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REVIEW

Measuring infant handedness reliably from reaching: A systematic review

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ABSTRACT
Researchers have utilized reaching paradigms to measure infant handedness for more than a century. However, methods vary widely. Recent research has identified that the number of trials used in assessment is critical with the recommendation that at least 15 trials are necessary to reliably classify infants into handedness categories via statistical cutoffs. As a first step towards establishing best practices for the field, we identified, categorized, and synthesized findings according to trial number from studies that utilized reaching to index handedness in infants across the first two years of life using PRISMA guidelines. Database searches were conducted in PsycINFO, PubMed, and Ovid MEDLINE®. All articles published through May 2018 were included. Additional records were identified through other sources. After removing duplicates, 1,116 records were screened using the online software program Abstrackr. Of these records, 125 full-text articles were further assessed for eligibility, and 87 articles were included in the qualitative synthesis. Results revealed that the majority of papers published since 1890 (70%) do not meet the 15-trial minimum criterion for statistically reliable measurement of infant handedness. Broad themes from articles meeting the measurement criterion and implications for future research are discussed.

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KEYWORDS Infant; handedness; hand preference; laterality; reaching

Introduction

Handedness, or a bias in the use of one hand over the other, has long-held the attention of researchers because at least 85% of the adult population is right-handed (Annett, 1985, 2002). Efforts to understand the developmental origins of this robust patterning in adults have led to more than a century of publications on infant hand use. Yet, there is no "gold standard" measure for infant handedness. Methods to assess infants for handedness vary widely, and results are likewise mixed. Various investigators have started to draw attention to the lack of measurement consensus in the field and its potential

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impact on interpreting data by empirically examining the number of trials used to assess infant handedness. Directly comparing two of the more widely-used measures, Campbell, Marcinowski, Latta, and Michel (2015) determined that trial number indeed affected how infants were classified at monthly intervals as well as how infants were classified into handedness trajectories spanning a 7-month period. Fagard, Margules, Lopez, Granjon, and Huet (2017) analysed different combinations of trials from a single assessment and similarly concluded that the number of trials is critical, resulting in their recommendation that 15 trials are necessary to reliably classify infants into handedness categories.

To our knowledge, there has been no attempt to synthesize prior work on infant handedness according to a measurement benchmark such as trial number. The rationale for undertaking this task was to begin to disentangle prior findings as well as to establish best practices for the field going forward. We therefore conducted a systematic review of the infant handedness literature applying the Fagard et al. (2017) 15-trial minimum recommendation. With at least 15 trials, the binomial test can be used to statistically determine infants' preferences. Our primary objective was to determine how many published studies met criterion for reliable measurement. Although preference has been assessed from various manual skills in infants such as holding duration or manipulation, we focused on reaching as it is the most commonly utilized metric in infant handedness paradigms. Our secondary objectives were to summarize trends in the research that met criterion, and to pose questions to guide future research.

Methods

This systematic review of the literature on infant hand preference for reaching was conducted and reported using the Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) guidelines (Moher, Liberati, Tetzlaff, & Altman, 2009).

Eligibility criteria

Only peer-reviewed published studies that calculated hand preference from a reaching and grasping measure in typically developing infants (aged 4 months to 2 years) were included. We chose 4 months as the starting point in our survey of the literature because it is the typical onset of reaching, and 2-years-old as the cutoff when children are considered toddlers. Studies involving atypical infant populations were included only if analyses were conducted separately for a control group of typically developing infants; however, only data from typically developing infants were included in the review. Studies were excluded at the full-text screening stage if they were literature reviews; book chapters without original data; written in a language other than English; reaching was not scored separately from other manual action types (e.g., manipulation, holding, grip strength); hand preference was not calculated (i.e., frequency of left vs. right hand use); no trial-level data were provided; or multiple ages were examined and data could not be extracted for the target age range of the review (Figure 1). All study designs (e.g., case study, single timepoint, cross-sectional, longitudinal, mixed methods) were considered. No studies were excluded based on additional methodological considerations such as how responses were elicited from infants, or the type of object(s) used.

Information sources and search strategy

The literature search was conducted in three separate databases: PsycINFO, PubMed, and Ovid MEDLINE® in May 2018. No date restriction was used, and all articles published through May 2018 were included. Searches used

