I See What You're Saying: A Literature Review of Eye Tracking Research in Communication of Deaf or Hard of Hearing Users

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ABSTRACT

Deaf or hard-of-hearing (DHH) individuals heavily rely on their visual senses to be aware about their environment, giving them heightened visual cognition and improved attention management strategies. Thus, the eyes have shown to play a significant role in these visual communication practices and, therefore, many various researches have adopted methodologies, specifically eye-tracking, to understand the gaze patterns and analyze the behavior of DHH individuals. In this paper, we provide a literature review from 55 papers and data analysis from eye-tracking studies concerning hearing impairment, attention management strategies, and their mode of communication such as Visual and Textual based communication. Through this survey, we summarize the findings and provide future research directions.

CCS CONCEPTS

• **Human-centered computing → Accessibility theory, concepts and paradigms**.

KEYWORDS

Deaf or Hard of Hearing, eye tracking, eye gaze, communication, attention

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1 INTRODUCTION

Human eyes are the windows into our mind and we can understand an individual's behavior by analyzing their gaze patterns. Our eyes don't just help to see the world around us but also play an important role in complex cognitive processing without requiring conscious effort. Eye contact is an important part of social interactions and gaze patterns have set the base to gain insight into autism [70]. Research on eye movement and eye monitoring flourished in the 1970s, with considerable advancement in both eye-tracking literature and psychological theory so as to connect eye-tracking data with cognitive processes [53]. Eye-tracking heavily contributes to the field of Human-Computer Interaction (HCI) by playing important roles such as an input-method for interaction, an analysis tool for usability testing, and a way to understand human behavior in natural and controlled environments. Thus, with the help of eye-tracking technologies we can understand many cognitive processes, interpret an individual's emotional state, and answer complex behavioral patterns.

Studies have shown that along with verbal cues, humans tend to unconsciously identify non-verbal cues to establish perceptions about others [60, 78]. Blink and head nods have been found to hold huge importance in indicating engagement in social interactions. Gupta, et al. performed an eye-tracking study which indicated that participants had more empathy in a face-to-face conversation and tended to synchronize their eye blinks and head nods [45]. Similarly, Nakano et al. found that if the mouth and eyes of a speaker were visible in a video then the listeners would synchronize their eye blinks with the speaker's eye blinks [90]. Results from other studies [52] also indicate that listeners' blinks are often interpreted as communicative signals and directly influence the communicative actions of speakers. Research by Fred Cummins have tried to figure out the relationship between gaze and blinks in dyadic conversations [33]. Studies performed by Sandgren O. et al shows that when a task was to be performed between two people, the executor spends nearly 90% of the time focusing his eyes on the mission, 10% on the director's face, and less than 0.5% elsewhere [103]. The listener looks more at the speaker than the other way around, however, at key points the speaker, when speaking, seeks an answer by looking at the listener, producing a brief time of shared gaze [9]. Weiss has shown that eye movements play an important role in providing non-verbal cues and various aspects of conversation such as turn-taking or attentiveness, which appear to be directly tied to an individual's eye movements [121]. In both, one-on-one as well as group conversations, the eye gaze of the audience plays an important role in defining conversational turn-taking speaker from the audience.

Deaf or Hard of Hearing (DHH) individuals have heightened visual senses compared to the hearing individuals, however, that is best revealed when attention is considered [10]. Studies show that DHH individuals use their visual senses more to compensate for the hearing limitations [10] and to understand, interpret, and communicate with the world around them. One study [74] has indicated the connection between cross-modal cortical recruitment and visual capacity in congenitally deaf cats, a phenomenon where cross-modal reorganisation to visual senses occurs in the absence

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of auditory senses. They found that two aspects of vision were improved by auditory deprivation: motion detection and peripheral location. Inspired by the study performed on deaf cats [74], the authors [40] proposed that there is a possibility of cross-modal reorganization after auditory deprivation in humans as well. Data analysis from another eye-tracking research shows that the deaf participants have a lower threshold for motion than that of the hearing participants [105]. Based on these findings, the authors believe that the auditory-visual cross-modal neural activity supports the improved visual capacity seen in deaf humans. The study also suggests that DHH individuals often display faster reaction times to moving stimuli as well as stationary stimuli in the periphery, as compared to hearing individuals, indicating the likelihood of general improvement of reaction times for peripheral stimuli [105]. The DHH individuals rely heavily on visual communication methods such as sign language and lip-reading, thus, using their eyes to communicate. Since sign language, a main communication mode adopted by DHH community, is a visual language, studying the perception of DHH individuals is important, and understanding the gaze patterns could provide insight into DHH individuals' behaviors while communicating.

