleep, researchers next work with families to create an environment that is conducive to the infant or toddler falling asleep. Environmental modifications for encouraging sleep include swaddling for newborns, dimming the lights, playing white noise or lullaby music, and giving the family space and privacy to soothe the child to sleep; see section below on commonly used hearing protection, which can be applied at this step or after the child is asleep. Researchers report less consistency in pre-scan visit activities completed prior to awake scans, but these often involve weighing the baby, allowing the family time to acclimate to the scanning environment, and other

Table 2
Endorsed materials, facility considerations, and scan practices by age group.

	Only Scans Newborns (n = 7)	Only Scans Infants (n = 5)	Only Scans Toddlers (n = 4)	Scans Multiple Ages (n = 29)
Materials Needed				
Baby blankets	**100%**	**80%**	50%	**93%**
Extra diapers	71%	**80%**	50%	**86%**
Rocking chair	57%	**80%**	0%	**86%**
Changing table	**85%**	**100%**	0%	79%)
Foam bed for scanner table	43%	**100%**	25%	62%
Vacuum pillow/papoose	**100%**	20%	0%	62%
Baby scale	43%	40%	50%	52%
Snacks/water for family	43%	60%	**100%**	52%
Magazines/reading materials for parents	43%	40%	**100%**	45%
MRI-safe weighted blanket	289%	40%	25%	45%
Pacifiers	57%	60%	0%	41%
Toys/books	0%	60%	**100%**	38%
MRI-safe pack-n-play	0%	0%	0%	31%
Customized head coil	40%	20%	0%	13%
Apparatus to allow parent on scanner bed with toddler/infant[a]	0%	0%	0%	7%
Baby clothes[a]	0%	0%	0%	3%
Necessary Scan Preparations				
Ask family to skip naps on day of scan	14%	60%	25%	52%
Provide family with standard MRI sounds ahead of scan	14%	40%	25%	45%
Send home ear protection (ear plugs, headphones) for infant/toddler to practice wearing	14%	20%	25%	38%
Ask family to wake infant/toddler early on day of scan	14%	40%	25%	34%
Mock scanner practice	0%	20%	**75%**	28%
Ask families to increase ambient noise at home while infant/toddler sleeps	0%	0%	0%	24%
Best Scan Practices				
Research staff available to answer questions during scan	**100%**	**100%**	**75%**	**93%**
Staff member stays in magnet room during scan	57%	60%	**100%**	**83%**
Parent stays in magnet room during scan	14%	**80%**	25%	55%
Measure infant/toddler sleep pulse	**86%**	20%	0%	52%
Use MRI-compatible camera to capture infant/toddler face during scan	**71%**	40%	0%	38%
Measure infant/toddler sleep respiration	**86%**	20%	0%	34%
Use quantified in-vivo motion monitoring (e.g., FIRMM)	29%	20%	**75%**	28%
Measure infant/toddler sleep state (e.g., with EEG)	0%	0%	0%	7%
Monitor in-ear sound levels during scan[a]	0%	0%	0%	3%

Table 2 (*continued*)

	Only Scans Newborns (n = 7)	Only Scans Infants (n = 5)	Only Scans Toddlers (n = 4)	Scans Multiple Ages (n = 29)
Recommended Facility Qualities	(*n* = 5)	(*n* = 5)	(*n* = 4)	(*n* = 24)
Access to restrooms	**100%**	**80%**	**100%**	**88%**
Parking	**100%**	**100%**	**100%**	**83%**
Ability to dim lights	**80%**	**100%**	**100%**	**83%**
Adjoining waiting room (s)	**80%**	**100%**	**100%**	**79%**
Ability to play audio during the scan (e.g., white noise, lullabies)	20%	40%	**100%**	67%
MRI center is easy to locate	**100%**	**80%**	**75%**	63%
Option for families to be in magnet room	40%	**100%**	**75%**	63%
Ability to decorate MRI suite to look more family-friendly	20%	20%	**100%**	33%
Proximity to hospital	60%	20%	50%	8%

Note. [a]Indicates write-in responses from participant researchers. The number of researchers who reported on each question is indicated in the header of each column, except for questions pertaining to facilities at the bottom of the table, where the number of responses decreased due to attrition. Items endorsed by at least 75% of the sample are bolded.

cognitive or developmental assessments.

3.3.4. Participant monitoring

Another topic addressed in our survey pertains to monitoring of the infant or toddler during active data collection. Experts agree that it is advisable for one or more research staff stay in the magnet room during the scan, and it is common for experts to use extra monitoring of the infant's state, particularly for newborns, such as the use of an MRI-compatible camera and/or pulse oximeter (see Table 2). A number of experts also use quantified real-time motion monitoring, such as FIRMM (NousImaging, 2020). Real-time motion assessment enables monitoring of infant state, as fussy and awake babies tend to move more, and provides metrics about the duration of data needed to fulfill acquisition goals.

