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Review Article

Automated Language Environment Analysis: A Research Synthesis

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Purpose: The Language Environment Analysis (LENA®) represents a breakthrough in automatic speech detection because it makes one's language environment, what adults and children actually hear and say, efficiently measurable. The purpose of this article was to examine (a) current dimensions of LENA research, (b) LENA's sensitivity to differences in populations and language environments, and (c) what has been achieved in closing the Word Gap.
Method: From electronic and human searches, 83 peer-reviewed articles using LENA were identified, and 53 met inclusionary criteria and were included in a systematic literature review. Each article reported results of 1 study.
Results: Originally developed to make natural language research more efficient and feasible, systematic review identified a broad landscape of relevant LENA findings focused primarily on the environments and communications of young children but also older adults and teachers. LENA's automated speech indicators (adult input, adult–child interaction, and child production) and the audio environment were shown to meet high validity standards, including accuracy, sensitivity to individual differences, and differences in populations, settings, contexts within settings, speakers, and languages. Researchers' own analyses of LENA audio recordings have extended our knowledge of microlevel processes in adult–child interaction. To date, intervention research using LENA has consisted of small pilot experiments, primarily on the effects of brief parent education plus quantitative linguistic feedback to parents.
Conclusion: Evidence showed that automated analysis has made a place in the repertoire of language research and practice. Implications, limitations, and future research are discussed.

In the 1990s, Betty Hart and Todd Risley reported that children living in professional homes were exposed to 30 million more words on average than children reared in poverty during the first 4 years of life (Hart & Risley, 1995). They discovered that by age 3 years, children in professional families who were talked to more by adults had attained a vocabulary more than two times greater than children in impoverished families (1,100 vs. 500 words). These data were based on hour-long recordings in the children's homes monthly that were transcribed.

Naturalistic speech is spontaneous, provided by a number of speakers of multiple characteristics (e.g., men, women, adult, and child) in the typical contexts at home or other authentic setting (e.g., classroom). The challenges to accurate, automated detection include environments that are sometimes silent and noisy, including overlapping speakers and electronic sounds, the vast volume of auditory data of potential interest, and the imperfect speech of young, language-learning children as compared with conventional adult speech recognition (Richards, Gilkerson, Paul, & Xu, 2008). The current state of speech and speaker system technology has matured to where large aspects of naturalistic language recording and analysis are now automated. The Language Environment Analysis (LENA) implements Hart and Risley's innovative approach in an efficient, automated, digital measurement system. Thus, questions of how LENA has been used, what has been learned, and the implications are relevant. Given the lack of a systematic review of research using LENA, we sought to fill this gap in the literature.

LENA Development

LENA was developed with the aim of accurately and automatically estimating the speech occurring naturally in the home environment and, thus, providing a means of taking Hart and Risley's findings to the next level by informing parents and preventing the Word Gap. Development focused on (a) a wearable recording device with the acoustical properties needed to record near and far speakers, (b) accurate speech recognition software, (c) automated scoring

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aligned with Hart and Risley's system, and (d) infrastructure to implement the system at scale. The LENA Research Foundation convened a team of scientists and engineers to develop LENA.

A wearable digital recorder was developed—the LENA Digital Language Processor (Version 0122; Xu, Yapanel, & Gray, 2009)—that enables 16 hr of continuous recording. Secured in a pocket in the child's clothing, a microphone embedded in the LENA supports high-quality recording. Because speech technology systems today are able to identify target child vocalizations and the phoneme segments of speech sounds that make up words with accuracy, it proved possible to automatically recognize three of Hart and Risley's indices: adult input (adult word count [AWC]), interaction (conversational turns [CT]), and child production (child speech–related vocalizations [CSRV]) from audio recordings. Recognizing the need for alternative speech indicators, LENA's Advanced Data Extractor was developed to support listening, manipulating, and coding using an investigator's own procedures (LENA Research Foundation, 2011).

Pattern recognition and speech signal processing algorithms were developed to perform automatic detection. The basic approach is to identify the high-quality speech audio for automated analysis. *High-quality speech segments* are defined as speech occurring near the child that is void of noise and not overlapping with other speakers and/or electronic sounds (i.e., TV and radio). It is from this portion of total audio that accurate counts of speech are made (Richards et al., 2008) by parsing speech to distinguish consonant from vowel sounds (phones) and estimate approximate word counts using a previously validated regression model. In the analysis, a child's speech-related vocalizations are distinguished from other vocalizations (i.e., adults) and counted. CSRV include child productions ranging from babbling and quasivowels to fully articulated verbalizations. Child age–specific modeling is used to differentiate speech-related vocalizations from cries and vegetative sounds (Oller, 2010; Xu, Richards et al., 2009; Xu, Yapanel, Gray, & Baer, 2008).

AWC estimates are the number of clear words spoken by an adult near the child. CT counts are the number of alternations between clear adult and key child vocalizations bounded by at least 5 s of nonvocal behavior, on the basis of rules suggested by Hart and Risley (1995). In this formulation, either the child or adult may initiate a turn, but responses may not serve as the initiation of a subsequent turn. Thus, both child–adult and adult–child sequences would be counted as only one turn. The algorithm used makes these counts using the system's ability to distinguish adult from child voices (Richards et al., 2008) but does not evaluate qualitative factors, such as lexical diversity, grammatical and syntactic complexity, communicative intent, speech duration, or emotional valence. However, because LENA's CTs are a measure of the reciprocal exchange occurring between child and adult, they are the strongest automated indicator of communicative interaction quality. This is because, as the number of reciprocal exchanges increase, so do AWCs. When parents are speaking frequently, they are evoking more cognitively complex concepts, such as recalling the past or actions in the future, and are using richer vocabulary (Hart & Risley, 1995). Additionally, as lexical diversity is increased, grammatical and syntactic complexity also are increased (e.g., Hoff, 2003; Rowe, 2008).

