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The Use of Eye-Tracking in the Investigation of Prelinguistic Infants: A Review

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Abstract

Advances in technology have yielded new techniques for investigating phenomena in the area of early childhood developmental science. Electronic eye-tracking allows for a more detailed and objective way to measure infant attention as compared to traditional methods, such as the Preferential Looking Paradigm. As the use of this technique increases, it becomes important for researchers to understand both the benefits and challenges of its use with young prelinguistic infants. The accuracy of gaze determination and ease of use with young populations make eye-tracking a worthwhile method to consider. Challenges, however, do exist that make replicability and generalizability difficult. The purpose of this paper is to provide a succinct, review of literature of eye-tracking techniques with prelinguistic infants, challenges of its use for diagnostic purposes and conclusions for how researchers should proceed.

Keywords

Eye-tracking, Infant development, Language

Introduction

Early childhood developmental science has changed how prelinguistic children's acquisition of skill is investigated. The Preferential Looking Paradigm (PLP) was historically the dominant research method used to measure young children's viewing behavior. These subjective measures are being usurped by more objective measures providing detailed evidence of eye-tracking patterns. Eye-tracking has been linked to a variety of developmental topics including language [1-3], social cueing [4,5], mother's attachment [6,7], face perception [8-11] and motor development [12]. Additionally, the use of eye-tracking with young children as a potential diagnostic tool is gaining popularity [13]. Despite the precision of digital eye-tracking measures, its use with infants presents unique challenges making replicability and generalizability difficult. A small cohort of researchers is beginning to create open data repositories [14] and multi-site collaborations [15] in an attempt to advance research targeting very young children. One contribution to this collaborative initiative is to provide researchers with a foundational literature review. This systematic review provides readers a succinct background on the use of eye-tracking in developmental research with prelinguistic infants, potential challenges (i.e., methodological and technical considerations, subject recruitment, replicability, etc.), its use as a diagnostic tool and conclusions.

History of Eye-movement Methodology

The Preferential Looking Paradigm (PLP) and the single-stimulus habituation paradigms represented the vast majority of commonly used methods of eye measurement [16-18]. Simple PLP technique was initially designed as a way to understand how infants perform on tasks of visual acuity. Eventually, this technique was used to determine various aspects of infant looking, including visual acuity, facial perception, object preferences and vi-

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sual attention [16,19].

Modifications to the simple PLP occurred in order to focus on other domains of infant development [20-23]. To maintain the accuracy of infant gaze direction, lighting and target contrast were adjusted, allowing for reflected, mirror images on the child's pupil [17,18]. These images were recorded as infant fixation [17,18]. Perceptual awareness gradually worked its way to the forefront of research involving young infants and with it the use of the PLP.

Despite the prevalent use of this technique, there are certain aspects of its specificity that simply cannot match the use of a computerized eye-tracking system [24]. Limitations regarding the accuracy of trained coders to measure where in space the infant gaze is directed remains a challenge for the PLP [16,24]. Not only are observers inaccurate to spatial position, the ability to measure vertical and horizontal changes in gaze position presents an even greater challenge [16]. In addition, this technique has been characterized as time-consuming and difficult from both the data analysis and stimuli development perspectives [16,21].

While eye-tracking can be construed as a version of the PLP, the ways in which it gathers and collects eye-gaze data is unique. The differences are three-fold: 1) The specificity and accuracy of measurement replace subjective determinations of looking behavior, 2) The units of data gathered are multidimensional and sampled at a high rate (i.e., 60 - 2000 Hz) and 3) Data can be represented visually using dynamic, aggregated plots superimposed on stimuli images (e.g. heatmaps, gaze plots). Eye-tracking can be a tool that provides a detailed description of eye-gaze behavior within individual subjects. These individual differences are critical to understand developmental trajectories.

The applicability of eye-tracking outside of developmental science has been pursued. Market research and website usability studies often incorporate eye-tracking measures to determine functionality and ease of use during webpage navigation [25]. Additionally, the use of eye-tracking to investigate mental workload during driving tasks [26] driver distractibility [27,28], and reading [29] have also been studied. The use of eye-tracking in seemingly tangential fields offer infant researcher methodological elements to consider. Despite obvious differences in the populations of study, similarities exist within segments of the procedures administered. Stimulus design considerations and calibration are both components that are relevant to each respective field and require individualization based upon the population under study. It is quite possible that findings from usability and distracted driving studies may shed light on the developmental progression of attention. This has the potential to elucidate developmental researchers on certain processes that may be evident at an earlier point in time.