In this paper, we provide a literature survey based on previous studies that focuses on eye-gaze behaviours of DHH individuals and discuss several overarching research categories that are based on Visual (e.g. sign language) and Textual (e.g. captions) media and further discuss the context (e.g. classrooms) of the research . Our main contribution is to provide a literature survey that summarizes the understanding of behaviour patterns based on research that explore eye-tracking studies on DHH individuals and discuss key research directions for the future.

2 METHODOLOGY

Following our motivation, our search criteria for relevant research were to conduct systematic searches on ACM, IEEE, and Google Scholar databases. Moreover, searches were also conducted on databases from linguistic and psychology fields to find relevant research. Our search terms were devised based on the authors' previous experiences in the field and they included various combinations of terms like - deaf; hard of hearing; DHH; cochlear implant; eye-tracking; eye-gaze; gaze; sign language; captions; visual communication; lip-reading; etc. Once a suitable article was found, we reviewed its references as well as articles which have cited those papers. The initial search found approximately 69 articles of interest.

2.1 Study Selection

To narrow down our search results, we restricted the main criteria to include papers from eye-tracking, gaze behavior, hearing impairment, and their communication methods. For the initial screening process, we searched the title and abstract of each paper to identify if the papers were related to our research interest and if a paper was related to our interests, we went through the entire article. In total, we found 55 papers which satisfied our criteria of research. For example, we did not consider any research relating to reading (e.g. reading texts in books), as it did not consider a communication method specific to DHH individuals (e.g. Sign language, lip reading, etc.).

2.2 Data Analysis Approach

We adopted a qualitative research strategy to thematically analyze our data [16]. The analysis was focused on understanding the importance of visuals for DHH individuals in a communication situation. Therefore, the papers were coded based on a number of categories including participant types, communication modes and the context of use (utility).

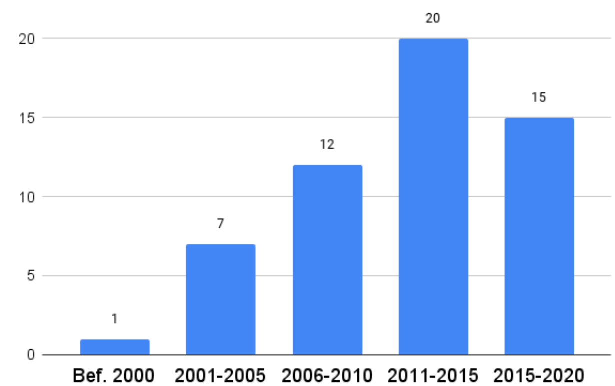

Figure 1: The bar graph shows number of papers published between 1994 and 2020

3 RESULTS

3.1 Data Sources

Figure 1 denotes the distribution of the articles found over the years. During our research, we saw a large number of studies in accessibility domain taking help from eye-tracking technologies. Eye-tracking seemed to gain popularity starting from the late 1900s and shows promising contributions till today, both in Human-Computer Interaction and accessibility domains. In total, we found 55 literature that fit our area of interest focusing on a range of topics such as cognitive and visual processing, sign language, lip-reading, word processing of textual content and design recommendations. Though the majority of papers focus only on the DHH individuals, there are 4 papers that focus on cochlear implant users as well as 22 papers that compare deaf and hearing individuals' and their differences in attention management strategies.

3.2 Research Themes and Categorization

We identified several emerging themes and sub themes in the literature through our coding process (Figure 2). The primary categorization consisted of two main themes. First, the *Communication Mode*, where the literature focused on the communication method of DHH individuals, and the next main theme was *Context*, where the literature covered several contexts, situations or research focuses. We chose to separate our database in these classifications and show how these techniques were connected to one another

Table 1: Articles in each category

Main Category	Sub Category	Number of Papers	Articles
1. Visual Communication (32)	a. Sign Language	14	[2, 27, 36, 37, 50, 87–89, 112–115, 120, 122]
	b. Facial expression	4	[61, 70, 84, 119]
	c. Animation	3	[51, 57, 58]
	d. Lip reading	11	[23–26, 34, 80, 102, 117, 118, 123, 124]
2. Text based (11)	a. Captions/Subtitles	11	[22, 30, 42, 62–64, 68, 72, 86, 98, 109]
3. Context (12)	a. Classroom	4	[66, 67, 79, 96]
	b. Prototype	3	[47, 77, 92]
	c. Attention Management	5	[48, 55, 91, 105, 127]