The initial accuracy of LENA's automated analyses was established through comparisons between automated versus human transcribers in a sample of 70 hr of audio data. The agreement percentages between the two methods were high—82%, 76%, 71%, and 76% for adult, child, TV, and other speech (Xu, Richards, & Gilkerson, 2014; Xu et al., 2008). Additional validity claims for CSRV were supported because CSRV proficiency was highly and positively correlated with a child's chronological age and standardized, norm-referenced measures of expressive language (Richards et al., 2008).

Research Using LENA

Historically, limitations have been linked to the demands and complexities inherent in language sampling with human transcription, as well as live observation by human observers or video coding. Human observation is subject to the conspicuous presence of observers or large devices in natural settings and potentially introduces reactivity bias. The return on investment using both of these traditional approaches has been cost-prohibitive. Consequently, researchers and practitioners, among them Hart and Risley, have been forced to use only small samples of children/adults with short recording durations and limit the number of occasions. Slow, awkward, and costly methods have been roadblocks to clinical uses of naturalistic information, for example, providing parents with feedback that could actually confirm that they had made changes in their interactions with children. The advent of LENA sets the occasion for continued research on the Word Gap. With LENA, it proved possible to replicate and extend the generality of Hart and Risley's original findings in new and larger samples of children. LENA also provided a means of guiding parental input and evaluating the effects of intervention strategies.

Since LENA's introduction, a growing body of peer-reviewed research literature has been reported on a range of topics broader than the Word Gap, all previously challenged by the limitations of conventional measurement. In some cases, this work has included large samples and volumes of naturalistic data. New work has focused on a wider range of participants, including children with and without developmental delays/disabilities, as well as adults, including older adults, teachers, and non-English speakers. It has also been used in a range of settings beyond the home. Thus, we sought to examine the dimensions of this new body of work. We addressed three primary questions:

1. What are the current dimensions of LENA research?
2. Are LENA data sensitive to differences in populations and language environments?

3. What progress has been achieved in closing the Word Gap?

Method

Study Database Development

We used the Preferred Reporting Items for Systematic Reviews and Meta-Analyses approach (Liberati et al., 2009). To obtain relevant articles, we used four steps: article identification, screening, eligibility, and inclusion (see Figure 1). Only empirical, peer-reviewed articles written in English that included LENA for data collection and/or a language intervention component were included. The Zotero database was used for project management.

Several search paths were used to identify articles. First, an initial electronic literature search of the ERIC, Education Full Text, MEDLINE, PubMED, Academic Search Complete, Web of Science, Google Scholar, and PsycINFO electronic databases was completed. Search terms used various combinations of (infant or toddler or preschool or child) and (language or vocabulary or communication or talk or interact or word or gesture) and (intervene*[1] or strategy* or development) and (parent or mother or father or caregiver or teach* or adult or childcare) and (poverty or at risk or low SES or disab*) and (Word Gap) in the United States and internationally from 2008 to 2016. This identified 31 articles (see Figure 1).

A second search of the same sources focused on LENA specific terms *LENA* and *Language envir**. This search yielded an additional 26 articles. Hand or ancestral searches of articles cited in the identified articles resulted in the addition of 13 more. Lastly, the LENA Research Foundation's research director reviewed our full list of articles and provided 13 recently published articles. Thus, a total of 83 article titles and abstracts were identified and screened. This total was reduced to 66 with removal of duplicate articles. One additional article was removed for not meeting criteria, and 12 more were eliminated because they either were not published in English or did not report quantitative LENA outcome data. This resulted in 53 peer-reviewed articles for full text review. Because all articles reported the results of only one study, there was only one study reported per article.

Article Review

The 53 articles/studies were individually evaluated to address the research questions using a web-based Qualtrics coding survey developed by the research team. This survey consisted of 60 questions aligned with the research questions. The articles were coded by three postdoctoral researchers who were all interested in LENA research. All coders learned the coding system by studying the survey questions, practicing coding of articles, and receiving feedback. To complete training, coders were required to reach agreement with experts' consensus coding of two articles (a randomized control trial and a single-case design study). Coders demonstrated proficiency by reaching 85% agreement or higher coding in both articles.

This Qualtrics data set was uploaded to Microsoft Excel for analysis. Eleven articles (21%) were chosen at random and independently coded by coders to evaluate interrater agreement. Percentage agreement was calculated by counting the exact matching answers to each coding question using the formula: percentage agreement = [100 (#matches/total questions)]. Intercoder agreement was high (M = 92.7%, range = 88.2%–97.3%).

Results and Discussion

What Are the Current Dimensions of LENA Research?