Eye-Tracking Systems

The use of eye-tracking as a measure of performance in young children has increased over the last decade [24]. Computer-aided eye-tracking instrumentation allows researchers to create a more objective approach to data collection. This focuses on task-specific studies of visual attention (i.e., reading, scanning an image, etc.). As infant research has progressed, additional areas of interest have emerged, including infant perception and processes associated with language acquisition and word learning [30-32], and face processing [33-35]. Eye-tracking techniques provide another level of analysis. The functional options available provide researchers with a set of tools that allow for sophisticated data collection and visualization.

Current systems use either single or binocular corneal reflection to determine the point of gaze. Affordances developed within newer systems allow for larger head movements that may have prevented its use with younger populations in years past. Introductions of larger "head box" space accommodate for the variability in motion young participants exhibit. The ability of the system to regroup and compensate when head movement causes loss of eye visualization means that both gross and intricate eye movements are captured and can be analyzed. This detail can provide researchers insight into looking behaviors at a micro level. Flexibility within programming and experimental procedural set-up allow researchers to use a variety of stimuli, ranging from photographs to live, dynamic scenes. While at first glance, this may seem parallel to older techniques, what is unique is the level of detail acquired. It is important to note, however, that this methodology does not come without its own challenges. [36] Wass and colleagues (2014) described how precision and accuracy can be compromised with young populations which can result in decreased data robustness. Individual and between subject differences were noted. These were dependent upon age of subject, time of testing session (i.e., early or late within the session), and slower reaction time latencies.

There exists a variety of eye-tracking options available to researchers interested in pursuing this line of work. Manufacturers of systems that are viable for infant populations include: 1) Tobii Pro Technology, 2) SR Research (i.e, Eye Link) and 3) Positive Science Eye Tracking (i.e., head mounted systems). Both the Tobii Pro Technology and SR Research systems are considered static binocular (i.e., captures 2 eyes when tracking) eye-trackers, meaning that they are not easily transportable and are typically used within a laboratory setting [37]. Each system provides freedom of head movement without being bound to a chin strap apparatus. This affordance is necessary when conducting eye-tracking experiments with very young infants. The SR Eye Link 1000 Plus samples at a very high rate (i.e., up to 2000 hz) as compared to the Tobii Pro Spectrum which samples up to 1200 hz. This makes the SR EyeLink 1000 Plus one of the most precise eye-trackers available (retrieved from https://www.sr-research.com/products/eyelink-1000-plus/). For researchers interested in capturing eye-tracking data in more naturalistic settings, head-mounted eye-trackers provide that option. Positive Science Eye-Tracking manufactures a head-mounted eye-tracker option that allows the participant to move about their environment. The system uses monocular (i.e., one eye capture) eye-tracking to capture eye-gaze behavior. Infant participants are fitted with a cap that includes a camera arm that extends from the forehead to directly in front of the eye (retrieved from http://www.positivescience.com/hardware). One limitation of the Positive Science eye-tracking system is that it requires the eye-tracker be tethered to a laboratory kit. For infant research, this means that the participant's exploration is bound by a 20 ft cord which, in order to extend that range, must be manipulated by the investigator. At present, this system is used to investigate various elements of infant development, including joint attention [38], infant motor development [39,40], and infant interactions [41].

Each system has inherent challenges and limitations. All systems are capable of collecting gaze behavior from young infants. Tobii Pro Technology and SR Research manufacture eye-trackers that provide the greatest precision and accuracy but are restricted to being used within a singular space. Positive Science, on the other hand, has developed a head-mounted system that allows for gaze data collected within naturalistic settings. A significant shortcoming however, is the participant is confined to exploration within a set 20 ft range. In spite of these challenges, these advancements have changed the ways in which eye movements are measured and expanded the population to which it can be used. As a result, more sophisticated research questions have been posed concerning underlying processes in infant development.

Additional technical reports focusing on eye-tracking outside the scope of this paper can be found in the following articles [29,42,43]:

Data Robustness and Generalizability

The implications that result from poorly designed eye-tracking studies or the misinterpretation of data gathered creates the potential for reporting outcomes that are not valid. Eye-tracking use with very young subjects brings with it an inherent concern for the robustness of data and overall generalizability to the broader population. Infants, by their very nature, are a diverse population with individual differences outweighing similarities. This can create challenges in designing procedures to accurately represent the nature of the research in question. Eye-tracking, as a data collection tool, has the capability to provide a high degree of accuracy when procedures and protocols adhere to a set of prescribed standards. At present, few methodological papers exist that describe the use of eye-tracking with infant populations.