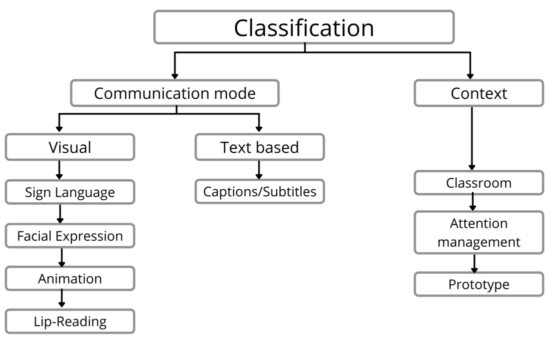

Figure 2: Classification of the literature

and how eye-gaze has helped us understand vital information in these domains.

In each individual category, we list down several other sub-categories of interest. In the *Communication Mode*, the literature primarily focused on different communication modes used by DHH users such as sign language, lip-reading, etc. Here, we identified two main sub categories: *Visual Communication and Text-based communication*

Visual Communication primarily looks at how spoken/translated communication or direct communication is observed and understood visually such as in sign language: Sign Language- Consisting of hand gestures, finger-spelling, hand movement and body movement; Facial expression- Understanding the importance of face in sign language and it's significance in emotions detection; Animation of sign language- Animated characters mimicking production of sign language as an actual human; Lip-reading- Focusing on how the face and facial features such eyes, mouth and nose play important part in signing and lip-reading.

Text-based Communication primarily explored how spoken or direct communication was observed and understood by reading texts such as captions display on the television. Therefore, text-based communication research investigated: Captions and subtitles-Specifically, textual representation of lectures, speech or demonstrations.

These research have been explored under different scenarios and situations. Therefore, in the *Context* theme, the Context of Use explores the literature discussed in: Classroom- Studies that focus on enhancing education and making classroom learning accessible; Attention management- Focuses on the DHH individuals' strategies for better attention management; Prototype- Technology prototypes designed especially for DHH individuals

3.3 Eye Tracking Devices Used

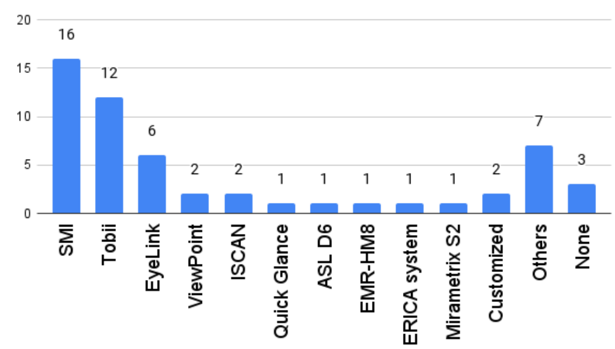

Figure 3: Eye-tracking devices and the number of studies they are used in (others - webcams, etc.)

Our analysis focused on the devices used in these studies to see which technologies were preferred specifically while examining communication behaviors. We came across different devices from various well-known companies, however, as shown in the Figure 3 some devices were used more than others. EyeLink by SR research[1], some models from Tobii Technologies[2] and several models from

[1] https://www.sr-research.com/
[2] https://www.tobii.com/

SensoMotoric Instruments[3] were utilized more in these studies of communication behaviors.

4 FINDINGS

4.1 Visual Communication

Studies that focus on understanding how DHH individuals perceive visuals, including sign language and lip-reading, fall under this category.

4.1.1 Sign Language: According to the World Health Organization (WHO) report, 5% of the population (466 million people) has auditory impairment, [4] making hearing impairment one of the most important accessibility related topics. DHH individuals use their visual senses often [10] as sign language, being a visual language, is one of the main modes of communication used by the DHH individuals. Sign language production is considered a highly complex task, as it involves a combination of major components like head movement, facial expressions, lip speech, hand and body movements, finger-spelling, and total body orientation [87, 89] and the DHH population heavily rely on their visual system to perceive what is being said. Hence, it becomes important to understand their gaze patterns and figure out if there are any unknown links between their gaze patterns and the sign language. Along with gaze and blink patterns, we are not only concerned with the signs a person would make using their hands but also consider their facial expressions, mouth movements, body language, and spatial movements. Therefore, the research found in this sign language category focuses on different sign languages, animation, language and grammar structure, etc.

