The Language ENvironment Analysis (LENA) System: A Literature Review

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Abstract

The Language ENvironment Analysis (LENA) System is a relatively new recording technology that can be used to investigate typical child language acquisition and populations with language disorders. The purpose of this paper is to familiarize language acquisition researchers and speech-language pathologists with how the LENA System is currently being used in research. The authors outline issues in peer-reviewed research based on the device. Considerations when using the LENA System are discussed.

1 Introduction

In the past, research on language acquisition involved short recordings or periods of in-person observations (Hart & Risley, 1995; Keller et al., 2007). This form of data collection could be cumbersome and required extensive time for analysis. The costs and logistics associated with these methodologies might be particularly unwieldy. The Language ENvironment Analysis (LENA) System is a new tool created to address these issues by combining a wearable audio recorder with automated vocal analysis software (LENA Research Foundation, 2014). The LENA Foundation's initial intention was to provide a device that parents could use to easily monitor the amount of language stimulation their child receives, however, the utility of such technology in the research world did not go unnoticed. In hopes of gathering the most naturalistic samples possible, researchers are currently using the LENA System to investigate various aspects of language acquisition including the effects of parent-child talk, television, bilingualism, communication disorders, and intervention among others (Christakis et al., 2009; Greenwood, Thiemann-Bourque, Walker, Buzhardt, & Gilkerson, 2011; Marchman, Martinez, Hurtade, Gruter, & Fernald, 2016; Suskind et al., 2015; VanDam et al., 2015).

1.1 The LENA System

The LENA System's hardware includes a digital language processor (DLP) that can audio record for up to 16 hours. It measures 3-3/8" x 2-3/16" x 1/2", weighs less than two ounces, and consists of a display screen, a USB port for uploading, and two buttons for powering and recording. The processor is held in a specially designed t-shirt or vest with a pocket on the front to secure the device. The audio quality is a 16-bit channel at a 16kHz sample rate (Ford, Baer, Xu, Yapanel, & Gray, 2008). Once the recording is complete it can be uploaded to the LENA software. Recordings are stored in the software by participant, allowing repeated recordings of one participant to be saved and compared over time. Once uploaded and recharged, the same participant or a new participant can use the DLP again without affecting the data stored in the software. The LENA System automatically segments the recordings into 12 categories including speakers, environmental sounds, and silence using Gaussian mixture models. A daylong audio file typically consists of 20,000 to 50,000 segments (VanDam et al., 2016). The software then estimates: *adult word count* (AWC), *child vocalization count* (CVC), and *conversational turn count* (CTC). The amount of background noise, electronic sounds, meaningful speech, and silence that were part of the child's listening environment are reported as percentages of the total sound present in the day and are displayed in user-friendly LENA generated graphs along with the AWC, CVC, and CTC. Additional details can be extracted using ADEX software provided by the LENA Foundation (Ford, et al., 2008; VanDam, Ambrose, & Moeller, 2012).

In addition to the raw data counts, Richards, Gilkerson, Paul, & Xu (2008) discuss the Automatic Vocalization Assessment (AVA) generated by the LENA System, which is correlated with traditional expressive language standard scores including those from the Preschool Language Scale - 4th Edition (PLS-4) (Zimmerman, Steiner, & Pond, 2002) and the Receptive-Expressive Emergent Language Test - 3rd Edition (REEL-3) (Bzoch, League, & Brown, 2003). To learn more about the LENA hardware and software, consult Ford et al. (2008) and Oller et al. (2010).