3.4. Cost

Given the relatively high failure rate of infant and toddler scans, flexibility from a scanning facility is crucial for early life neuroimagers. One area where this flexibility comes into play is in cost structure. Our results demonstrate that experts book the scanner for a median of 120 min (*IQR*=90–120), yet only plan for the baby to be in the scanner for a median of 45 min (*IQR*=40–60). This means the scan itself takes less than half (37.5%) of the time the scanner is booked, and that scanning infants or toddlers often costs over double the amount it would cost to collect the same amount of data from adults. Cost reductions from MRI facilities and larger budgets from funding agencies are therefore necessary for researchers to budget appropriately for infant/toddler MRI research. Our survey revealed that some MRI facilities offer cost breaks if the research team provides their own MRI technician, and that 53% of groups report having someone from the research team operate the scanner during visits. Additional accommodations included no charge for sessions involving (a) MRI hardware/software issues (93%), (b) cancellation within 24 h of the scan (62%), or (c) no-shows (53%). Researchers also experienced cost breaks during off-peak hours (e.g., 6 pm-6 am), which is especially helpful for scanning older infants and toddlers during natural sleep. Finally, one in five experts (22%) have negotiated with their facility to pay only for the amount of time the infant or toddler *is in the scanner* instead of paying for the amount of time the scanner is

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Box 1
Sleep Interview Topics. Experts in infant and toddler neuroimaging were asked to rank the top three most important topics to discuss with families during a pre-scan sleep interview. The baby sleeping icon was created by *iconpacks* on thenounproject.com under a free Creative Commons license.

The Sleep Interview

A pre-scan sleep interview allows researchers to prepare the scanning environment to optimally promote infant or toddler sleep during the visit. Experts agree these are the top three most important topics to cover in a pre-scan sleep interview:

❯ The **most important** questions to ask pertain to the infant/toddler's sleep schedule (e.g., what time they go to bed, when they take naps, etc.). This information is crucial for knowing when to schedule the scan visit. For scans that happen during natural sleep, it is typically more effective to schedule the visit during nap time, or after the child's bedtime. For awake scans, it may be preferable to schedule the visit shortly *after* a nap so that the child is well-rested and less likely to be fussy.

❯ The **second most important** topic is how long it generally takes the infant/toddler to fall asleep. Again, this is useful for knowing when to ask the family to arrive for the visit and when to book the scanner, especially for researchers who pay for time the scanner is booked rather than the amount of time the scanner is used during the visit.

❯ The **third most important** topic to cover is how easily the infant/toddler wakes up once asleep. Although not a perfect measure, the answer to this question may give some insight into how successful the scan is likely to be. Answers that indicate the child can sleep through loud or varying noises are especially promising (e.g., because they have siblings at home, live in an urban environment, often sleep while outside of the home, etc.). For infants who have not had experience sleeping in louder environments, it is particularly important to provide the family with MRI sounds prior to the visit so the infant has an opportunity to habituate to these noises.

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booked. This is of vast service to investigators, as inflated resource needs in infant/toddler imaging can undermine research budgets and, further, the presence of institutional support can influence funding determinations.

3.5. Study design considerations

A challenge among researchers who study infant longitudinal brain development is whether to prioritize protocol consistency or to optimize parameters for participant age. On one hand, maintaining consistency minimizes the introduction of confounds resulting from changing sequence parameters or visit-related features such as time of scan. On the other hand, certain MRI sequences are more effective for specific age groups and using sequences that are optimized for one developmental stage and not another introduces systematic bias that could artificially inflate or mask age-related change (Turesky et al., 2021). Our data show that experts are split on which approach is optimal: 48% of experts prioritize maintaining consistency in longitudinal research designs, and 42% prioritize optimizing the protocol for the age being scanned. Experts report a similar split for cross-sectional developmental studies with 40% valuing consistency and 60% valuing optimization.