Some studies have found that signed languages conform to the same grammatical constraints and have the same linguistic structures as that of spoken languages [75, 104]. Sign languages also use unique modality structures to express linguistic meaning. It is highly plausible that linguistic concepts in verbal language will be conveyed by some similar formation in sign language. Use of eye gaze to convey linguistic contrasts, including agreement marking, is a special feature of the sign language system formed by the visual modality [5, 32, 39]. To understand how sign languages and verbal languages are connected, one needs to understand the structure of sign languages. During our research, we were able to find how American Sign Language (ASL) conveyed some linguistic structures of the English language. Research says that there are over 500,000 American Sign Language (ASL) users in USA [51, 57, 58]. ASL intonations are performed with the aid of non-manual actions, along with recognizing the rhythmic phrases and applying stress to words and phrases [122]. The non-manual markers found in the investigation were gaze, eye blinks, head shakes, brow-raise, etc. These non-manual markers tend to split the linguistics into two sections, lower face (below nose region) and upper face (above nose region). The lower face, along with semantics and lexical information, seemed to provide adjectival and adverbial information. While the upper face and head/body provided details that are grammatical and prosodic. During the phrases and sentences, however, the non-manual markers can shift and lower face ones can merge with those of the upper face. Non-manual markers such as eye-blinks, change of gaze, head nods, change of signing locations, and change of body/head position can mark the phrasal boundaries. Nevertheless, the non-manual markers such as eye blinks and head shakes may also convey empathy or contradiction. Wilbur further reveals that eyebrows lead to declarative statements [122]. For yes/no or conditional questions, relative clauses, etc., the "up" position of eyebrows was used, and the "down" position was used for "wh"-questions [8, 31, 73].

The verb structure in ASL is divided into three parts: Plain, Spatial and Agreeing verbs [113]. The gaze patterns accompanying these verb types were decoded using eye-tracking. In spatial verbs, for example, the word PUT, can have a different location in space (PUT-up or PUT-down). Eye-gaze was found to be directed towards the locative arguments rather than the object of the transitive verbs or the topic of intransitive verbs as Neidle et. al. predicted [93]. While for the agreeing verbs, eye-gaze was directed towards the location of the object. The gaze patterns in agreeing verbs are seen to mark the person and the number of the subject first and then the object. Though both of the verbs types have similar gaze patterns, they can be distinguished by the gaze direction, it is directed lower in space for spatial verbs than for agreeing verbs. Moreover, gaze seemed to hold grammatical relation between subject and object whereas for spatial verbs it holds the semantic role of source and goal. Also, there are claims that non-manual markers such as head tilt and eye-gaze agreements mark the same spatial location as the manual agreement markers. In other words, gaze marked the subject and head-tilt marked the object. However, for plain verbs, the eye-gaze was rarely directed towards the object. This is explained by the fact that only the verbs which had manual agreement were marked by non-manual,i.e. gaze agreement.

Thompson et. al. show that pronominal references in ASL, just like verbs in ASL, are expressed through the use of location in space [113]. In a later study, Thompson et. al [115] use eye-tracking technology to confirm the previously stated claim that eye gaze does not help distinguish between second and third person. However, eye-tracking data analysis shows that locative pronouns are marked by gaze. Baker and Padden's [7] note that the signers' blinking behavior is distinct from that of English speakers, and hypothesize that ASL, being a visually interpreted and controlled language, fostered behavioral systematicity, in which both signers and addressees blink at constituent boundaries. They also note that there are general variations between similar syntactic structures and blinking patterns. They equate conditional statements with conditional questions in particular and note that signers blink between the conditional clause and the declaration but not between the conditional clause and the question. Wilbur shared an interesting study [122] where they investigate the relationship between periodic eye blinking done by fluent ASL signers and their effective linguistic generalization. Signer's eye blinks are sensitive to the syntactic structure from which intonational phrases are derived. These results help decide how intonational knowledge can be given in a signed language, which is usually conveyed by a pitch in spoken languages. However, these findings prove that sign language cannot completely mirror the spoken language [115].