Characteristics of Studies Reviewed

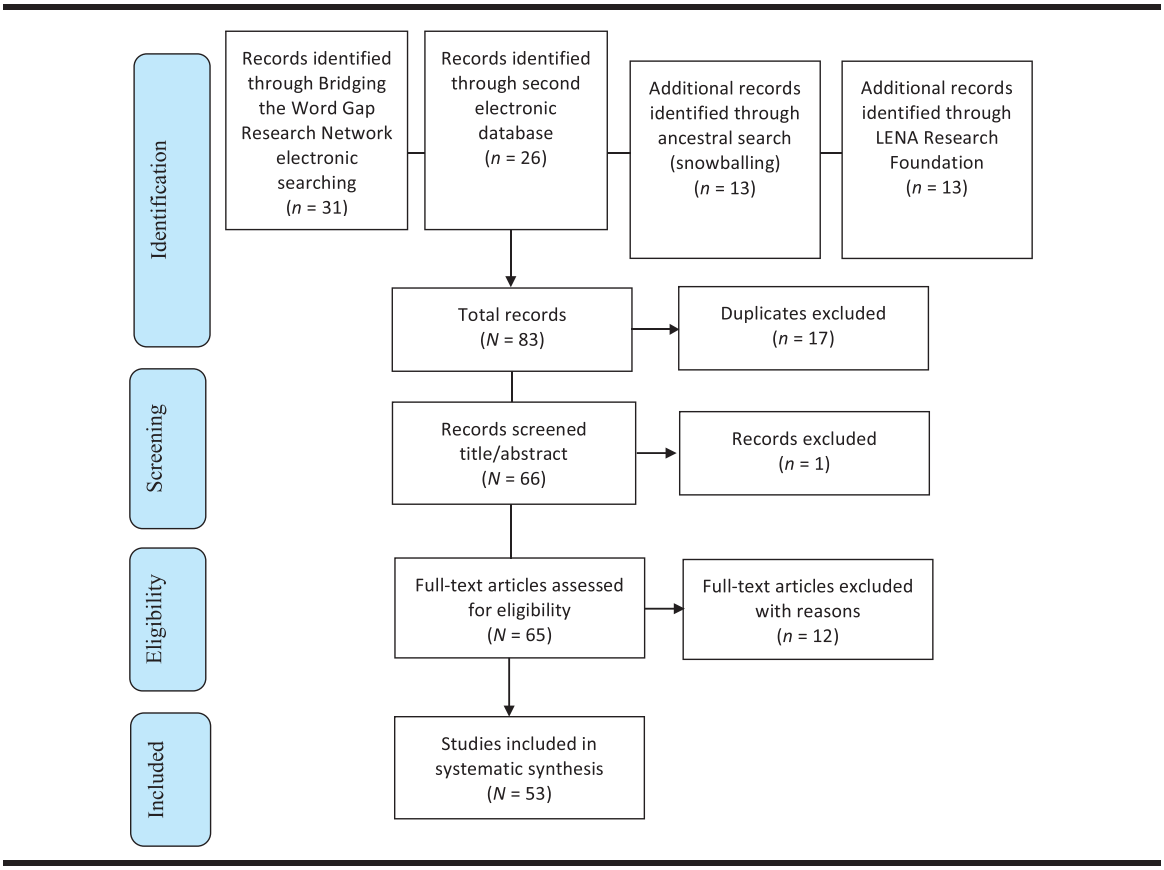
Table 1 presents a summary of the 53 studies included in this review by year of publication beginning in 2009 through May of 2017. Ninety percent were conducted in the United States and the remainder in Canada, China, England, and South Korea. The mean number of publications per year was 3.0, ranging from two to four between 2008 and 2012. Thereafter, an upward inflection in number was observed with a mean of 9.5 articles, ranging from eight to 10 between 2013 and 2016. Three additional articles were published in the first 5 months of 2017.

Table 2 provides a summary of study-level characteristics. Studies reported include children who were infants, toddlers, preschoolers, kindergarteners, and early elementary students. The enrollment of girls and boys in studies was roughly equal with nine studies not reporting. Only nine studies reported enrolling low socioeconomic status (SES) children (see Table 2). Most of the studies enrolled typically developing (TD) children, followed by children with deafness/hearing impairment (HI), autism spectrum disorder (ASD), speech/language delay, other risk/disability (e.g., preterm babies and Down syndrome), and serious emotional/behavioral problems. Adult participants were parents, teachers, parent–caregiver and parent–teacher dyads, and senior citizens and their caregivers. Many study authors omitted reporting adult participants' information, in particular, attained education levels, age, and minority status.

LENA was worn by a child when research questions focused on the adult input directed to the child and the child's vocal production (96% of studies). LENA was worn by adults in only 4% of studies. One was a feasibility study of the language environment in a retirement home with LENA worn by older adults (Li, Vikani, Harris, & Lin, 2014). Findings indicated that during 27% of their waking time, older adults were in the presence of electronic sound (i.e., TV). Daily AWC production was wide ranging with 14-fold differences between individuals. The other study focused on classroom teachers' discourse: lecture, class discussion, and group work (Wang, Pan, Miller, & Cortina,

[1]Asterisk used to broaden the electronic search term.

Figure 1. Study flow diagram. LENA = Language Environment Analysis.



2014). The authors reported success detecting these three instructional forms using their own algorithm compared with human observers, suggesting that feedback to teachers on the basis of the LENA recordings was possible.

Population Characteristics

There were 3,586 child participants and 2,170 adult participants reported at the child and adult levels of analysis. Study sample sizes ranged from 1 to 373 children (see Table 1). However, because of overlap in study samples in some reports, these overall participant numbers were not accurate. The greatest overlap occurred when researchers used LENA's growing corpus of daylong recordings (Gilkerson, Richards, Warren, et al., 2017) for analyses in 13 studies. In other cases, Caskey, Stephens, Tucker, and Vohr (2014) used the same sample as Caskey, Stephens, Tucker, and Vohr (2011). Carr, Xu, and Yoshinaga-Itano (2014) used a subset of the Aragon and Yoshinaga-Itano (2012) Colorado Hearing Impairment Program study sample, and Ambrose, VanDam, and Moeller (2014) and VanDam, Ambrose, and Moeller (2012) used subsets of a corpus collected by the Outcomes of Children With Hearing Loss Study (Moeller, & Tomblin, 2015). After adjusting for overlaps in participants, our best estimates were 1,578 unique child and 526 unique adult participants reported across all studies in this review.

Research Topics

Review of the studies resulted in a cross-categorized list of six topical groupings on the basis of questions addressed and designs used. In rank order of occurrence, the topics were individual differences (n = 13, 25%), cross-linguistic issues (n = 13, 25%), population differences (n = 10, 19%), context differences (n = 10, 19%), and word gap intervention research (n = 7, 13%).

Settings

Studies took place in the home (66%) and in neonatal intensive care units (NICU)/clinics, classrooms, and child care and senior living facilities. Studies also reported comparing findings in the home versus (a) the classroom (Wiggin, Gabbard, Thompson, Goberis, & Yoshinaga-Itano, 2012), (b) child care (Christakis et al., 2009), and (c) NICU (Johnson, Caskey, Rand, Tucker, & Vohr, 2014). Three studies (6%) did not report the setting.