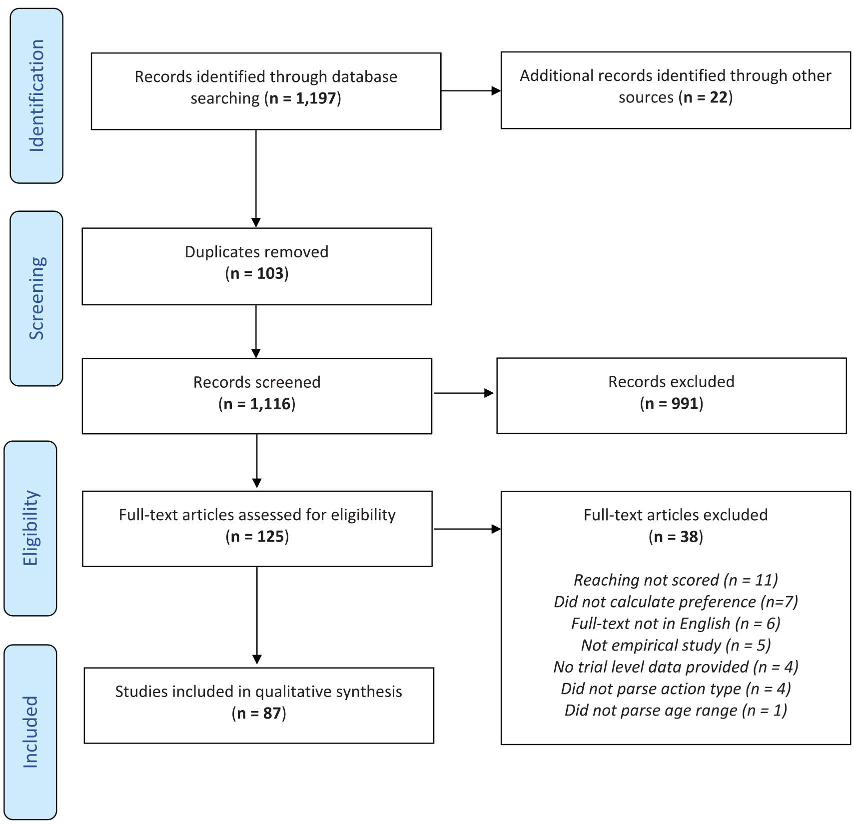

Figure 1. PRISMA flow chart.

the following combination of terms: "handedness," "laterality," "hand preference," "reaching," "prehension," and "infant." When permitted by the search engine options, searches were narrowed by age range, human subjects, and peer-reviewed articles only. Additional records were identified through other sources including review of individual academic websites of authors identified through database searching; citations within articles identified through database searching; and hand search via Google Scholar using the above combination of search terms.

Study selection

Results from each database search were uploaded to Abstrackr (Wallace, Small, Brodley, Lau, & Trikalinos, 2012), an open-source online abstract screening software for systematic reviews. Both authors manually screened all of the abstracts. Discrepancies were resolved through discussion and full-text review. All articles identified through other sources were subjected to full-text review by the first author to determine eligibility and inclusion in the systematic review. Duplicates were removed and a final list of included studies was compiled by the first author.

Data collection process and data items

Data extracted from eligible studies included the study design and age(s) examined, the number of participants, and the number of trials. Data were first entered into a spreadsheet created by the second author. The first author then verified all data items independently in a second step. For the subset of eligible studies where 15 or more trials were administered, an interpretation of the major themes was also performed by the first author and included in the systematic review.

Risk of bias

Risk of bias in individual studies was mitigated by detailed reading of the methods and results sections of each full-text article during eligibility screening, as well as during data collection. Risk of bias across studies (e.g., selective reporting, publication bias) was presumed to be low or nonexistent as the literature on infant handedness is known to have mixed findings. Risk of bias was not formally analysed given that the search focused on methods, and not results.

Synthesis of results

Eligible studies were classified into one of three results categories: (1) studies that examined hand preference for reaching in infants with underspecified methods; (2) studies that examined hand preference for reaching in infants that utilized less than 15 trials in the assessment; or (3) studies that examined hand preference for reaching in infants that utilized 15 or more trials in the assessment. Only studies utilizing 15 or more trials are discussed in detail in the results.

Results

Study selection

Database searching identified 1,197 records, and 22 additional records were identified through other sources. After removing duplicates, 1,116 records were screened at the abstract stage. Of these records, 125 full-text articles were further assessed for eligibility. Full-text articles were excluded if reaching was not scored ($N = 11$; Bates, O'Connell, Vaid, Sledge, & Oakes, 1986; Caplan & Kinsbourne, 1976; Cochet, 2012; Geerts, Einspieler, Dibiasi, Garzarolli, & Bos, 2003; Kohen-Raz, 1966; Lynch, Lee, Bhat, & Galloway, 2008; Ramsay, 1984, 1985; Streri, 2002; Vauclair & Cochet, 2013; Vauclair & Imbault, 2009); hand preference was not calculated ($N = 7$; Atun-Einy, Berger, Ducz, & Sher, 2014; Corbetta & Bojczyk, 2002; Corbetta & Thelen, 1996; Coryell & Michel, 1978; Ekberg et al., 2013; Morange-Majoux, Peze, & Bloch, 2000; Rönnqvist & Domellöf, 2006); full-text was not in English ($N = 6$; Flament, 1974; Ojima, 1986; Shiotani et al., 2010; Sounalet, 1975; Tachibana, 2009; Xintian, Minggao, Huikun, & Kuihe, 1984); not an empirical study ($N = 5$; Harris, 2003; McDonnell, 1979; Meunier et al., 2013; Michel, 2002; Palmer, 1964); no trial-level data were provided ($N = 4$; Crichton-Browne, 1907; Nice, 1918; Smith, 1917; Sully, 1896); did not parse action type ($N = 4$; Piek, Gasson, Barrett, & Case, 2002; Provins, Dalziel, & Higginbottom, 1987; Tirosh, Stein, & Harel, 1997; Tirosh, Stein, Harel, & Scher, 1999); or did not parse age range ($N = 1$; Cochet & Vauclair, 2010). A total of 87 studies were included in the qualitative synthesis. A PRISMA flow diagram is given in Figure 1.