[3] http://www.smivision.com/en.html
[4] https://www.who.int/news-room/fact-sheets/detail/deafness-and-hearing-loss#:~:text=Over%205%25%20of%20the%20world's,will%20have%20disabling%20hearing%20loss

One study focused on understanding the effect of hand orientation and perception on comprehension of sign language [36]. In this work, the authors found that identification of sign language was poor in low peripheral vision compared to near fovea and that participants were less accurate in identifying a sign from back view of the hand compared to front view of the hand. Another study [37] focused on understanding gaze patterns of beginner and native signers when perceiving sign language and found that both the groups perceive hand movement in peripheral vision, however, beginner signers focus on or near the mouth region to comprehend additional information from lip-reading while native signers focus on or near eye region to understand grammatical and referential information. Several studies have reported similar findings that the viewer fixate their eyes on the face, while they view hand movements, gestures and finger-spelling in their peripheral vision [57, 80, 87, 89, 107]. Following these insights, it becomes important to study how face plays an important role in sign languages.

4.1.2 Importance of face in sign language: Eye tracking research points out that DHH individuals mainly fixate their eyes on the face or upper body and perceive lower body and hand movements in their peripheral vision when viewing sign language [3, 87, 89, 107]. This indicates that face holds a significant role in sign language. Facial expressions help enhance a visual conversation by adding emotions to it. Facial expression processing is essential for an effective social interaction because for sighted individuals, facial perception is a vital ability for the identification and understanding of the emotional states of other individuals [119]. If the facial expression holds so much importance in general communication then sign language, being a visual language, would probably make excessive use of facial expressions to convey additional details.

Facial expressions not only help DHH individuals in linguistic cues but also help in emotional and social cues [70]. When perceiving sign languages deaf viewers must pay close attention to the face and facial expressions because of two reasons - first, when there is a lack of access of tone-of-speech information, the face conveys the bulk of useful social information, and secondly, sign language uses facial expressions to communicate verbal signals that are usually conveyed by the mouth in the spoken language [70]. Neidle [93] and Kacorri et. al. [57] claim that facial expression is an important part of ASL as they convey linguistic information during signing. Few studies takes help of eye-tracking to provide data that suggest that facial processing is different for deaf and hearing individuals. According to McCullough and Emmorey [83], American deaf individuals were able to detect different and subtle facial expressions and that native and experienced ASL signers were able to relate these facial expressions with the different grammatical structure [12, 65].

With the help of eye-tracking, researchers were able to find that Theory of Mind (TOM), the ability of predicting and interpreting other's behaviour, is affected by access of language and conversational methods [84]. Though visual and auditory cues are important to decode a person's emotional state, studies suggest that deaf individuals can successfully figure out emotions even with a lack of auditory input [56, 70, 106]. This indicates the adoption of strategies, known as enhancement hypothesis, where deaf individuals rely on visual signals as a guide for understanding the state of mind of another person and can more easily identify facial expressions than hearing persons [106]. To evaluate the hypothesis that facial expressions contribute to emotional and linguistic cues for the deaf participants, a study was conducted to examine how different sections of the face (such as whole face, or face isolated above and below the nose i.e. top and bottom halves) hold importance in emotional judgment and identification of individuals based on static facial images [70] for both deaf and hearing individuals. Data gained from eye-tracking shows that both groups used top halves for identification and bottom halves for emotion judgment and further results indicate that deaf participants' performance was dropped when there was no access to the mouth region. This provides insight into understanding that the mouth region of the face holds information regarding the emotional state.

With the help of eye-tracking, authors found that DHH participants focused more on the eyes while hearing participants focused more on the nose region when viewing static images of faces [119]. These findings point out the difference in social interactions between East Asians, where prolonged eye-contact is considered rude, and Western culture [4, 13]. Another study evaluated the gaze patterns and emotion detection of DHH individuals while viewing dynamic emotions [61] and found that deaf individuals were quicker in recognition of emotions when compared to hearing individuals. The findings discuss that deaf individuals might have a high motion detection [105] in the peripheral region and also found that deaf participants were fixated less often on the mouth region as compared to the hearing participants, suggesting that fixation on the eyes would allow deaf participants to detect changes in the mouth region from peripheral vision. This further suggests that deaf individuals have a wider peripheral span, a claim made by Stevens and Neville [108].