Calibration

Variability in calibration procedures is one way in which protocols differ. This is an important element that must be maintained in order to assure consistency. Calibration is necessary to align the eye-tracker and decrease drift from the target. This is achieved by the subject gazing at a target displayed on a screen in predetermined locations, ranging from 2 to 9 points. It can be assumed that as the number of calibration points increases, so does the accuracy of gaze. Use of fewer calibration points may result in less reliable data. Given the population at-hand, however, it is necessary to consider "trade-offs" for use of more calibration points. Very young infants have limited attention spans which make it increasingly difficult to achieve high levels of participation in tasks such as these for long periods of time. Additional calibration points have the potential to lengthen this process which could result in attrition. An additional point to consider is that very young infants have difficulty in shifting attention from one stimulus to another. This has ramifications for calibration that researchers must consider. More calibration points is not always the better option, particularly in infant eye-tracking research. Given these factors, there is presently not a general guide on the number of calibration points to use with young infants. The current infant eye-tracking literature lacks consistency, yielding a wide array of calibration points used. It does not seem to be without reason that more detailed descriptions of eye-tracking methods should be available to investigators. This, unfortunately, is not the case.

Methods to adjust and customize (i.e., MATLAB and E-Prime) calibrations exist. Frank, Vul, and Saxe [44] created a MATLAB code that includes calibration checking and adjustments. The development of this code was born out of the realization that systematic calibration errors were occurring consistently within their infant studies. This was identified as point-of-gaze behaviors that occurred within several degrees of visual angle from where the infant was actually looking. According to Frank (retrieved from https://web.stanford.edu/~mcfrank/materials/calib.html), the consistency of the errors made it difficult for the eye-tracker's calibration display to detect. Additional information that includes materials used and the corresponding downloadable links can be found at https://web.stanford.edu/~mcfrank/materials/calib.html.

Infant attention

Young infants, by their very nature, require external sources to help them attend to specific object locations. Verbalization of instructions is not a viable solution when attempting to engage infant attention. Alternative solutions that often involve additional people and resources should be considered. Calibration requires the infant to fixate on a small target for a specified duration of time before the instrument can register and record accuracy of gaze. Certain product manufacturers have included customized calibration points that combine visually stimulating pictures with sounds to attract attention. Infant attention during calibration is not the only factor to consider. Post-calibration, task duration, and fatigue during the presentation of experimental protocol are additional elements that must be considered. Inattention and diverted gaze that results from distracted and tired infants could confound results and may cause errors in data interpretation.

Kulke, Atkinson, & Braddick [45] described evidence of infant "sticky fixations" that result from a young infant's ability to shift attention toward a competing stimulus. The capability to disengage from a stimulus is a product of developmental change and increases as the infant ages. In addition, Aslin and Salapatek [46] note, that for young infants', saccade accuracy is challenging often resulting in underperformance. This inability to correctly identify the target then remedied by additional saccades that rectify the fixation. These developmental patterns are important to consider during the creation of infant eye-tracking paradigms. Designing stimuli and procedures, as well as understanding the impact "sticky fixations" have on data analysis and interpretation are crucial. The metrics used to describe infant looking and attention (i.e., fixations, saccades, visits, etc.) must be appropriately applied in situations where there is evidence of long latencies occurring.

Figure 1: Example of parent lap used as seating in infant eye-tracking research.

Figure 2: Example of high-chair used during infant eye-tracking research.

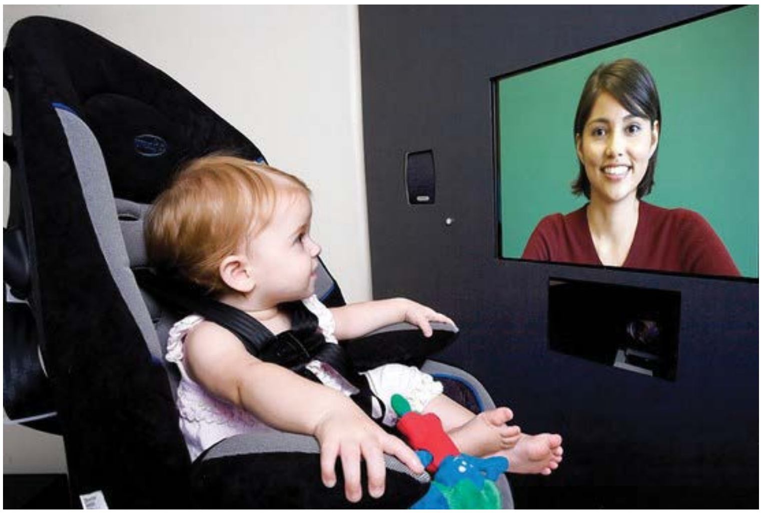

Figure 3: Example of car seat used during infant eye-tracking research.