In order to establish reliability, human transcribers coded 70 full day English recordings and their results were compared with those obtained by the automated software (Xu, Yapanel, Gray, & Baer, 2008). This data was collected as part of the Natural Language Study (NLS), the LENA Foundation's normative study (Gilkerson & Richards, 2008). The LENA System correctly identified 82 and 76 percent of the segments humans coded as adult speech and child vocalizations respectively, indicating reasonable levels of agreement (Christakis et al., 2009; Warren et al., 2010; Xu et al., 2008; & Zimmerman et al., 2009). Validity has also been shown in Spanish, French, Mandarin, Korean, and Vietnamese (Canault, Le Normand, Foudil, Loundon, & Thai-Van, 2015; Ganek & Eriks-Brophy, in revision; Gilkerson et al., 2015; Pae et al., 2016; Weisleder & Fernald, 2013). Although these studies show high fidelity, recording in a child's natural environment can produce a degraded auditory signal that may negatively impact validation. Possible causes of interference might include environmental factors such as background noise, overlapping speech, and reverberation, speaker variation like pitch or voice quality, and hardware variability. Although LENA clothing has been rigorously tested, fabric sound absorption rates may also impact accuracy (Xu, Yapanel, & Gray, 2009).

2 Data Collection & Analysis

The authors undertook an extensive search for peer-reviewed studies that reported use of the LENA System. The search occurred over a four-year period (2012-2016) and included numerous databases including Medline, PsycINFO, and Google Scholar. The search term "LENA System" was most commonly used. Articles were also found through the LENA Foundation website which keeps a list of recently published papers as well as through conversations with other LENA users. Articles that dealt primarily with validation, the development of new algorithms, or that used the DLP to record but did not use the commercially available software were excluded. The primary purpose of this paper is to familiarize readers with how the LENA System is used to investigate language acquisition and disorders. Therefore, articles that focused on the LENA System itself, rather than these populations, are not included in the present discussion. Two articles were found that did not rely on the LENA software. Ota and Austin (2013) recorded for two hours pre- and post-treatment. They chose 15-minute segments coded by human coders for child turns, adult words, and conversational cohesiveness. Wang, Miller, and Cotina (2014), on the other hand, created and validated their own algorithms for identifying the type of talk in a classroom without using pre-existing LENA software.

The first author reviewed each article and extracted information regarding each study's methods and participants. Each variable was chosen through conversations with LENA users or by identifying issues that arose within the literature itself. The following is a list of the data that was reviewed:

Methods	**Participants**
Study Type	Number of Participants
LENA Variable	Ages
Number of Recordings	Languages
Length of Recordings	Socio-Economic Status
Time Intervals Analyzed	Additional Needs
Additional Assessments	
Additional Software	
Transcription Software	
Human Coders	

Table 1: Areas reviewed

3 Results: Methods

Thirty-eight articles were found using the criteria listed above. Below are the results from the table regarding the methods of reporting presented in LENA studies. An upcoming publication by Ganek and Eriks-Brophy will provide greater detail regarding the literature consulted in this review as well as in depth methodological analyses.

3.1 Type of Study

Studies were divided into three types: comparative studies that examined LENA results between at least two cohorts, longitudinal studies that measured children's progress over time, and cross-sectional studies that investigated children's ability at a specific point in time. Sixteen of the papers reviewed were comparative. They generally matched typically developing children to children with a communication disorder, though some compared language groups or treatment versus control groups. Eleven longitudinal studies evaluated child development over time. Both comparative and longitudinal studies measured the effects of treatment. Treatments including traditional speech therapy (Warren et al., 2010), formal established treatment programs such as Hanen's *It Takes Two to Talk* (Manolson, 1992; Weil & Middleton, 2011), and treatment associated specifically with provision of LENA feedback (Pae et al., 2016; Suskind et al., 2013). The remaining eleven cross-sectional studies often relied on a single day of recording.

3.2 LENA Variables

As mentioned above, the LENA System provides information on the adult word count (AWC), child vocalization count (CVC), conversational turn count (CTC), an automatic vocalization assessment (AVA), and background noise. Four studies used LENA ADEX software to collect additional variables such as male versus female adult speech (Johnson, Caskey, Rand, Tucker, & Vohr, 2014; Ramirez-Esparza, Garcia-Sierra, & Kuhl, 2014; Sacks et al., 2013; Warren et al., 2010). Abney, Warlaumont, Haussman, Ross, & Wallot (2014) used ADEX to identify child vocal onset times before running a custom script. However, currently published research seems to focus primarily on AWC along with CVC and CTC. Eight articles utilized information about background noise and only two focused on AVA scores.