Method

The majority of studies reported using one or more of LENA's automated language measures (see Table 1). Nine studies reported using at least one of these categories in addition to one or more of the automated LENA acoustical measures: television, distant and overlapping speech,

Table 1. Studies reviewed in chronological order by year (*N* = 53 studies).

Study		Setting	Child participants	Adult participants	Automated LENA outcomes	No. of recordings	Duration (hr)
1	Christakis et al. (2009)	C	329	329	CT, CSRV, AWC, TV	8.2[a]	10–16
2	Zimmerman et al. (2009)	C	275	275	CT, CSRV, AWC, TV	6, 18[a]	4–16
3	Oller (2010)	C	1	3	CT, AWC	11	9.8[b]
4	Oller et al. (2010)	C	232	—	ADEX	802	—
5	Warren et al. (2010)	H, S	104	104	CT, CSRV, AWC	438	4–16
6	Caskey et al. (2011)	C	36	—	CT, CSRV, AWC, SI, N, M	68	10–16
7	Greenwood et al. (2011)	C	30	30	CT, CSRV, AWC	865	10–16
8	Aragon & Yoshinaga-Itano (2012)	C	373	373	CT, CSRV, AWC	373	10–16
9	VanDam et al. (2012)	C	30	—	CT, CSRV, AWC	30	4–16
10	Wiggin et al. (2012)	C	8	—	CT, CSRV, AWC	8	8.6[b]
11	Burgess et al. (2013)	H, C	10	19	AWC	2–4[a]	10–16
12	Charlton & Law (2013)	S	14	—	CT, CSRV, AWC	5[a]	0–5
13	Dykstra et al. (2013)	S	40	15	CT, CSRV, AWC	2[a]	3
14	Irvin et al. (2013)	S	67	21	AWC	67	0–5
15	Ota & Austin (2013)	S	96	48	ADEX	3[a]	0.5
16	Soderstrom & Wittebolle (2013)	C	11	—	CT, AWC, CSRV	3[a]	8.8[b]
17	Suskind et al. (2013)	C	17	17	CT, AWC	8[a]	12–16
18	Weisleder & Fernald (2013)	C	23	23	ADEX	1–6[a]	10–16
19	Yoder et al. (2013)	—	69	—	O	3[a]	12–16
20	Abney et al. (2014)	C	1	—	CT, O	47	2.5–12.5
21	Ambrose et al. (2014)	C	28	—	CT, AWC	6.1[a]	8–16
22	Thiemann-Bourque et al. (2014)	C	18	18	CT, CSRV, AWC	36	4–16
23	Carr et al. (2014)	—	83	—	ADEX	—	10–16
24	Caskey et al. (2014)	C	36	—	CT, CSRV, AWC	72	19–16
25	Jackson & Callender (2014)	H, S	57	—	CSRV	—	5–10
26	Johnson et al. (2014)	C	33	60	CT, CSRV, AWC	99	16
27	Li et al. (2014)	C	—	24	AWC	24	10–16
28	Ramírez-Esparza, García-Sierra, & Kuhl (2014)	C	26	—	CT, CSRV, AWC	104	5–10
29	Sacks et al. (2014)	C	11	11	CT, CSRV, AWC	55	16
30	VanDam (2014)	C	—	—	ADEX	—	—

(*table continues*)

Table 1. *(Continued).*

Study		Setting	Child participants	Adult participants	Automated LENA outcomes	No. of recordings	Duration (hr)
31	Vohr, Topol, Watson, St Pierre, & Tucker (2014)	C	56	64	CT, CSRV, AWC	68	4–16
32	Wang et al. (2014)	S	—	4–16	ADEX	—	1–5
33	Warlaumont et al. (2014)	H, S	183	—	CSRV, O	—	—
34	Xu et al. (2014)	—	226	—	CSRV	1,363	1–5
35	Canault et al. (2015)	C	18	—	CSRV, AWC, TV, N, O	18	10–16
36	Gilkerson, Richards, & Topping (2015)	C	36	36	CT, CSRV, AWC	36	10–16
37	Gilkerson, Zhang, et al. (2015)	C	22	—	CT, CSRV, AWC	66	10–16
38	Kashinath et al. (2015)	C	5	—	CSRV, AWC	1[a]	4–16
39	Susperreguy & Davis-Kean (2016)	C	40	40	ADEX	120	4
40	VanDam et al. (2015)	C	273	—	CSRV	10.4[a]	10–16
41	Zhang et al. (2015)	C	22	22	CT, AWC	19[a]	4–16
42	Charron et al. (2016)	C	5	5	TV, N, SI, M, AWC, CT, CSRV	2[a]	16
43	Ko, Seidl, Cristia, Reimchen, & Soderstrom (2016)	C	13	13	CT, AWC	3–5[a]	16
44	Pae et al. (2016)	C	84	84	AWC, CT	3, 27[a]	16
45	Sosa (2016)	C	26	26	CT, CSRV, AWC	78	10–16
46	Suskind, Leffel, et al. (2016)	C	23	23	CSRV, AWC, N	14[a]	10
47	Wood et al. (2016)	C	81	81	CT, CSRV, AWC	81	10.3[b]
48	Woynaroski et al. (2016)	C	20	—	ADEX	2[a]	16
49	Suskind, Graf, et al. (2016)	C	22	22	CT, AWC	16[a]	16
50	Ramírez-Esparza, García-Sierra, & Kuhl (2016)	C	25	25	AWC	4[a]	8
51	Gilkerson, Richards, Warren, et al. (2017)	C	329	329	AWC, CSRV CT	3,213	4–16
52	Irvin et al. (2017)	S	1	—	CT, AWC, CSRV, O	1	5.6
53	Marchman, Martínez, Hurtado, Grüter, & Fernald (2017)	C	18	18	AWC	2.2[a]	5.3–13.1
	Total	—	3,586	2,170	—	—	—

Note. Em dashes indicate "data missing/not reported." LENA = Language Environment Analysis; C = clinic; H = home; CT = conversational turns; CSRV = child speech–related vocalizations; AWC = adult word count; TV = television; ADEX = advanced data extractor; S = school; N = background noise; M = meaningful speech; O = other speech; SI = silence.