3.6. Safety and health
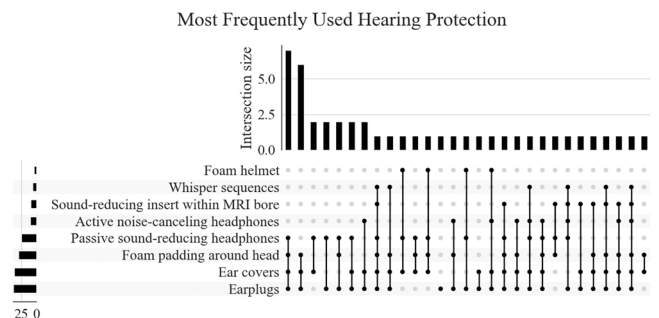
3.6.1. Hearing protection

The sound pressure level of traditional 3 T MRI scanners typically ranges from 90 to 99 dB (Ellis et al., 2020; Tkach et al., 2015), but rsfMRI and task-based fMRI sequences – which are among the most commonly collected scans in infant and toddler MRI – can reach a sound pressure level of 118 dB, which is roughly equivalent to an aircraft during take-off (Amaro et al., 2002). Given that sound pressure levels above 85 dB have been shown to negatively impact the auditory system (National Institutes of Health, 2019), appropriate hearing protection during MRI scans is essential. Sounds below 70 dB are generally considered safe (National Institutes of Health, 2019), but for very young infants, particularly those who are preterm or very low birthweight, persistent sound levels above 60 dB may increase stress levels and negatively impact growth trajectories (Graven, 2000). For context, 60 dB is roughly the equivalent of conversations in a restaurant or office (Purdue University, 2000).

The most commonly used forms of hearing protection for infant and toddler scans include earplugs that provide 22–29 dB noise reduction, ear covers such as minimuffs (7 dB noise reduction), passive sound-reducing headphones (up to 29 dB sound reduction), and foam padding around the head that serves the dual purpose of reducing conductance as well as movement (see Fig. 4). Active noise-canceling headphones can provide up to 60 dB of sound reduction according to manufacturer websites, but presently we find that few researchers endorse using these for infant and toddler MRI scans. It is possible that this relatively new technology will gain prevalence in coming years, especially if costs are reduced and adaptations are made to best serve infant/toddler head-coil geometry.

3.6.2. Radiology review & incidental findings

An important topic that spans all MRI research is how to address incidental findings among research participants. Policies regarding the mandatory review of research scans and discussion of results with participants differ at an institutional level, or even at the level of a research lab. Management of infant/toddler MRI incidental findings is complicated by lack of data about population-level prevalence of incidental findings among typically developing infants, by research sequences not being designed to detect neural anomalies, and by potential additive costs of clinical review. Our survey addressed several important aspects of this topic: prevalence of incidental findings among research

Fig. 4. Most frequently used hearing protection during infant and toddler MRI scans. The number of researchers using each individual form of hearing protection is indicated by the bars on the y-axis. The bar graph along the x axis indicates the number of researchers who report using each combination of hearing protection. nearly all researchers apply at least 3 forms of hearing protection to infants and toddlers during MRI visits.

participants, institutional policies, and practices for communicating findings to families. Across labs and studies, experts estimate that a median of 3% of infant and toddler MRI scans will reveal a neurological abnormality (*IQR*=1.75–5.25). However, incidental findings can occur in as many as 20% of scans depending on the study population. For example, there are higher rates of incidental findings in samples of preterm infants and in the context of delivery complications that increase risk of perinatal stroke. These estimates do *not* represent population-level incidence of neurological abnormalities during early development given that most developmental MRI studies utilize convenience and not nationally representative samples (LeWinn et al., 2017). Moreover, these estimates are further complicated by the plasticity of the developing brain. Approximately 34% ($n = 13$) of experts report personally observing neurological abnormalities in infants resolve with age. The possibility that a neurological abnormality may spontaneously resolve with age and therefore have little measurable impact on a child's functional development is an important consideration to weigh when disclosing incidental findings to families. In terms of best practices, half of experts queried believe it is necessary to provide a copy of the MRI scan or a letter describing the findings to families, and one third believe it is necessary to refer families to a specialist for follow-up. Another area lacking consensus is whether a pediatric neuroradiologist should read every infant or toddler scan (55%, $n = 21$) versus only scans flagged by the research team (47%, $n = 18$). Indeed, there was not a single recommendation for handling incidental findings that was endorsed by at least 75% of experts, and this was observed among US-based and non-US-based experts (see supplementary materials).

3.6.3. COVID-19 related precautions

At the time of survey administration in February 2021, 27% of experts reported institution level restrictions on in-person research activities. In addition, experts who conducted MRI research studies during this time reported significant drops in productivity due to enhanced institutional procedural restrictions and/or due to decreases in family interest for voluntary research. We divided the number of infant and toddler scans that experts estimate completing since scanning resumed at their institution by the number they would typically complete during that same time frame. Based on these numbers, we estimate that infant/toddler MRI scanning was happening at 42% capacity even at institutions that allowed in-person visits (*IQR*=27–50). In terms of procedural changes, the most commonly recommended precautions included utilization of masks by staff and parents, physical distancing, and booking the scanner for extra time to include enhanced cleaning protocols (see Table 3 for all recommended COVID-19 precautions). The extent to which these protocol adjustments impact effectiveness of infant and toddler MRI data acquisition remains an open question.