3.3 Length of Recordings

VanDam et al. (2015) reported length of recording in total hours recorded across all participants while most reported the average number of hours/minutes each participant recorded. Full 16-hour recordings, the longest a LENA DLP can produce, were most commonly used (*M*=12.3, *SD*=3.3). The LENA System software requires recordings to be at least 10 hours long to complete a full automatic analysis. While 25 studies fell between 10 and 16 hours long, some studies asked participants to record for much shorter windows of time. In these cases, LENA analysis alone was usually not relied upon. Instead, researchers conducted their own analysis unrelated to the LENA variables, or added additional assessments.

3.4 Number of Recordings

Most of the papers recorded a single day (*M*=7.4, *SD*=11.6). Those that recorded for more than that usually did so to counteract any potential observations effects (Sacks et al., 2013) or to engage in longitudinal data collection (Weisleder & Fernald, 2013). Two papers reported the total number of recordings for all participants, while others presented the average for each individual.

3.5 Interval of Analysis

Some researchers chose to limit the amount of recording they used in analysis, often times using LENA data to govern segments of interest (ex. high CVC; Oller, 2010). Some researchers selected 5-minute segments, sometimes only looking at the first minute or 30 seconds (Jackson & Callender, 2014; Ramirez-Esparza et al., 2014). In 20 cases, however, no interval is stated. It is assumed that a full day recording (10+ hours) was used for analysis.

3.6 Additional Data and Software

LENA software is not always capable of providing all the data that researchers are looking for. Seven studies developed their own customized algorithms to locate their desired outcomes, such as vocal onset times (Abney et al., 2014; Warlaumont et al., 2010), consonant and vowel counts per utterance (Xu, Richards, & Gilkerson, 2014), pitch and speaking rate (Ko, Seidl, Cristia, Reimchen, & Soderstrom, 2015), and classroom speakers (Wang et al., 2014). Praat (Boersm & Weenink, 2013) and SALT (Miller & Chapman, 2013), widely available software programs, have also been used for analyzing speech sounds and language development (Burgess, Audet, & Harjusola, 2013; Ko, et al., 2015).

3.7 Human Transcription and Coding

The LENA System does not provide a transcription of the recordings. However, researchers frequently find it helpful to transcribe the data for analysis. While some validation studies refer to transcription software (Canault, et al., 2015; Gilkerson et al., 2015), none of the studies reviewed for this paper reported which tools were used in transcription.

About a quarter of the studies did not transcribe but instead simply coded recordings, marking pertinent information rather than providing a full transcript. Commonly coded variables included infant directed versus adult directed speech, activity, and language spoken, among others.

4 Participants

This section refers to the participants observed in each study. Please refer to the upcoming publication by Ganek and Eriks-Brophy for further detail.

4.1 Sample Size

The Natural Language Study (NLS) (Gilkerson & Richards, 2008), the LENA Foundation's normative study, included 329 participants. Seven studies used NLS data either as their primary source or as a comparative group. Studies for which new data was collected ranged from between one (Oller, 2010) and eighty-one (Wood, Diehm, & Callender, 2016) participants (*M*=24.9, *SD*=18.9).

4.2 Participant Age

The LENA System is validated from age 2 months to 48 month (Gilkerson & Richards, 2008). Twenty-five of the studies reviewed here had participants within this age range. Nine, however, expanded to five year olds and two observed children younger than two months old (Caskey, Stephens, Tucker, & Vohr, 2011; 2014), while two other studies had cohorts above the age range including older adults (Li, Vikani, Harris, & Lin, 2014; Vohr, Watson, St. Pierre, & Tucker, 2014). The expanded age ranges were dealt with by enlisting human coders, ignoring specific LENA outcomes, and providing additional evidence that participants had language ages within the normative range.