Study characteristics

Each study included in the qualitative synthesis was classified into one of three categories based on the number of trials used in the assessment of infant handedness from reaching. In addition to trial number, the design of the study and age(s) examined as well as the number of participants was extracted. Studies that did not meet the minimum of 15 trials can be found in Tables 1 and 2. The systematic review revealed a small subset of studies that reported on infant hand preference for reaching, but did not clearly define what constituted a trial and/or how many trials were used in the design. These studies with underspecified methods are listed in Table 1. Of the 14 studies in Table 1, nine studies were longitudinal, three studies were cross-sectional, one study utilized a mixed design, and one study collected data at a single timepoint. The studies in Table 1 sampled infants from 4 to 24 months of age. The number of participants ranged from 1 to 178, and the articles were published between 1890 and 2013.

The majority of articles identified in the systematic review were classified as not meeting criterion for reliable measurement of infant handedness. The articles that utilized less than 15 trials to assess infant handedness from reaching are given in Table 2. Of the 47 studies in Table 2, 17 studies were longitudinal, 13 studies were cross-sectional, one study utilized a mixed design, and 16 studies collected data at a single timepoint. The studies in Table 2 sampled infants from 4 months to 24 months. The number of participants ranged from 2 to 228, and the articles were published between 1966 and 2016.

Table 1. Studies examining hand preference for reaching in infants with underspecified methods.

Source	Design/age(s) examined	*N*	Number of trials
Baldwin (1890)	Longitudinal over the first year of life	1	Observation; no discrete trials
Marsden (1903)	Longitudinal over the first year of life	1	No more than 14 trials per session
Major (1906)	Longitudinal 4–20 months[a]	1	Observation; no discrete trials
Dearborn (1910)	Longitudinal over the first year of life	1	Observation; no discrete trials
Woolley (1910)	Single timepoint: repeated observations at 7 months old	1	468 and 70 trials across two tasks[b]
Shinn (1914)[c]	Longitudinal over the first year of life	1	Observation; no discrete trials
Fenton (1925)[c]	Longitudinal over the first year of life	1	Observation; no discrete trials
Lippman (1927)	Mixed design 4–18 months	178	384[d]
Watson (1930)[c]	Longitudinal 150 days to 12 months	20	10–20 trials per session
Gesell and Ames (1947)	Longitudinal 4–15 months; 20 months[a]	8	Not specified
Young, Lock, and Service (1985)	Cross-sectional 8–15 months	80	Observation; no discrete trials
Konishi, Mikawa, and Suzuki (1986)	Longitudinal at 9 and 18 months	44	Not specified[e]
Ramsay and Weber (1986)	Cross-sectional in two age bands: 12–13 months and 17–19 months	36	Up to 40 trials across three sessions one week apart; descriptive data not provided
Sacrey, Arnold, Whishaw, and Gonzalez (2013)	Cross-sectional at 1 and 2 years of age	20	Unspecified number of items in an array; no discrete trials

[a]Additional data were reported but are not included here because they are outside of the age range of this systematic review.
[b]Numbers reflect summed totals; the number of trials per session and the number of test sessions was not specified.
[c]Details of study obtained from Giesecke (1936).
[d]Number reflects summed total across all infants; number of trials/observations per infant was not specified.
[e]Criterion for preference was reaching for a toy with one hand three or more times.

Table 2. Studies examining hand preference for reaching in infants that utilized less than 15 trials.