[a]Per child/mean per child. [b]Mean across children.

Table 2. Study-level characteristics (*N* = 53).

Country and design			Child characteristics			Adult characteristics		
Country	**Study count**	**%**	**Child sample size**	**Study count**	**%**	**Mean education**	**Study count**	**%**
United States	45	84.9	21–40	19	35.8	> high school	34	64.2
Canada	3	5.7	0–20	18	34.0	Not reported	15	28.3
England	1	1.9	81–100	4	7.5	< or = high school	4	7.5
China	2	3.8	> 301	4	7.5	**Mean age**		
Korea	1	1.9	201–300	3	5.7	Not reported	47	88.7
Not reported	1	1.9	41–60	2	3.8	30–40	3	5.7
Design			61–80	2	3.8	< 30	1	1.9
RCT/quasi	4	7.5	100–200	1	1.9	41–50	1	1.9
Natural expmt	1	1.9	**Mean child age**[a]			70–80	1	1.9
Single case	3	5.7	Toddler	35	34.3	**% minority**		
Descriptive	36	67.9	Preschool	32	31.4	Not reported	37	69.8
Psychometric	9	17.0	Infant	25	24.5	0–24	14	26.4
Languages[a]			Kindergarten	6	5.9	50–74	1	1.9
English	49	75.4	Early elementary	3	2.9	75–100	1	1.9
Spanish	11	16.9	Not reported	1	1.0	25–49	0	0.0
Chinese	2	3.1	**% male**					
French	1	1.5	0–49	23	43.4			
Korean	1	1.5	50–100	21	39.6			
German	1	1.5	Not reported	9	17.0			
			SES					
			Not low SES	47	88.8			
			Low SES	6	12.2			
			Disability[a]					
			TD	28	52.8			
			Deaf/HI	12	22.6			
			ASD/PDD	10	18.9			
			SPLD	7	13.2			
			Other	7	13.2			
			Not reported	2	3.8			

Note. RCT = randomized control trial; quasi = quasi-experimental design; expmt = experiment; SES = socioeconomic status; TD = typically developing; HI = hearing impaired; ASD = autism spectrum disorder; PPD = pervasive development disorder; SPLD = speech and language delay.

[a]Where values summed greater than 53, variables occurred multiple times in studies.

electronic sounds, noise, silence, and background noise. Other speech was the most commonly reported acoustical outcome. Eight studies used LENA's advanced data extraction tool and a researcher's own coding.

Most studies reported recordings that were 10 hr or longer, but wide variations in duration were reported (see Table 1). Automated LENA outcomes on the basis of recordings shorter than 10 hr/day are not considered representative of a full-day sample by the developers, and daily percentile benchmarks are not automatically reported (LENA Research Foundation, 2015). However, shorter duration recordings have been used to address comparative questions that are not daylong inferences. Similarly, there was a wide range in the frequency of recordings made.

Designs reported were descriptive, correlational, and/or comparative and, thus, did not produce experimental causal findings. Only seven studies used some form of experimental design to evaluate intervention effects (see Table 2). Several were randomized control trials or pilot tests of a language intervention facilitated by home visitors (e.g., Suskind, Leffel, et al., 2016). One was a natural experiment, wherein parents were asked to introduce a book-reading activity with their children (Gilkerson, Richards, & Topping, 2015). Natural experiments are those in which exposure to conditions is not controlled by the experimenter at random (Meyer, 1995). LENA outcomes were compared during reading versus nonreading times determined by parents. Three other studies used single case experimental designs to examine the effects of LENA's quantitative feedback with or without an adult educational session (Sacks et al., 2014; Suskind et al., 2013; Zhang et al., 2015). All three were baseline (A) versus treatment (B) designs, the very weakest single case design in controlling threats to internal validity (Kennedy, 2005). Stronger single case designs require demonstration of more than one effect, for example, the ABAB design (Kennedy, 2005).

Descriptive statistics, followed by regression analysis, analysis of variance or covariance, and *t* tests were the most frequently used to report findings. Two studies used chi-square tests of differences in frequencies. Half of the studies used graphical displays of their data in combination with other simple data analytic techniques.

Are LENA Data Sensitive to Differences in Populations and Language Environment (87% of Studies)?

Naturalistic research using LENA seeks to describe and understand basic interactional mechanisms in children's language acquisition and communication. Compared with traditional measures, the advantages that LENA presented to this work included efficient recording of data in real time, daylong or multidaylong recordings, limited bias due to observer or video equipment presence, automated detection of speech and auditory quality, and high-quality digital audio recordings for secondary analyses using researcher-developed coding and algorithms.

Individual Differences (25% of Studies)

LENA was used to provide information on the individual differences in children's language environments, communication patterns, and in some cases, established links between greater adult input and better child outcomes (e.g., Ambrose et al., 2014). These studies involved preterm infants, children with HI and developmental disabilities (i.e., ASD), and TD participants who were assessed in multihour recordings that occurred in the NICU, home, and preschool classroom. Findings extended Hart and Risley's original reports of individual differences in the home on the basis of only 1-hr recordings of low, average, and high SES families.

The reported wide-ranging variability in overall adult input and child production in these studies also replicated Hart and Risley's findings of large differences in the amount of individual family–child talk and interaction. Recent reports have extended these findings to other English-speaking, middle-to-high SES samples (Greenwood, Thiemann-Bourque, Walker, Buzhardt, & Gilkerson, 2011) and a Spanish-speaking, low SES home environment sample (Weisleder & Fernald, 2013) on the basis of analyses of much longer daily recordings. New reports using LENA indicated that more frequent exposure to adult talk was associated with better child language outcomes (Ambrose et al., 2014; Caskey et al., 2011, 2014; Dykstra et al., 2013; Irvin, Hume, Boyd, McBee, & Odom, 2013), also replicating Hart and Risley's findings.