4.3 Language Use

Expansion outside of English speaking populations has been limited. Most studies include only English speakers, though there have been five studies that have included English-Spanish bilingual children and six including monolingual Spanish speakers. There has also been one study conducted in Mandarin (Zhang et al., 2015) and one with a trilingual English-Spanish-German speaker (Oller, 2010). This study relied on a human coder rather than the LENA results, avoiding a validation issue.

4.4 Socio-Economic Status (SES)

Socio-economic status (SES) is a measure of a person's social position based on income, education, and occupation. Hart and Risley (1995) famously reported a correlation between SES, language stimulation, and language abilities. Their study, and those like it, inspired the creation of the LENA System. Even though the impact of SES on language outcomes is widely known, few of the studies reported here were able to control for it. Ten studies failed to report SES and another six reported that comparative groups were matched either to each other or to census data. Six represented a range of maternal educational levels. Nine of the studies reported that their samples skewed towards high SES participants while five others reported collecting only low SES participants. Two studies also reported an SES mismatch between comparative groups (Jackson & Callender, 2014; Wood, et al., 2016).

4.5 Populations

Most LENA System use in research has been conducted on typically developing children. However, eight studies have focused on children with autism spectrum disorder, six on hearing loss, one on Down syndrome, two on pre-term infants, and three on language delay.

4.6 Settings

Due primarily to the normed age ranges for the LENA System, most studies included recordings completed in the home. Six papers conducted recordings in a classroom setting specifically to evaluate possible differences in language stimulation in a different environment (Burgess, et al., 2013; Dykstra et al., 2012; Irvin, Hume, Boyd, McBee, & Odom, 2013; Jackson & Callendar, 2014; Soderstrom & Wittebolle, 2013; Wiggin, Gabbard, Thompson, Goberis, & Yoshinaga-Itano, 2012).

5 Discussion

LENA researchers are working to identify the best methods for integrating this new tool into the exploration of child language acquisition. Their work can help those new to the use of automated vocal analysis recognize best practices for LENA use.

When reading LENA studies, it is important to be aware of the LENA Foundation's normative study, the NLS. Almost 20 percent of the studies reviewed for this paper rely on this cohort either for primary data or comparative information. Interpreting LENA results, then, relies on the reader's understanding of the methods and participants included in the NLS. Additionally, repeatedly relying on a single data set can reduce the generalizability of research results.

To aid in the diversification of LENA data sets, a consortium of LENA researchers have recently joined forces to create Homebank, an online repository for LENA recordings (VanDam et al., 2016). The goal of this database is to provide researchers interested in advancing commercially available automated vocal analysis systems with extensive LENA data. The LENA System is capable of providing information on a variety of different aspects of a child's auditory environment, however, there are a number of features it does not capture. For example, 12 of the articles coded LENA recordings by hand for adult versus child-directed speech. Homebank encourages researchers as well as clinicians to donate data so that those interested in creating algorithms to identify variables similar to this one can do so.

At this point in time, the LENA System does not produce a transcription of the audio recording. Many researchers are still transcribing recordings by hand, which allows them to capture qualitative information like vocabulary and syntax along side quantitative data. Hart and Risley (1992), among others, found that quality of language input was as important if not more important than the quantity of language input. Without involving a significant amount of human-power, however, aspects that might characterize the quality of the interaction could be difficult to extract. Researchers and clinicians alike would appreciate reliable transcription software. Unfortunately, technology is not currently able to reach this goal. Outside of the LENA Foundation's own transcription protocol (Gilkerson, Coulter, & Richards, 2008), LENA literature rarely specifies how transcription was completed (transcriptionist training protocols, software programs utilized, etc.). Providing adequate details about transcription could allow for better replication and generalization of results in the future.