4.1.3 Animations of Sign Language: It is not uncommon to have hearing and DHH individuals co-enroll in the same classes and interpreters play an important role to help this co-enrollment happen. However, there are some limitations like the interpreter's knowledge and translation skills [120], difference in the number of interpreters needed and the number of interpreters available. Even if these issues are resolved, other issues might arise related to the field an interpreter belongs to or have expertise in. For example, an interpreter who is efficient in signing technical terms of biology might fall short when it comes to signing terms from engineering or astronomy. Hence, recent research has started to focus on producing animated interpreters. Thus, if animations for hand gestures and facial expressions are well developed, it would enable the use of these animated interpreters for any field that requires sign language interpretation. Therefore, one would not need to depend on physical sign language interpreters. Virtual animated interpreters could also be useful in static contexts such as classroom lectures, keynotes, or even in mobile contexts such as conversations with another individual while walking. The recent increase in the use of Virtual and Augmented reality applications and technologies could benefit from animated interpreters too.

Huenerfauth et al. show that DHH participants had better sign perception when viewing animation with facial expressions [51]. They showed that both the American Sign Language (ASL) and Pidgin Sign English (PSE) have enhanced accessibility benefits for deaf illiterate participants when animation included facial expressions as compared to animation without facial expressions. Kacorri et al. further explore eye-tracking technology to evaluate the importance of facial expressions in animated sign language [58]. One of the research quantifies how native signers' eye gaze differs when viewing human ASL signer videos or synthesized ASL animations (with differing quality levels) [57]. Participants shift their eyes less often between the face and the body/hands when they view human signer videos compared to when they view animations. There was a strong connection between the subjective scores (grammatical, understandable and natural) awarded to the animation by the native signers and the time they spent looking at the face of the virtual human character. This would be the first reported result suggesting a relationship between eye-tracker metrics and the subjective judgments of sign language animation efficiency of the participants.These papers also show how eye-tracking analysis is appropriate for usage in a user-study to test sign language animations as a complementary measuring tool [51, 58, 85].

4.1.4 Lip-reading: Jeffers and Barley [54] describe speech-reading/lip-reading as *"the art of understanding a speaker's thoughts by watching the movements of his mouth and his facial expression"*. Research suggests that lip-reading alone can provide information for speech perception. Lip-reading has been an important role to gain access to spoken language by children who were born deaf [124]. As discussed earlier, DHH individuals have heightened visual sense, hence lip-reading is an important form of communication.

Several studies have shown that DHH individuals tend to keep their focus on the eyes and view mouth movements in their peripheral vision to consume data from lip-reading, while others focus primarily on the mouth to read lips [61, 80]. Studies suggest that to gain information about lip-reading, one must understand and know the language in use. The study by Sandgren et. al [118] uses an eye-tracking technique to understand the different strategies adopted by the DHH and hearing individuals when they encounter familiar or unfamiliar languages. In this study, eye-tracking based results found that the task, subject, and language play an important role in lip-reading. Findings point out that the deaf individuals focused on the mouth region irrespective of the language used while hearing individuals focused for a long time on the speaker's mouth when the language was unfamiliar and a shorter time on the eyes when the language was familiar. Chinese adults with natural hearing appear to pay more attention to the speaker's eyes, whereas deaf adults with audiovisual voice processing obtain verbal signals from the speaker's lips [118]. Another study highlights the fact that when it comes to comprehension, accuracy and time for both the deaf and the hearing groups have same results, indicating that the skill of visual-speech can be obtained by anyone who understands where to focus their attention [124]. Mastrantuono et al. take a different approach to understand the importance of visual speech and compare its use with spoken language and sign language [80]. They found that deaf participants were able to comprehend information equally well as compared to the hearing participants. The eye-gaze patterns also indicate that deaf participants focus on the lower face region most of the time, using mouth movement when processing sign language and lip-reading for sign supported speech.

4.1.5 Summary for visual communication. From the above data, we understand that the hearing individuals focus more on the lips when the language is unfamiliar and focus more on the eyes when the language is familiar [118]. While the DHH individuals focus more on the eyes when conversing using sign language and focus on lip-reading when conversing with non-signing individuals [61, 80]. When using sign language, DHH individuals tend to keep their focus on the eyes of the speaker, thus maintaining foveal vision [3, 87, 89, 107]. This strategy allows them to follow the speakers eye-gaze to predict object/subject location, emphasis on particular signs, turn-taking etc. It also enables them to view facial expressions and lip-reading in their parafoveal vision, where the bottom half of the face is used for lip-reading and speech recognition and the top half is used for understanding emotions. In terms of the language structure, lower-face non-manual markers are used to identify adjectival and adverbial information along with semantic and lexical information, while the upper-face non-manual markers provide grammatical, intonation, tune and rhythmic structures.