4. Discussion

This study consolidates practices, recommendations, and lived experience across experts in infant and toddler neuroimaging using direct expert reports. We identify variable rates of scan success across labs and mixed practices regarding longitudinal study design. However, several points of consensus stand out: researchers are careful about hearing protection, with most researchers utilizing at least 3 sound reduction techniques. Toddlers tend to require the most preparation prior to the scan visit. Researchers also tend to agree on the factors that contribute to scan success, including the importance of a sleep interview prior to any visit that entails scanning during natural sleep.

One of the major takeaways from this study is that acquiring infant and toddler MRI data is a time-consuming and expensive endeavor, with nearly one in five scan visits resulting in *no* usable data. In addition to high failure rates, unpredictable waking, fussing, and motion during attempted scans further decrease the amount of usable data even when the scan visit is successful. These difficulties are heightened within

Table 3
Recommended COVID-19 Precautions.

COVID precaution	Number of experts who believe the precaution is advisable
Symptom check with families prior to visit	**34 (92%)**
Symptom check with staff prior to visit	**32 (86%)**
Everyone wears face mask	**31 (84%)**
Schedule extra time for cleaning	**31 (84%)**
Reduced number of staff at visit	**29 (78%)**
Temperature check of family upon arrival	26 (70%)
Maintain social distancing	26 (70%)
Remote screening/consent	25 (68%)
Staff wears extra PPE (gloves, face shields)	21 (57%)
Temperature check of staff upon arrival	20 (54%)
Staff get tested regularly	15 (41%)
Contact tracing	14 (38%)
Use floor markings to aid distancing	12 (32%)
Ask about baby mask preferences	3 (8%)
Parents get COVID test prior to visit	3 (8%)

Note. COVID-19 precautions that are deemed advisable by at least 75% of experts are bolded.

specific age groups, with researchers consistently reporting children between the ages of 1 and 3 years as the most difficult age to scan. Data collection challenges in this age range contribute to a dearth of published literature on MRI-based metrics of human brain development from 1 to 3 years of age (Copeland et al., 2021). Enhanced accommodations and flexibility from MRI facilities would improve feasibility of scanning this age group, which in turn will fill an important gap in our scientific knowledge about typical and atypical brain development.

Early life neuroimaging requires unique considerations in terms of acquisition techniques, data quality, cost, and safety, and scientists invest significant time, effort, and resources into protecting their participants while obtaining this valuable data. However, the institutional and funding structures that support adult neuroimaging will not go as far in supporting the acquisition of high-quality, reproducible infant and toddler MRI scans. And yet these data are integral for advancing our collective understanding of human neurodevelopment. Moreover, inter-institutional variability in the support provided for early life neuroimaging impacts funding decisions and the pragmatism of this scientific endeavor for research labs. As such, MRI researchers tend to cluster at specific academic institutions that are usually located in or near urban settings. The location of research labs impacts the makeup of participant samples; without more universal support for early life neuroimaging across institutions, recruiting and retaining diverse samples for developmental neuroscience studies will continue to be a challenge within the field (LeWinn et al., 2017). In the present study, we found that 52% of experts report being dissatisfied with the racial/ethnic and sociodemographic diversity in currently published pediatric neuroimaging studies.

Another takeaway from this study is that using multiple methods of hearing protection is needed, and that infant hearing protection may need special consideration during the first 6 months postpartum as the auditory system undergoes particularly rapid development during this time (Graven and Browne, 2008). In adults, the National Institutes of Health recommends reducing sound levels to below 85 dB which is achievable with the use of earplugs and ear covers such as minimuffs. However, sound levels should be further reduced by an additional 20–30 dB for very young or preterm infants. To meet this standard, headphones that provide additional sound reduction are an essential supplement to the use of earplugs and ear covers. All three of these hearing protection methods are utilized by almost all infant and toddler researchers.