Table 1: A brief glimpse into the variability of procedures used within infant eye-tracking studies.

Studies	Participants	Methodology	General Findings
Jones & Klin (2013) [13]	110 infants	Car seat or reclined bassinet	Decline in eye fixation in infants later diagnosed with autism spectrum disorder
	2-24 months	5-point calibration[1]	
		Videos of people	
Lui, et al. (2011) [47]	23 infants	Car seat	Whole face stimuli showed no differences
	4-9 months	5-point calibration[4]	Over time, decreased fixation duration on internal features of other race faces
		Videos of same and other race faces	
Hunnius & Geuze (2004) [33]	10 infants	Infant chair	Adapted gaze behavior to stimuli characteristics
	12-26 weeks	2-point calibration[3]	Direct attention to mother's eyes and mouth.
		Dynamic stimuli of mother	
Hunnius, Wit, Vrins & Von Hofsten (2011) [48]	31 infants: 4 months	Parent lap	Demonstrated avoidant looking at threat based emotional expressions
	29 infants: 7 months		
		9-point calibration[4]	
		Faces of people	
Frank, Vul & Saxe (2011) [44]	129 infants	Parent lap	Over time, attention directed to parts of complex scenes that are socially intriguing.
	3-30 months	2-point calibration[1]	
		Live action videos	
Gredeback, Fikke, & Melinder (2010) [49]	40 infants	Experimenter lap	Infants followed the gaze of unfamiliar individual rather than mother
	2-8 months	2-point calibration[2]	
		Visuals of people engaging in a task	

Methodology for data analysis used: [1]MATLAB; [2]Tobii Studio; [3]Author designed; [4]Not documented.

Physical design of the room

The physical design of the laboratory space can vary greatly from study to study. It does seem, however, that similarities exist within certain parameters. One is the type of seating options used. Three variants are mostly seen (see Figures 1, Figure 2 and Figure 3). These include infant car seats/carriers, infant highchairs or use of the caregiver's lap. Each requires adjusting for height and distance from the eye-tracking device as well as other safeguards (i.e., support system for infant head and trunk, harness system, headphones for the caregiver, etc.). Determination of other physical space elements is less easily defined and quantified throughout the eye-tracking literature. Variations on lighting, space surrounding the eye-tracking instrument, use of a separate room, etc. are just a few ways in which investigations vary Table 1 provides a brief glimpse into the variability of procedures used within infant eye-tracking studies [47-49]. At present, there are a number of infant labs that employ eye-tracking as a data collection tool. Table 2 provides additional information on labs currently using eye-tracking within their cadre of research instruments.

Table 2: Additional information on labs currently using eye-tracking within their cadre of research instruments.

Developmental Science Lab	Website Address
UCLA Baby Lab	
Stanford Language and Cognition Lab	http://langcog.stanford.edu/index.html
University of California, Davis Infant Cognition Lab	http://oakeslab.ucdavis.edu/
Uppsala University Child and Baby Lab	https://psyk.uu.se/uppsala-child-and-baby-lab/research/
Emory Infant and Child Lab	http://www.psychology.emory.edu/cognition/rochat/lab/
University of Rochester Baby Lab	http://babylab.bcs.rochester.edu/methods.html
New York University Infant Action Lab	http://psych.nyu.edu/adolph/index.php?page=et
University of Virginia Early Social Development Lab	https://pages.shanti.virginia.edu/Social_Development_Lab_3/

Data Analysis

A diversity of programs and approaches are used to manage eye-tracking data (see Table 1 -as indicated with footnote). Within the infant eye-tracking literature, few present information around the types of analysis programs and use of additional approaches. Presently, a small cadre of researchers have attempted to shed light on data analysis techniques [36,50] and the use of data filtering [51] as a mechanism for visualizing infant eye gaze data. These considerations and software programs, while available, are not commonly cited as being used in the literature surrounding eye-tracking and young children. Others, it seems, use ancillary programs, like MATLAB that require coding experience and expertise. While this may control for some elements of data reliability and validity, differences still exist across investigators and labs in how programs and codes are developed and used. Two avenues that are currently being explored are the use of multisite teams (i.e., Open Science Framework) that involve the collaborative approach to data collection that results in large-scale replicability studies and large populations. Frank, et al. [15] and the many Babies project uses Open Science Framework as a collaborative workspace that involves multiple investigators from infant labs both nationally and internationally. The site allows researchers to become part of a data collection team whereby they can download and use previously developed stimuli and protocols. The data, once collected, is then shared with the project administrators. The result is a large compilation of infant data that is representative of diverse populations, which, in turn, is generalizable to a broader population. The second is the use of open data repositories (i.e., Databrary, Child Language Data Exchange System (CHILDES), Cross Linguistic Lexical Norms (CLEX), Word Bank that allow researchers to use and analyze previously collected data. These collections of infant data are available to researchers interested in replication or novel studies of infant development. It seems, however, that few of these open repositories exist and the ones that do are focused on child language data which outnumber those specific to development or those that focus on eye-tracking in general. Proponents of movement toward the use of open repositories and multisite collaborations argue that this will increase our ability to make claims about infant development [52]. Data transparency is also highlighted as integral to the scientific process [14]. Given the variability across labs and investigators in both experimental protocols and data analysis of eye-tracking measures, this new direction of developmental science can lead to better overall standards of research practice.