Source	Design/age(s) examined	*N*	Number of trials
Cohen (1966)	Single timepoint: 8 months	100	12
Seth (1973)	Longitudinal: monthly 5–13 months	19	3
Bresson, Maury, Pieraut-Le Bonniec, and de Schonen (1977)	Longitudinal: 17–40 weeks with subset followed weekly and others followed three consecutive weeks only in the testing range	22	8
Ramsay (1980)	Cross-sectional: 5, 7, and 9 months; most 5-month-olds retested at 9 months of age	48	4
Goodwin and Michel (1981)	Single timepoint: 19 weeks	76	7
Michel (1981)	Longitudinal: 16 and 22 weeks	20	4
Lewkowicz and Turkewitz (1982)	Cross-sectional: 6 and 8 months	48	12 or 15[a]
Michel and Harkins (1986)[b]	Longitudinal: 16 and 22 weeks	20	4 (16 weeks); 8 (22 weeks)
Goldfield (1989)	Longitudinal: weekly 6 months until crawling	15	Up to 6
Shucard and Shucard (1990)	Single timepoint: 6 months	20	12[c]
Xintian, Minggao, Huikun, and Kuihe (1991)	Cross-sectional: 6–9 months; 10–12 months; 1–1.5 years; 1.5–2 years	200[d]	14
Benson, Cherny, Haith, and Fulker (1993)	Longitudinal: 5, 7, and 9 months	228	12
Butterworth and Morissette (1996)	Longitudinal: monthly 8.5–14.5 months	27	4
Morange and Bloch (1996)	Cross-sectional: 4, 5, 6, and 7 months	32	12
Corbetta and Thelen (1999)	Longitudinal: weekly 16–30 weeks; biweekly 30–52 weeks	4	8–12
McCarty, Clifton, and Collard (1999)	Cross-sectional: 9, 14 and 19 months	36	8
Fagard and Marks (2000)	Cross-sectional: 18 and 24 months	20	10
Van Hof, Van der Kamp, and Savelsbergh (2002)	Longitudinal: 18 and 26 weeks	18	6[e]
Stroganova, Posikera, Pushina, and Orekhova (2003)	Cross-sectional: 8 and 11 months	90	4–9
Stroganova, Pushina, Orekhova, Posikera, and Tsetlin (2004)	Single timepoint: 11 months	52	4–10
Fagard and Lockman (2005)	Cross-sectional in two age bands: 6–12 months and 18–24 months	83	7–9[f]
Corbetta, Williams, and Snapp-Childs (2006)	Longitudinal: 6–8 months to 10–12 months (17 weeks of observation per infant)	2[g]	8[h]
Fagard and Lemoine (2006)	Single timepoint: 12- to 15-month-olds	24	5[f]
Sacco, Moutard, and Fagard (2006)	Single timepoint: 10- to 14-month-olds	12[f]	7–10[f,i]
Marschik et al. (2008)	Single timepoint: 5 months	20	12
Suzuki, Ando, and Satou (2009)	Single timepoint: 18 months	38	9
Morange-Majoux and Dellatolas (2010)	Single timepoint: 17 weeks	24	6[j]
Scola and Vauclair (2010)	Single timepoint: 19 months	40	6[k]
Berger, Friedman, and Polis (2011)	Study 1 = Single timepoint: 13 months	88	6–12
	Study 2 = Longitudinal with 9 infants assessed five times at locomotor milestones and 24 matched controls assessed once	33	6–12
Esseily, Jacquet, and Fagard (2011)	Single timepoint: 14 months	22	7[l]
Morange-Majoux (2011)	Single timepoint: 4–6 months	31	2

(*Continued*)

Table 2. Continued.

Source	Design/age(s) examined	*N*	Number of trials
Jacquet, Esseily, Rider, and Fagard (2012)	Longitudinal: 8, 11, 14, 17, and 20 months	26	7[m]
Sacrey, Karl, and Whishaw (2012)	Longitudinal: biweekly 6–12 months	8	3[n]
Morange-Majoux, Lemoine, and Dellatolas (2013)	Longitudinal: biweekly 20–30 weeks	12	10
Potier, Meguerditchian, and Fagard (2013)	Cross-sectional: 12, 16, and 20 months	41	5
Rat-Fischer, O'Regan, and Fagard (2013)	Cross-sectional: 16, 18, 20, and 22 months	48	5
Corbetta, Friedman, and Bell (2014)	Single timepoint: 12 months	47	10–11
Fagard, Sirri, and Rama (2014)	Cross-sectional: 18 and 24 months	32	7
Jacobsohn, Rodrigues, Vasconcelos, Corbetta, and Barreiros (2014)	Longitudinal: 12, 15, and 18 months	19	3[o]
Morange-Majoux and Devouche (2014)	Single timepoint: 6 months	36	9
Nelson, Konidaris, and Berthier (2014)	Cross-sectional: 11 and 14 months	42	5
Pogetti, de Souza, Tudella, and Teixeira (2014)	Single timepoint: 5 months[p]	15	4
Campbell, Marcinowski, Latta, et al. (2015)	Longitudinal: monthly 8–14 months	150	7[q]
Chen, Tafone, Lo, and Heathcock (2015)	Longitudinal: biweekly 2–7 months	16[g]	3
Domellöf, Barbu-Roth, Ronnqvist, Jacquet, and Fagard (2015)	Cross-sectional: 8 and 10 months	12	7
Mumford and Kita (2016)	Single timepoint: 10–12 month range	16	10
Petkovic, Chokron, and Fagard (2016)	Longitudinal: every two months 6–12 months	10[g]	7

[a]Hand use data from children who received 15 trials cannot be separated from children who received only 12 trials.
[b]Children received more than 15 trials at older timepoints in this study, and these data are reported in Table 3.
[c]Six trials were given over 2 sessions separated by up to 12 days.
[d]Reported N excludes children over 2 years of age in the study.
[e]Trials were repeated up to three times if the infant did not reach.
[f]Data are from the simple grasping task.
[g]Reported N is for typically developing children only.
[h]Children received 16 trials per session, however only 8 were used to calculate reaching preference.
[i]Data are from grasping in the spontaneous condition.
[j]Data are from the free condition.
[k]Data are from Study 4: Tasks 1 and 2, which were analysed together as unimanual preference.
[l]Trial number calculated excluding the bimanual item.
[m]Children received 7 trials on the Baby Handedness Test, and a separate 7 trials on the Bishop QHP.
[n]Children were filmed reaching for a minimum of 10 min or 20 successful reaches, however only 3 reaches were analysed.
[o]Task given until 3 reaches were recorded.
[p]Data are from the baseline condition with full vision.
[q]Trial number was calculated for the Fagard task excluding the bimanual items. Data from the Michel task are reported in Table 3.