Cross-Linguistic Extensions (25% of Studies)

Cross-linguistic research using LENA reported language-associated differences and updated psychometrics of the automatic measurement in English and other languages. For example, one case study of a TD child in a three-language home context (Oller, 2010) quantified differences in the child's English, German, and Spanish language daily exposure contributed by parents and a nanny speaker at home. In other work, Wood, Diehm, and Callender (2016) reported that young Spanish–English bilinguals from low SES backgrounds showed lower-than-average performance on LENA measures of CSRV and CTs than did monolingual English-speaking peers.

Jackson and Callender (2014) reported finding a significant difference in average hourly child vocalizations between home and preschool environments in samples of monolingual English-speaking children versus Spanish–English dual language learners. Dual language learning children had a higher rate of vocalizations at home than at school compared with monolinguals. On the one hand, these findings suggested the need for more intensive efforts to promote language learning in these children in one or more settings. On the other hand, additional considerations apply, such as lack of opportunity to learn, language delay/disability, and the need to make the least-biased assessments possible of a child's language ability. In clinical settings, LENA's naturalistic home and school language data can be used to augment traditional assessments so that inferences about a child's language ability may be better informed and prevent excess referrals to special education for speech delays (Kashinath, Pearman, & Canales, 2015).

Other reports extended the accuracy and validity claims of LENA's automated indicators (i.e., AWC, CT, and CSRV). Three were in English (e.g., Yoder, Oller, Richards, Gray, & Gilkerson, 2013), one was in French (Canault, Le Normand, Foudil, Loundon, & Thai-Van, 2015), and one was in Chinese (Shanghai dialect and Mandarin; Gilkerson, Zhang, et al., 2015). Reports indicated a strong, positive relationship between (a) LENA's automatic indicators on the basis of a daylong vocal recording in English and (b) a measure of expressive spoken language in groups of young children with and without ASD (Yoder et al., 2013). The feasibility of using LENA in a Spanish-speaking home in Colorado focused on deaf child participants and those who are hard of hearing (Aragon & Yoshinaga-Itano, 2012), in addition to use with low SES Spanish speakers (Ramirez-Esparza, García-Sierra, & Kuhl, 2016). Reports replicated positive correlations between LENA's automated indicators and criterion language tests (e.g., Dykstra et al., 2013; Zimmerman et al., 2009).

Collectively, these findings have extended the evidence of LENA's sensitivity to individual differences in language environments and communication patterns in multiple settings, with diverse participants, and at levels of detail beyond that possible with traditional measures of the language environment and parent–child interaction. Also, results have extended LENA's statistical reliability and validity beyond general accuracy statements to relationships to other, traditional expressive language measures. The findings also suggest the potential benefit of interventions designed to promote CT in English and other languages relative to increasing traditionally measured language outcomes.

Population Differences (19% of Studies)

LENA has been used to investigate language environment and vocal communication pattern differences between children with and without developmental problems. Participants included in these studies were children with ASD (i.e., Warlaumont, Richards, Gilkerson, & Oller, 2014), HI (i.e., VanDam et al., 2012), Down syndrome

(Thiemann-Bourque, Warren, Brady, Gilkerson, & Richards, 2014), speech/language delay/disability (VanDam et al., 2015), and other risks or disability (e.g., serious emotional/behavior disorders; Charlton & Law, 2013).

Researchers reported that children with developmental risks/delays had significantly greater than typical challenges in their language environment, communication patterns with adults, or both. For example, Warren et al. (2010) reported that children with ASD produced fewer vocalizations and had fewer turns with their parents. CT with children with ASD were most often initiated by the adult and not the child and with greater latency in child response to initiations. Thiemann-Bourque et al. (2014) reported finding that parents of children with Down syndrome spoke fewer words to their children than did parents of TD children. However, parents did continue providing consistent levels of input across the early language learning years, yet child vocal behaviors remained low compared with TD children after the age of 24 months. Collectively, these findings suggested the potential value of interventions targeting children's initiations and responsiveness to initiations.

Analyses of LENA's auditory information by researchers led to the identification of a unique auditory signature in young children with ASD compared with TD children (Oller et al., 2010; Xu, Richards et al., 2009). Peculiarities of voice have previously been noted in children with ASD, including prosody and articulation factors affecting rhythm/syllabicity (Oller et al., 2010). This team developed an algorithm successful in predicting a child's command of the infrastructure of identifying syllables from LENA's auditory data. Findings indicated systematic changes with age and the ability to discriminate between children with and without divergent development. In related work, Carr et al. (2014) reported making better ASD screening decisions for children who are deaf or those who are hard of hearing by combining LENA data with data from the Child Development Inventory Social subscale.

Context Differences (19%)

LENA has been used to investigate differences between and within contexts, speakers, and time of day. For example, Wiggin et al. (2012) reported that children with HI benefited significantly from receiving a summer preschool program compared with just home language alone because they were exposed to significantly more complex language in preschool than at home. Burgess, Audet, and Harjusola-Webb (2013) reported similarities in comparisons between the home and preschool environment of children with ASD. Combining LENA's automated indicators with language samples analyzed by Systemic Analysis of Language Transcripts (Miller & Iglesias, 2012) indicated that young children were exposed to high-quality adult language in both school and home environments, including frequency and diversity of words.

LENA was used to investigate differences in communication patterns resulting from changes in contexts within settings. These comparisons focused on differences in specific activities, types of toys, speakers, and time of day. For example, Soderstrom and Wittebolle (2013) reported that structured activities generated the highest levels of adult language but not necessarily the most child vocalizations. Susperreguy and Davis-Kean (2015) reported mother's use of math talk during mealtime. Several reports documented reductions in talk associated with high electronic media use (e.g., Zimmerman et al., 2009). Sosa (2016) reported that play with electronic toys compared with toys and books significantly decreased the frequency and quality of language input and infant communications. They recommended, as did Ambrose et al. (2014), that electronic toys be discouraged in favor of books and traditional toys.