Clinical Implications

The use of eye-tracking in the investigation of autism has gained momentum. In recent years, researchers have developed a better understanding of early differences in the eye-gaze behaviors of children who are at-risk and are later diagnosed with Autism [53,54]. Much of this center on attention to specific facial features (i.e., eyes and mouth) and language learning. Evidence suggests that children who are later diagnosed with Autism do not exhibit shifts in attention around these facial characteristics like their neurotypical counterparts [53,54]. Autism is one of several developmental disabilities where the use of eye-tracking has become a tool for understanding differences in behavior and social and linguistic attention between children who are typically developing and those diagnosed or at-risk for developmental delay. While Autism has certainly been the most heavily researched developmental disability [55-57] others have also been investigated. Eye-tracking has been used to explore cognitive performance in girls diagnosed with Rhett Syndrome [58] visual preference for faces in persons with Fragile X [59], dyslexia [60], specific language impairment [61] and working memory in individuals with and without aphasia [62]. Most of this previous research, however, focused on older children. What is less well-known, is the feasibility of using eye-tracking as a diagnostic tool in infants. Methodological challenges are concerns that need to be addressed involving special populations as well in infants. The design of experimental protocols, the determination of instrumentation set-up and use and data collection and analysis have the potential to be mired with inconsistencies. Unique characteristics of each population at hand requires special consideration when determining appropriate protocols and data analysis tools and procedures. Researchers must consider the following: 1) Attention to task and ability to follow directions, 2) Sensitivity to sensory stimuli (i.e., the moving targets in the calibration sequence), 3) Timing of item presentations to reduce the risk of participant fatigue or disinterest, 4) Ocular maturity or macular degeneration, and 5) Visual acuity of the participants to track changes in the digitally presented stimuli. Despite evidence to suggest that differences within specific domains of development exist within special populations, generalizability of the current eye-tracking results is questionable due to differences in protocol. Additional research is needed to confirm what markers are indeed early indicators of the disorder and not related to differences individual children or methodological approaches.

Conclusions

The focus of this paper was to provide a systematic review of the challenges associated with the use of eye-tracking with prelinguistic infants. Results from this review suggest the need for more objective and detailed methodological approaches surrounding eye-gaze behavior. Eye-tracking is a tool by which infant eye-gaze behavior can be characterized and described with greater specificity than previously used techniques. However, there are inherent challenges and concerns related to experimental procedures and data analysis. A lack of consistency with regards to calibration, seating, the physical design of the procedural space, and sample size are just a few ways infant eye-tracking research differs among investigators. There is a need for more transparency regarding experimental protocols that allow for the transfer of knowledge about best practices around eye-tracking with infant subjects. Some researchers are championing the use of multi-site collaborative projects, data repositories, and encouraging pre-registration of studies. This has the potential to move the field toward more robust data and the ability to replicate and generalize results. It is important that these efforts be focused on developmental science in general, and not solely on discrete domains of development or only within certain academic affiliations.

Eye-tracking with special populations of children is gaining momentum and has a potential to expand our knowledge of special populations of children. Its use to identify similarities and differences within patterns of development has clearly impacted what is understood about developmental disorders. It also provides an avenue for researchers to ask questions about prelinguistic populations that have the potential to provide greater insight into when, within developmental trajectories, deviation occurs. This could lead the way for diagnosis and intervention much earlier in life. While this direction is exciting, it also warrants a note of caution. Research in this area is in its infancy and further work is needed to fully understand how early investigations of eye-gaze behavior may lead to its clinical use. There is still much work to be done regarding general, typical developmental patterns. It is first important that those questions are addressed and vetted before movement is made toward using tools, like eye-tracking, in diagnostic ways.

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