The remaining eligible articles in the systematic review met the criterion for reliable measurement of infant handedness. The articles that utilized 15 or more trials to assess infant handedness from reaching are given in Table 3. Of the 28 studies in Table 3, 21 studies were longitudinal, six studies were cross-sectional, no study used a mixed design, and one study collected data at a single timepoint. The number of participants ranged from 8 to 388, and the articles were published between 1936 and 2018. Two studies were included in more than one results category (Campbell, Marcinowski, Latta,

Table 3. Studies examining hand preference for reaching in infants that utilized 15 or more trials.

Source	Design/age(s) examined	*N*	Number of trials
Giesecke (1936)[a]	Longitudinal: 6–17 months	8	20–35
Ramsay and Willis (1984)	Longitudinal: weekly from 5 months until 8 weeks post babbling onset	30	20
Carlson and Harris (1985)	Longitudinal: every 3 weeks 24–39 weeks; 52 weeks (7 sessions total)	32	54
Michel et al. (1985)	Cross-sectional: 6–13 months	96	28[b]
Goldfield and Michel (1986)	Cross-sectional: 7–12 months	57	18[c]
Michel and Harkins (1986)[d]	Longitudinal: 32, 40, 51, 60, 74 weeks	20	20[b]
Humphrey and Humphrey (1987)	Cross-sectional: 5–8 months; 9–12 months	100	15
Harkins and Michel (1988)	Cross-sectional: 6–13 months	42	28
McCormick and Maurer (1988)	Longitudinal: 3 sessions at 6 months each separated by 1 week	36	24
Cornwell et al. (1991)	Cross-sectional: 9, 13, and 20 months	63	15–48
Michel (1992)	Longitudinal: 7, 9, and 11 months	28	28
Michel et al. (2002)	Longitudinal: 7, 9, and 11 months	154	28
Hinojosa et al. (2003)	Longitudinal: 7, 9, and 11 months	25	28
Michel et al. (2006)	Longitudinal: 7, 9, 11, and 13 months	51	28
Kotwica et al. (2008)	Longitudinal: 7, 9, 11, and 13 months	38	28
Fagard et al. (2009)	Cross-sectional: 6, 8, and 10 months	21	20–30
Ferre et al. (2010)	Longitudinal: monthly 6–14 months	85	34
Meunier et al. (2012)	Longitudinal: 14, 17, and 20 months	10	25[e]
Souza et al. (2012)	Single timepoint: 5 months	23	15
Nelson et al. (2013)	Longitudinal: monthly 6–14 months	38	34[f]
Babik et al. (2014)	Longitudinal: monthly 6–14 months	275	34
Michel et al. (2014)	Longitudinal: monthly 6–14 months	328	32
Nelson, Campbell, et al. (2014)	Longitudinal: monthly 6–14 months	38	32
Campbell, Marcinowski, Babik, et al. (2015)	Longitudinal: monthly 6–14 months	90	32
Campbell, Marcinowski, Latta, et al. (2015)	Longitudinal: monthly 8–14 months	150	32[g]
Marcinowski et al. (2016)	Longitudinal: monthly 6–14 months	131	32
Fagard et al. (2017)	Longitudinal: 9 and 11 months	46	34
Campbell et al. (2018)	Longitudinal: monthly 6–14 months	388	34

[a]Data are from subjects 1–8. The ages tested, the testing interval, and number of trials varied by subject.
[b]Data are from the reaching task.
[c]Data are from the handedness task.
[d]Children received less than 15 trials at younger timepoints in this study, and these data are reported in Table 2.
[e]Data are from the grasping task.
[f]Data are from the infant handedness procedure.
[g]Trial number was calculated for the Michel task. Data from the Fagard task excluding the bimanual items are reported in Table 2.

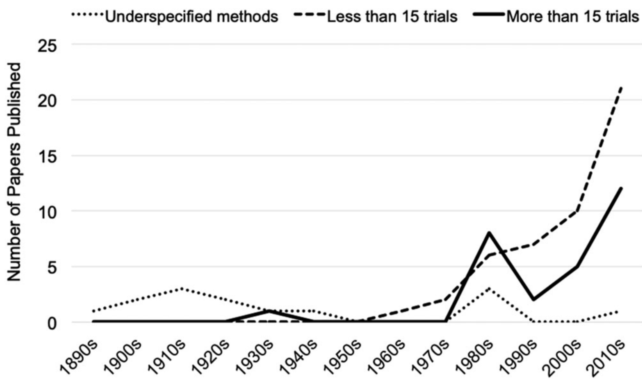

Figure 2. Historical timeline of the number of papers published on infant handedness for reaching between the 1890s and the 2010s categorized by underspecified methods, assessment using less than 15 trials, or assessment using more than 15 trials.

et al., 2015; Michel & Harkins, 1986); these studies had some data that did not meet the 15-trial criterion (reported in Table 2) and some data that did meet the 15-trial criterion (reported in Table 3).