Reports indicated that the vast majority of children's input was provided by mothers, fathers significantly less (e.g., Greenwood et al., 2011). Other findings indicated that very young children were more responsive to mother talk than father talk (Johnson et al., 2014). Greenwood et al. (2011) reported finding that talk accelerated to high points at midmorning and mid-to-late afternoon and decreased at the noon hour and evening. Soderstrom and Wittebolle (2013) also reported finding differences in the time of day. Taken together, these findings demonstrate the relationship between and within language environments (including speakers and time of day) and vocal communication on the basis of temporal correlations. However, because designs have rarely been experimental, causal relations related to adult speakers, activities, toys, and other daily events remain to be demonstrated.

What Progress Has Been Achieved in Closing the Word Gap (13% of Studies)?

LENA has been used as a proximal outcome measure and as a parent and caregiver feedback component in language intervention research (e.g., Ota & Austin, 2013; Suskind et al., 2013). The most investigated intervention with LENA combined brief adult education and quantitative linguistic feedback from recordings. For example, in a sample of 17 diverse nonparental caregivers (nannies) and TD children (Suskind et al., 2013), researchers provided adult caregivers with one education session, six daylong home LENA recordings, and six linguistic feedback reviews. The educational session focused on child language development and environment enrichment strategies. Caregivers received quantitative linguistic feedback to support increased awareness of their own linguistic behaviors. Postintervention, both AWC and CT, increased significantly compared with preintervention recordings, particularly for those families who started low on the basis of LENA's benchmark, comparative information. Similar short-term findings have been reported for parents in China (Zhang et al., 2015) and Korea (Pae et al., 2016) and a small randomized trial in the United States (Suskind, Leffel, et al., 2016). Findings indicate that the interventions increased adult and child talk at least short term. These results have not yet been reported in low-income or high-risk families.

Clinical Implications

LENA uniquely extends beyond traditional measures of language proficiency and clinical observation by bringing natural language environment and communication pattern data into consideration. Thus, LENA overcomes longstanding challenges clinicians have had in knowing what goes on at home or in classrooms and whether or not interventions are implemented in natural language environments.

LENA offers clinicians an automated natural environment tool to augment their clinic-based measures, including parent questionnaires or ratings, or even simple audio or video recordings for uses in screening, identification, treatment development, and progress monitoring. For example, it is possible to identify cases of children experiencing very low and highly variable home language environments on the basis of comparative information from LENA's Natural Language Study (NLS; Gilkerson, Richards, Warren, et al., 2017) that can be used to identify children and families most likely to benefit from restructuring adult language input.

LENA data appeared particularly beneficial to cases involving dual language learners and least-biased assessment in the multiple language context. With respect to children with identified delays, LENA data also provide the clinician with information of specific problems in initiating or responding to initiations in interactions and suggest strategies to ameliorate these problems. With respect to fidelity of intervention at home and school, LENA data appeared highly informative of adults' efforts to change their communication styles as directed and to increase child's language acquisition. LENA gathers information that enables parents and professionals to modify their input to a child. Lastly, the audio records can be listened to directly by professionals, as a window into the interactive environment for reflection and decision making.

Limitations

Accurately accounting for participants in studies when data from the existing LENA corpus (NLS; Gilkerson, Richards, Warren, et al., 2017) were used more than once was challenging. Tracking repeated use of samples provided some ability to correct participant counts. However, samples were not always precisely described; thus, it was not exactly clear who was participating and, thus, the correction may not be accurate. This may be a general issue in synthesizing secondary findings from studies using extant data sources, like the LENA corpus.

This review found that descriptions of participants' characteristics in studies were often incomplete, particularly the ethnicity, age, and gender of adults. Without this information, readers are left to assume that adult characteristics match those reported for the children. Most studies did not include low SES samples. Findings also indicated that the LENA research on the efficacy of interventions for addressing the Word Gap to date has been only small-scale pilot work, involving only a limited number of intervention contexts from a much larger intervention knowledge base (Roberts & Kaiser, 2011; Walker et al., 2017; Warren, 2015).

Consequently, our knowledge of interventions and change in process and outcomes where LENA is used is incomplete. Most studies reported findings in homes, then classrooms, and clinics—none were reported in community settings (e.g., library and grocery store). The lack of the community setting contribution to a child's daily language leaves us with a gap in knowledge of this language environment. The extensions of LENA to languages other than English in the United States and internationally (e.g., Chinese and French) have shown promise but also evoke the need for additional validity work to confirm the face validity and accuracy of automated counts made for speakers of languages other than English.

The volume of data collected and reported in this review indicated that participant compliance and use of the LENA was generally accepted. However, an occasional study reported an issue securing participants' consent to be recorded, given some uncertainty in participants' understanding of the internal review board protocol. This is understandable, given that recording private conversations is a sensitive subject and that confidentiality must be assured.

Consent procedures for LENA deal with privacy issues. For example, the handling of the audio information after it has been recorded must include safeguards for the inadvertent recording of private topics and guests who may be incidentally recorded. Given the purposes behind the research, participants can be assured that the audio recording will be erased after LENA processing and scoring, given that the audio is no longer needed. If the purpose is to maintain the recording for additional research, for example, in a preconsented, online corpus of daylong recordings, typical consent procedures may contain a post-recording approval or the option of deleting or editing a recording that may contain a private conversation or guest speakers not assented to be recorded.