While LENA software has proven to have high fidelity; it can still make coding errors (VanDam et al., 2012). Occasionally it will mislabel a speaker. For example, a woman who raises her vocal pitch may be coded as a child (Gilkerson et al., 2015). Additionally, when two speakers are talking at the same time (overlapping talk) the LENA software discards both utterances (Warren et al., 2010; Xu et al., 2008). In busy homes with large families, discarding overlapping speech would likely underestimate the true number of interactions that occurred. Similar issues may also impact LENA results obtained in classroom settings. However, both Xu et al. (2009) and Warren et al. (2010) state that recordings of 12 hours or longer provide reliably accurate LENA results. Labeling errors caused by speaker confusion or overlapping sounds are likely to have less significance in a large data set. Recordings over multiple days may also increase accuracy (Xu et al. 2009). Longer recordings are therefore more likely to demonstrate accuracy in LENA results, while also providing representation of language over multiple activities and settings. However, shorter recordings may be more accessible for human coding or transcription of elements the software is incapable of calculating. Additionally, recordings less than 10 hours cannot be compared to normative data provided by the device, which may be helpful in language acquisition research.

LENA studies conducted in classroom settings are particularly susceptible to reduced accuracy due to interfering noise and overlapping speech. Soderstrom and Wittebolle (2013) point out, however, that a reduced AWC due to overlap may actually portray a more accurate picture of the information a young child or a child with a language disorder is able to process given the difficulties associated with listening in noise (Crandell, Smaldino, & Flexer, 2005; Newman, 2010). All of the studies in classrooms reviewed here included multiple students in each classroom. It is unclear, however, if the DLPs were worn at the same time. Future studies might consider comparing or synthesizing data taken from multiple participants at the same time and location to investigate validity.

Families recording with the LENA System at home, without supervision by the researcher, are free to turn off the device at any time, leading to variability in length. Eight studies controlled for length of recordings by looking at per hour/minute rates rather than reporting full recording results. Three others relied on the first 12 hours recorded, a measure that the LENA System provides automatically (Vohr et al., 2014; Warren et al., 2010; Zhang et al., 2015). Additionally, four studies removed periods during which the child was sleeping to control for long segments of silence (Marchman, Martinez, Hurtado, Gruter, & Fernald, 2016; Sacks et al., 2013; Suskind et al., 2013; Weisleder & Fernald, 2013). In order to obtain the most reliable results, LENA users must consider how they might control for length of recording.

Some researchers required more information than the LENA System is able to provide. Twenty-six papers engaged in a mixed methods approach, combining LENA results with other types of data including standardized language assessments, interviews, daily logs, and other technology such as Actograph (Santos-Lozano et al., 2012) and look-while-listening tasks (Fernald, Zangle, Portillo, & Marchman, 2008). Combining automated vocal analysis with other data collection methods can provide a more holistic picture of a child's language development.

Expanding the use of the LENA System to larger more diverse populations may help to increase our understanding of language acquisition. The majority of LENA studies were conducted with English speaking families in the United States. LENA data collected from families that speak languages other than English might inform our understanding of language acquisition universally. Additionally, the LENA System is only normed between 2 and 48 months old so data for children outside this range may be invalid. However, Wang et al. (2014) showed that the LENA System was accurate in identifying child speakers up to grade four. Increasing the age range for LENA use could provide information on language use across the lifespan. Future LENA research should also strive to achieve a representative range of SES groups.

Furthermore, this tool has been used with children who have a variety of communication disorders including hearing loss, autism, Down Syndrome, and language delays. Future research might consider replicating and increasing the types of communication disorders being investigated so that more families could benefit from the LENA System. It is also important to note, however, that many children with language disorders rely on visual languages and communication systems that will not be represented in LENA analysis.

6 Conclusion

Since the LENA System was first released, researchers have been exploring its possible place in identifying and describing language acquisition and language disorders. It has already provided intriguing results about the natural language environments of children from a number of different linguistic backgrounds and with a variety of communication abilities. The LENA System is also being used as an intervention tool in many countries around the world.

Nevertheless, as the field continues to expand, LENA users must consider what the device's true capabilities are. The LENA System is a remarkable tool for collecting data in a child's language environment. Understanding its strengths and weaknesses as well as the methods for its use will allow for enhanced interpretation of data contributing to the growth of the LENA System in both research and intervention settings.

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