A historical timeline of all of the studies from the qualitative synthesis grouped by table for each decade starting with the 1890s through 2010s is given in Figure 2. The period spanning the 1890s to 1920s was exclusively studies with underspecified methods. Many of these studies were "baby biographies" that were popular in psychology at that time. The first study identified in the systematic review to meet criterion for reliable measurement was published in the 1930s. However, additional studies meeting criterion did not appear again in the literature until the 1980s. The 1980s brought a resurgence of interest in the topic of infant handedness, with a peak appearing in the historical timeline for studies with underspecified methods and studies meeting criterion, and a rising number of studies not meeting criterion for reliable measurement that has continued to the present day. Following a dip in publications in the 1990s, the number of studies meeting criterion has shown a linear increase across the 2000s and present decade. However, the number of studies conducted in this decade that do not meet criterion is nearly double the number that do meet criterion. Details of the studies meeting criterion for reliable measurement of infant handedness from reaching are discussed further in the next section.

Results of individual studies meeting criterion for reliable measurement

Age ranges for individual studies meeting criterion for reliable measurement were plotted using the minimum and maximum age in months that were

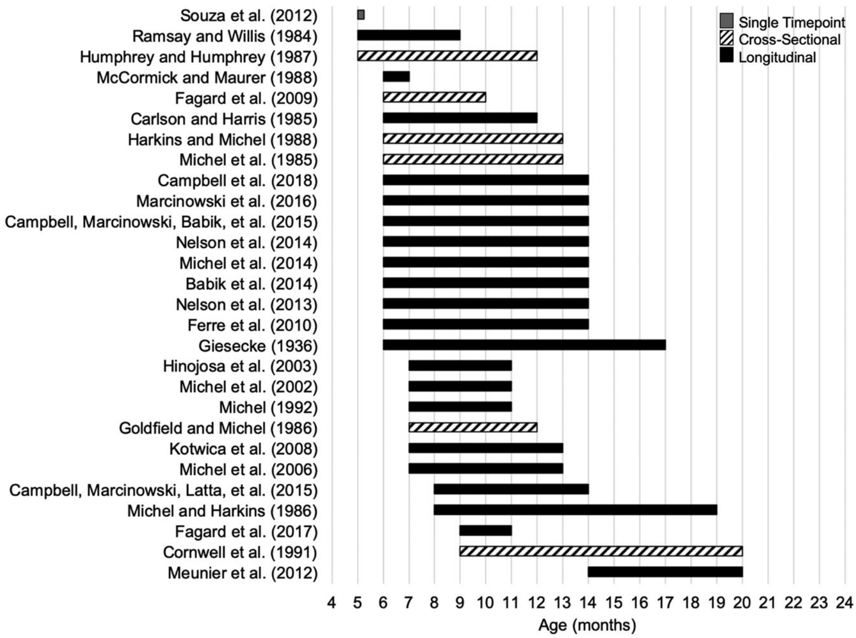

Figure 3. Age ranges for studies that reliably measured handedness from infant reaching. Range was calculated by subtracting the minimum age sampled in the study from the maximum age. Ages reported in weeks by the original authors were converted to months. Color denotes the study design such that grey indicates single timepoint, striped indicates cross-sectional, and black indicates longitudinal.

sampled regardless of the design (Figure 3). As Figure 3 illustrates, the majority of the studies assessed infants in the 6- to 14-month-old range. No study measured infant handedness with 15 or more trials at 4 months of age. One study collected data at 5 months only, and just three studies examined infants older than 14 months. No study identified in the systematic review reliably measured handedness for reaching between 21 and 24 months of age, revealing another age gap in the literature for future research. Next, the major themes from the papers meeting criterion are presented chronologically.

The first study to meet criterion for reliable measurement of infant handedness from reaching was a monograph by Giesecke (1936) that described eight case studies of infants examined longitudinally between 6 and 17 months of age. Notable findings from this work include that there are individual differences in the degree of preference between infants; handedness for reaching is related to side biases observed in other infant behaviours; and that the incidence of left-handedness (reported as 35% of the sample) may be higher in infants compared to adults.

Nearly 50 years passed before the next set of papers meeting criterion were published in the 1980s. Carlson and Harris (1985) continued with the theme of variability within and between infants in their longitudinal study over the first year of life. They also noted that infant hand use was susceptible to where the object was placed during testing, and introduced sex and familial handedness as measurement variables for infant studies. Similarly, Ramsay and Willis (1984) described variability in hand preference for reaching during the first year in a longitudinal design that also examined babbling onset together with hand use patterns. The authors emphasized differences between reaching hand preference and manipulation hand preference, indicating that it is critical to separate manual skills when measuring handedness. The next two studies by Michel, Ovrut, and Harkins (1985) and Goldfield and Michel (1986) utilized a cross-sectional design and also separately examined hand preference for reaching compared to hand use for other skills during the first year of life. The procedure introduced by Michel et al. (1985) formed the basis of an infant assessment that has been used in several publications meeting criterion, with slight modifications, through the present decade.