Other reports indicated occasional problems with parents forgetting to switch on their child's LENA as soon as the child wakes, resulting in short or lost collection opportunities. Researchers and clinicians need to take preemptive steps to educate and prompt parents' compliance with the desired recording schedule that may contain personal instructions, handouts with the LENA, and reminders (i.e., text messages, reminders). Because the LENA must upload audio data to a computer for processing and analysis, establishing a reliable system for returning LENAs for this purpose is a necessity. Reported reliable return systems have included the participant/client, a research assistant, community volunteer, or other couriers. Another LENA returning pathway to a central office for processing has been FedEx or other delivery services.

Though a huge breakthrough in children's automated speech detection, the speech recognition algorithms for LENA are not yet capable of recognizing the actual words in a young child's dictionary. LENA does not yet produce a transcription of recordings. Current algorithms have

several other limitations. The ability to differentiate between child-directed speech and speech overheard in the surrounding environment is one. Automated detection also has problems identifying multiple speakers and untangling overlapping speech in noisy environments like classrooms, particularly within child and adult speakers. Thus, questions of who is speaking to whom in classroom interaction research is challenging (Sangwan, Hansen, Irvin, Crutchfield, & Greenwood, 2015). LENA currently has no automatic capacity to identify the contexts within environments like the preschool classroom (Irvin et al., 2017), and the technology still awaits improvement in measuring language quality features (Cartmill et al., 2013; Rowe, 2012).

Research in Progress

New measurement tools linked to LENA are under development. For example, an online parent rating measure of children's expressive language development, the LENA Developmental Snapshot (Gilkerson, Richards, Greenwood, & Montgomery, 2017), is being used in conjunction with LENA's automated measurement of child vocalizations. Researchers are also exploring combining LENA with other digital sensors, including (a) digital indoor spatial location sensors to investigate the distribution of talk during a preschool day in identified classroom activity locations (Irvin et al., 2017), (b) eye-tracking sensors to investigate the cognitive and experiential factors in language learning (Odean, Nazareth, & Pruden, 2015), and (c) accelerometers to study the codevelopment of infant limb movements and language development (Abney, Warlaumont, Haussman, Ross, & Wallot, 2014). Other work includes developing daylong databases (data infrastructures) in addition to the LENA Foundation's NLS corpus (Gilkerson, Richards, Warren, et al., 2017). For example, HomeBank is another repository of daylong recording for naturalistic language research (VanDam et al., 2016). Both repositories continue to grow the number of recordings and will support future research.

Future Research

Future research is needed to address current limitations. When authors are reporting secondary analyses of LENA data, they need to clearly document the source of the data and the features of the data used, including subsets or records filtered on participant, risk, or other characteristics. Additional benefits to the field will follow from authors reporting fewer concerns because of improvements in internal review board and consenting/assenting procedures and procedures that ensure compliance with LENA return schedules and operating instructions. Improvements in current speech recognition are needed that extract greater detail from the audio information if we are to advance naturalistic language research with young children.

A major effort is called for in advancing the early stage intervention research reviewed using LENA, beyond a small number of small pilot studies. The capacity to bridge the Word Gap, particularly in low SES families in low SES communities (Greenwood et al., 2017), will need to be based on a well-designed body of intervention/prevention research supporting evidence-based practices. The review indicated that only short-term changes in LENA outcomes attributed to interventions linked to parent group training combined with LENA data feedback. None of the intervention studies assessed whether or not the intervention was well implemented and how variability in intervention fidelity might moderate child outcomes. To scale up interventions, we will need evidence that we can train others to implement communication-promoting strategies quickly and efficiently and that they can reproduce changes in language environments that result in change in children. Longitudinal studies will be needed to demonstrate prevention of the Word Gap by age 4 years, increased school readiness, and later, school success, resulting from early intervention.

We need to know more about ways to incorporate families' strengths into interventions to enhance parental engagement, including fathers, where LENA data can contribute (Suskind, Suskind, & Lewinter-Suskind, 2015). For example, we know a mother's knowledge of child development, including the impact of talking to one's baby, is a moderator of children's vocabulary teaching (Rowe, 2008), suggesting the value of parent information campaigns. We also know that the vocabulary of a child's parents and siblings is a moderator and an important language component (Hindman, Wasik, & Snell, 2016). Practitioners need more information about which language-promoting strategies work best and how to sustain implementation within their everyday routines (Greenwood et al., 2017; Smith, Warren, Yoder, & Feurer, 2004).

Conclusion

This synthesis of 53 peer-reviewed publication papers examined how the LENA has been used in research to date. The review showed that the original goal of developing an automated, time-efficient solution to Hart and Risley's naturalistic language measurement approach has been largely accomplished. LENA presents advantages over traditional language sampling and use of human observation in the collection and use of information given the investment made. Some of the advances over a traditional child's language environment are the increased coverage of the naturalistic measurement from 1 to 16 hr per day, the potential for analyses of "big data," and the efficiency resulting from automated processing of the audio. The review showed that LENA is now well integrated into the repertoire of language research tools on the basis of the diversity of topics and research questions addressed.

Examination of the current dimensions of LENA research showed that the vast majority of work was child focused, with a child wearing the LENA to record input to the child and child vocalization. Only recently have studies begun reporting adult-focused findings for older adults in residential settings and classroom teachers' use of instructional

strategies. Examination of research on LENA's sensitivity to population and language environment differences (i.e., individuals, populations, and settings) was widely demonstrated with new findings on the basis of representative samples of language compared with prior work. This work represents important advances in our knowledge of language learning mechanisms, screening, intervention development, and evaluation. The emergence of comparative benchmarks may also assist with screening, setting baselines and target goals in family-based interventions, and future experimental studies designed to evaluate the efficacy of language interventions.

A goal of LENA development was to help low SES parents communicate in ways known to accelerate language acquisition. The review indicated that this work has only just begun. The few studies using LENA were small pilots, natural experiments, or single case studies. Given this scarcity of LENA use in intervention contexts, this review should motivate additional research and practice efforts. Solving a large social problem like the Word Gap is critically important to addressing inequity, potentially affecting thousands of young children in poverty.

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