It is important to note that evaluating the overall sound pressure levels produced by MRI sequences misses other aspects of the auditory environment that may impact the developing ear (McJury, 2021). For example, earplugs do not filter all frequencies equally, and different frequencies are blocked by foam versus silicone earplugs (Kvaløy et al., 2010). Future infant and toddler MRI research could use in-ear sound level monitoring across multiple frequencies to quantitatively assess different combinations of hearing protection, similar to work that has been completed in adults (Ravicz and Melcher, 2001). MRI sequences are also characterized by drastic shifts in auditory exposure. Sudden changes from relative quiet to loud, unfamiliar sounds disrupt the auditory system's natural ability to adapt to slowly increasing sounds, a process that protects hearing in the context of high sound levels (Fuchs and Lauer, 2019). Preliminary research in non-human animals suggests that prior exposure to loud but non-damaging sound levels may reduce loss of cochlear synapses following damaging sound level exposure (Fan et al., 2020). One area of further study could involve utilizing the auditory system's natural protective processes to improve scan success. It may be helpful to examine whether exposure to gradually increasing noise levels in the seconds preceding the beginning of an MRI sequence facilitates auditory adaptation in infants and toddlers who are completing MRI scans, and whether this adaptation decreases infant waking and startles during the scan.

Although there are several areas of consensus (e.g., success rates, importance of family comfort, hearing protection), heterogenous practices remain in other areas of infant and toddler MRI acquisition. One such heterogenous area that has particular implication for comparing results across studies is whether and how to adapt data collection protocols across different age groups in cross-sectional and longitudinal studies. Here, researchers are split nearly down the middle about whether it is more optimal to maintain consistency across visits that span different ages or to optimize protocols for the age being scanned. Comparing age-related findings across studies from different research groups is complicated by this heterogeneity in study design choice and will at minimum need to be evaluated as a confounding factor in future meta-analyses on age-related brain changes. A recent review argues that maintaining consistency in protocols across different stages of early development introduces systematic bias due to age-related differences in the effectiveness of particular sequence parameters or analytic choices (Turesky et al., 2021). Some groups may therefore detect what appears to be age-related change in brain metrics, but these developmental differences may be an artifact of sequence, preprocessing, or analytic choices that are more sensitive for one age versus another rather than resulting from meaningful neurobiological differences. The converse could also be true in that sequences, preprocessing, or analytic choices that are not equally sensitive for all ages could *mask* age-related effects. The lack of consistency across research groups on these important study design decisions interferes with the comparison of noted age-related change across different studies, which is crucial for evaluating reproducibility of effects.

Experts estimate that in their own research samples, the prevalence of incidental findings among newborns, infants, and toddlers is 3%. However, this estimate is limited given that research samples may not be representative of a general population and because rigorous review of all images is not a ubiquitous practice. There may therefore be neurological abnormalities that are missed by research staff and thus not included in the above estimate. Indeed, a retrospective analysis of anatomical images from 500 neonates enrolled in the developing human connectome project estimates the prevalence of neurological abnormalities to be as high as 47%. However, very few of these neurological abnormalities were associated with clinically significant delays in neurodevelopment at 18 months of age (Carney et al., 2021). These findings suggest that neurological abnormalities may be quite common in the neonatal period, and do not necessarily negatively impact long-term child development in many cases. This is consistent with reports from experts in our sample that 30% of identified neurological abnormalities in

infants and toddlers may resolve on their own without intervention.

The present results should be considered within the context of study limitations. In the present sample of experts, almost every researcher typically collects at least one type of functional scan in their infant and toddler neuroimaging studies. This may reflect actual prevalence of functional scanning in the field or may be an artifact of the search terms used in our recruitment strategy, which were skewed towards functional metrics. The extent to which these findings generalize to labs that exclusively collect anatomical MRI data is therefore unclear. Our sample was additionally composed predominantly of experts conducting research within the United States, which may have different ethical conventions compared to other countries. Finally, a small number of our experts conducted research at the same overarching institution, so practices that are required by that institution may be overrepresented in our data.

This report on strategies used *across* different labs and different institutions reveals commonalities and heterogeneity in MRI data acquisition strategies when working with infants and toddlers. The common practices identified in this analysis may serve as a basis for the development of gold standard methods that can be consistently employed across research groups. Greater consistency in data acquisition is an integral step towards more efficacious data sharing and replication of findings across research groups. Moreover, enhancing transparency about specific methods utilized across labs facilitates learning within a field that is still in its infancy and riddled with low success rates. These endeavors strengthen the foundation of open, rigorous, replicable science in early life neuroimaging.

CRediT authorship contribution statement

Cassandra L. Hendrix: Conceptualization, Methodology, Investigation, Formal analysis, Data curation, Writing – original draft, Visualization, Project administration. **Moriah E. Thomason:** Conceptualization, Methodology, Writing – original draft, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

I have included a link where manuscript data may be downloaded.

Acknowledgments

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.dcn.2022.101060.

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