Additional studies during this period began to explore consistency in infant handedness in greater detail, as well as biological variables. Michel and Harkins (1986) described the majority of their longitudinal sample as having a consistent preference for reaching to objects during the first year and a half of life. Similarly, McCormick and Maurer (1988) identified a subset of their 6-month sample as exhibiting a consistent hand preference across test sessions. McCormick and Maurer (1988) also examined familial handedness with respect to infant hand use, as did Harkins and Michel (1988); neither study found a direct correspondence between parental handedness and infant handedness when comparing the incidence of left handedness in particular. Michel (1992) later reported that maternal, but not paternal, handedness influences infant hand use during play in the first year with right-handed infants and female infants showing the greatest concordance with maternal hand use patterns. Expanding on the theme of sex differences in infant handedness, Humphrey and Humphrey (1987) reported that right hand preference emerges earlier in females compared to males, a finding consistent with Carlson and Harris (1985). Cornwell, Harris, and Fitzgerald (1991) measured hand preference in a sample of only girls, finding a pattern of increasing right preference for reaching across three timepoints. Notably, these authors also drew attention to the idea that hand use/preference is task dependent—an important study design and measurement consideration.

By the next wave of papers meeting criterion for reliable measurement in the 2000s, evidence of a general right shift in infant handedness for reaching was clear, and investigators began examining subgroup patterns using larger samples and more advanced statistical techniques (Michel, Sheu, & Brumley, 2002). Individual differences continued to be emphasized with additional articles that examined stability and consistency patterning to further characterize the shape of developmental change in infant preferences for reaching

(Ferre, Babik, & Michel, 2010; Hinojosa, Sheu, & Michel, 2003; Michel, Tyler, Ferre, & Sheu, 2006). Another theme from this decade was articles that began to connect infant handedness for reaching to non-lateralized motor skills. Kotwica, Ferre, and Michel (2008) found that stable handedness was linked to advanced object management skills, while Fagard, Spelke, and von Hofsten (2009) reported that hand preference influenced age-related strategies for grasping a moving object over a similar age range during the first year.

The 2010s brought a comparative perspective to the literature on infant handedness for reaching with a publication by Meunier, Vauclair, and Fagard (2012) that compared infant hand use in the second year of life to baboons on the same task. Hand preference in both species was influenced by the position of the item in the test array, echoing the prior finding reported by Carlson and Harris (1985) that object placement matters when assessing handedness. Souza, de Azevedo Neto, Tudella, and Teixeira (2012) similarly reported an effect of object position on hand preference in their sample of 5-month-old infants. In addition, this study found no relationship between reaching hand preference and intermanual performance asymmetry as measured by kinematic analysis.

Efforts to link infant hand preference for reaching to later emerging behaviours using a cascade framework has dominated the papers appearing in the last decade identified in the review. Links were reported between infant hand preference for reaching and later toddler hand preference for role-differentiated bimanual manipulation (Nelson, Campbell, & Michel, 2013); language outcome at 2 years of age (Nelson, Campbell, & Michel, 2014); unimanual hand preference (Campbell, Marcinowski, Babik, & Michel, 2015); and the emergence of stacking skill (Marcinowski, Campbell, Faldowski, & Michel, 2016). By contrast, Babik, Campbell, and Michel (2014) reported no link between lateralized hand use for reaching and the development of postural skills using a longitudinal multilevel modelling approach. These authors made the distinction between handedness *expression* as a preference that is measured at a specific timepoint, and handedness *development* as preference captured across multiple timepoints in a trajectory-based approach. Michel, Babik, Sheu, and Campbell (2014) performed a latent class analysis on a large sample of 328 infants that were measured nine times at monthly intervals. Results revealed three different trajectory groups for the development of infant handedness measured from reaching: a group with a left preference, a group with a right preference, and a group with no preference but trending right. Analyses using combinations of one to four months (out of nine) did not reliably predict these groups. The authors raised the important question of what it means for development to be classified into one of these handedness trajectory groups. Another equally interesting and yet unanswered question is can we predict which handedness trajectory an infant will be in? A first step at examining this question empirically was done by the most recent paper in this systematic review. Campbell, Marcinowski, and Michel (2018) found that neuromotor score (a composite of skills like sitting, crawling, and walking ability) was not useful for predicting which handedness group an infant belongs to. A summary of the evidence, limitations, and conclusions from the review are presented in the following discussion.

Discussion

Summary of evidence

Results of this systematic review found that while articles on infant handedness as measured by reaching have appeared in every decade since the 1890s with the exception of the 1950s, the majority of studies (70%) in fact do not meet the Fagard et al. (2017) 15-trial criterion for reliable measurement. Out of 87 eligible studies, 14 were found to be lacking details on the methods to determine trial number and another 47 utilized less than 15 trials to determine hand preference. All but two of the eligible studies that reported data from a single timepoint were categorized as not meeting criterion. Thus, it is not surprising that the literature has been mixed with regards to drawing robust conclusions about the timing and stability of infant handedness due to these patterns of data collection that predominate in the field. The consequence of using less than 15 trials is that there is no statistical basis for determining preferences. Therefore, we suggest that the studies identified in this systematic review as not meeting criterion should be interpreted with caution because the construct handedness was not measured reliably.