4.1.6 Future Directions. Video Coding: As we move more towards a virtually connected world, our focus should be on making technologies for remote working, virtual learning or digital communications accessible for the DHH individuals. As sign language plays an important role in communication and requires a lot of cognitive processing, some researchers are considering compressing the sign language videos using computing knowledge, which is called Video Coding [2, 27, 87, 89]. Eye-tracking has played an important role in understanding the structure of sign languages and also to understand the gaze patterns of DHH individuals when perceiving sign language, which in turn has helped us to perform video coding on the sign language videos. Using the information that the deaf individuals fixate on the face region (central vision), high acuity can be given to face and facial expressions, making them a higher priority in both temporal and spatial fidelity when video coding sign language. As deaf individuals access manual signs in lower acuity of peripheral vision, high temporal fidelity can be considered for hand and body movements, while spatial fidelity can be compromised. As the viewers do not fixate on the background objects, the background can be rendered in low spatial and temporal resolution without compromising on important and efficient data. As a future research direction, we can use these findings to reduce the storage of lectures or video recordings of meetings, specifically for the DHH individuals.

Interface design: The two main drawbacks of current video communication for sign language are screen-sizes and poor internet connections which can cause video distortions [27]. Since we are moving towards remote working/learning, interfaces can be designed to support the DHH individuals' ease of use and accessibility. In the current softwares used for remote working/learning, we can consider including the elements that support DHH accessibility such as interpreter's and speaker's window resizing, presentation screen size, captions and text display. We can also utilize color psychology and information architecture to enhance the experience for the DHH individuals.

4.2 Text

Comprehension of the written language is accomplished by understanding the basic theory that intrinsically words are relations between graphemes (a written symbol), phonemes (sound), and meaning [100]. The research into this area highlights two main factors - First, the learning process has been centered on the hearing population and hence it has focused mainly on the phonological codes. Secondly, the art of reading highly depends on the theory of understanding the sound structure (phonemes) of the language and deriving orthographies (graphemes) and meanings. Hearing individuals have access to auditory information, hence when learning to read, it is easier for them to make connections between the sounds (phonemes) and letters (graphemes) [35, 41, 44]. On the other hand, deaf individuals lack the auditory knowledge about the language they are reading, unlike their hearing peers. Moreover, at an initial stage, they lack sufficient knowledge about the language itself (vocabulary, syntax, grammar, etc.) [43], hence, it would be important to understand how deaf individuals' reading strategies differ from those of the hearing individuals. In a recent article, Blythe states that *"to fully understand how children progress to skilled adult reading, it is necessary to consider changes in both cognitive processing and eye movement behavior"* [15]. Hence, for a greater understanding of how young deaf children learn to read, the eye-movement study is essential in understanding professional literacy in the deaf community. There have been few studies that have focused on measuring the reading level of deaf population [17–19, 29, 38, 49]. Research shows that the reading level of young deaf adults has been considerably lower than their hearing peers for decades with recent researches indicating that only 5% of deaf individuals become excellent readers [59]. The main reason behind the illiteracy levels of deaf readers is very little or no access to the sound structure i.e. phonology of any given language. However, a meta-analysis done by Mayberry points that in the deaf community, reading competency depends on less (as little as 11%) on phonological decoding compared to the overall competency of spoken or sign language (35%) [81]. Chamberlain and Mayberry provide evidence in support of a strong association between sign language abilities and literacy skills [29].

The general reading span recorded is 7-9 letter spaces with fixation of about 200-250ms and brief saccades of (20-40ms) [20]. It is reported that saccades travel ahead in direction of reading (left to right for English), skipping up to 30% of the words, however, 10-15% of saccades regress to previously read the text to figure out the context [20]. The visual area, known as the Perceptual span, is responsible to provide useful information and to guide our eye fixation during reading [71]. Perceptual span of alphabet readers is a 3-4 letter space on the left and 14-15 letter space on right of the fixation [82, 99]. In their research, Bélanger and Rayner [20], provide important insight into how severe to profoundly deaf adult readers have a bigger perceptual span than hearing readers at the same reading level. They found that skilled deaf readers have a bigger perceptual span as compared to the skilled hearing readers (fixation of up to 18 letter spaces on the right of the fixation for the deaf readers and up to 14 letter spaces on the right of the fixation for the hearing readers). They also found that the less-skilled deaf readers have the same perceptual span as the skilled hearing readers. These findings support the claim that overall deaf readers have a bigger perceptual span as compared to the perceptual span of the hearing readers.