Despite finding that only the minority of studies (30%) published through May 2018 met criterion for reliable measurement, key advancements have been made in characterizing infant handedness from reaching. Taken together, perhaps the most salient take-away message is that there is no one-size-fits-all trajectory for infant handedness development. Starting with the earliest publication by Giesecke (1936) and continuing through the most recent publication by Campbell et al. (2018), investigator after investigator has discussed individual differences in infant handedness. There is noted variability between infants, as well as variability within infants, that has been captured through different designs throughout the decades, although the vast majority of studies have employed a longitudinal approach. In large samples, this variability has been parsed into group patterns using advanced statistical methods that go beyond simply categorizing infants as left- or right-handed and have allowed us to examine different shapes of development change and timing in the development of infant hand use preferences for reaching. Some infants exhibit consistent preferences, while others do not. Understanding the factors that lead to an infant being in one handedness trajectory over the other, as well as why a subset of infants exhibits a consistent hand use preference, remain outstanding questions for future work.

Another salient theme from this body of work is that hand preference is task-dependent. In other words, investigators should be careful to separate manual skills such as reaching from different types of manipulation and other hand use skills during assessment and analysis. What this recommendation means in practice is that a hand use preference for one skill does not necessarily translate into the same preference for another skill. In addition, preferences for different skills may be established at different points across development, and collapsing hand use across skills may mask critical differences in patterning. Furthermore, hand use for reaching in infants is sensitive to object placement during testing. These additional measurement considerations are important because reaching hand preference has been linked to other behaviours that show asymmetries such as head orientation, as well as behaviours that are not associated with laterality such as grasping a moving target. Additional research is needed to fully characterize cascades within handedness and within laterality more broadly, and to understand the implications of such cascades within a developmental context with these measurement recommendations in mind. Continuing to examine the links between infant handedness and other developmental domains is a promising avenue for future research. The rise in popularity of noninvasive brain measures like electrophysiology in developmental science may foster exciting brain-behavior studies that move the field away from characterizing behaviour to understanding the underlying neural mechanisms in hemispheric specialization and the pathways linking infant handedness to later developmental outcomes.

Although sex differences and familial handedness have been explored in the infant literature, these factors have received far greater attention in the adult handedness literature. For example, a meta-analysis of 144 studies by Papadatou-Pastou, Martin, Munafo, and Jones (2008) reported a greater incidence of left handedness in adult males. Papadatou-Pastou et al. (2020) have expanded on this work and suggest that left-handedness is associated with both study characteristics related to measurement and participant characteristics like biological sex. Comparable numbers of studies and participants do not yet exist to conduct similar analyses for infant handedness. Research in adults has shifted from the single-gene models that motivated infant studies in the 1980s to candidate genes and epigenetic mechanisms (for a recent review, see Schmitz, Metz, Güntürkün, & Ocklenburg, 2017). To our knowledge, infant handedness has yet to incorporate the developing genome into empirical paradigms or theoretical frameworks.

Limitations

With growing interest in infant handedness as shown by the rising number of publications in this decade, it is increasingly important to establish benchmarks for what constitutes acceptable measurement. Here, we have applied only one filter in categorizing prior studies—trial number. Setting a minimum number of trials in how we should measure infant handedness ensures that an assessment is adequate to calculate preferences reliably using statistical cutoffs. A minimum of 15 data points ensures that the investigator can utilize binomial scores. We want to note that researchers may want to administer more than 15 trials to account for potential attrition in their sample, while still obtaining enough data for statistical tests. Collecting at least 25 data points would permit the use of *z*-scores, which are widely used in the human and nonhuman literature (Hopkins, 2013). In addition to trial number, investigators also differ with regards to how they calculate what constitutes a preference once data have been collected (see Campbell, Marcinowski, Latta, et al., 2015; Fagard et al., 2017). Although we were aware of this additional variability of handedness cut-points in the studies reviewed, examining the formulas/statistics used in individual studies was beyond the scope of this project. We also did not examine the settings in which infants were tested or the object(s) that were used, and we acknowledge that it is possible that these contextual factors may make it easier or harder to achieve 15 responses. Nevertheless, we are optimistic that the field will also move towards standardization on these aspects of measurement in the future.

An additional limitation of this systematic review is that we focused exclusively on studies that measured handedness from reaching. Michel (2018) has argued that an appropriate assessment for infant handedness would include all aspects of manual function where the infant may exhibit asymmetries. That is to say that investigators should measure more than just reaching to understand the phenomenon of handedness in infants. On this point we suggest that any manual action measured for lateral biases in infants should apply the 15-trial minimum to calculate a reliable preference using binomial tests. However, this recommendation has only been empirically examined for reaching at limited ages in the range examined in this review, and not for other hand use behaviours like unimanual manipulation or role-differentiated bimanual manipulation. Furthermore, it is not known whether investigators are historically more likely, less likely, or equally as likely to meet a trial criterion in studies examining hand use preferences in infants from non-reaching behaviours. These considerations should guide further synthesis of this field.

Conclusions

Children do have hand preferences in infancy, and these preferences can be reliably measured from reaching given an appropriate number of trials to permit use of statistical cutoffs. This systematic review found that only a minority of published studies between 1890 and 2018 met the 15-trial criterion for eliable measurement as recommended by Fagard et al. (2017). We encourage investigators working in infant handedness to adopt this trial number minimum criterion as standard practice. Establishing best practices will allow the field to move away from disagreements on how to measure handedness and rather focus on the question "what does having a hand preference mean for development?"

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