With the help of eye-tracking, researchers were able to support the claim mentioned earlier that deafness influences eye movement and gaze patterns [61]. Researchers found that the skilled deaf readers skipped more words while reading, re-fixated on fewer words, and regressed (reread) less often as compared to skilled hearing readers. These findings were true for young deaf readers (age 8 to 12 years) too as compared to the young hearing readers [49, 126]. According to the researchers, these results might be because the deaf participants do not need to go through the phonological representation of words [20]. They also interpret that, to compensate for lack of phonological code and weak/no orthographic-phonology sense, deaf readers might have strong orthographic-semantic sense and strong visual-orthographic knowledge of words in both fixation and parafovea. However, less-skilled deaf readers had longer fixation compared to skilled hearing and skilled deaf readers suggesting that they might have weak orthographic-semantic knowledge. Researchers propose a hypothesis called the "Word Processing Efficiency" and state that deaf readers (skilled or less-skilled) process words more efficiently in a single fixation than their hearing counterparts. As these findings were true for young readers, the hypothesis that deaf readers have strong orthographic-semantic connections might help us make changes in the early education system which would lead to early development for deaf readers. We encountered many other researches that focused on understanding gaze patterns of DHH readers [1, 14, 17, 19–21, 46, 76, 97, 110, 111, 116, 125], however, we did not include them in our database as our paper is mainly concerned with the communication modes.

4.2.1 Captions and subtitles: Technologies such as captioning and subtitles provide additional input, enabling the DHH individuals to capture more information, however, it adds more to their visual and cognitive load [64]. Although, captions and subtitles serve as additional information, they also compete for focus with visual content, influencing individuals' gaze patterns [62, 64]. DHH individuals' have been observed to fixate their gaze for longer or make gaze shifts which in-turn distract the individual's focus from the visual content or the interpreters [79]. Moreover, the speed, location and design of these captions and subtitles highly influence the readability of the content. If these supportive technologies are not carefully considered then they might cause hindrances to the DHH individuals' attention rather than supporting it.

Placement, line-break and even color-coding of additional data should be optimized for better use of these technologies [42]. Subtitles specially for DHH individuals considers font, font-size, on-screen placement, and color contrast between text and the background. Subtitles for Deaf and Hard-of-Hearing (SDH) also focuses on providing information that includes emotions, sound effects and non-speech elements. Research on SDH indicates that better comprehension is achieved by editing or summarising the content rather than verbatim subtitles [94, 95, 101]. Data from eye-tracking studies suggests that edited subtitles are easier to process but verbatim subtitles are read faster than the edited ones [109]. A study shows how different visuals indicating Automatic Speech Recognition

(ASR) caption designs affect gaze patterns and accuracy in context processing [98]. They discuss that the current captions alone do not solve the accessibility limitations due to hearing impairment and hence focus on improving the usability and accessibility of captions. Another research analyzes that the participants had to split their attention between different information to interpret the context and in the process risk losing important data [11, 68, 69]. Authors pointed out that the loss of information along with the time and efforts spent in splitting their attention might affect their performance, and hence, might cause an overall affect on their career growth. These researches also contribute to solving various problems faced by the DHH individuals. There are several researches proving that DHH individuals spend more time looking at the visual content than the textual content [22, 98].

4.2.2 Summary of Text based communication. Textual reading has been centered around phonological codes, making it inaccessible in case of auditory deprivation. To compensate for the lack of phonological code and weak or sometimes even no orthographic-phonological sense, deaf readers tend to have strong orthographic-semantic sense and better visual-orthographic knowledge of words [20]. Captions can be helpful as an additional input to understand the context of the language, particularly in cases when the DHH individuals miss some part of the content or if there is a flaw in the interpretation. However, as the DHH individuals monitor changes in the captions from their peripheral vision, they have to make frequent decisions on when to switch gaze from the caption to the main scene. The effort and the time invested in this decision making can be a cause of distraction for the DHH individuals.

4.3 Context

4.3.1 Classroom: In a classroom environment, there are a lot of visual data to focus on such as the lecturer, slides, and demonstrations. In addition to these, the DHH individuals have to take further support from other visual sources such as the interpreters or captioning. Therefore, eye-tracking research has focused on different strategies adopted by the DHH individuals in classrooms to diversify their visual attention and help them focus on multiple visual data at a given point [66–68, 79, 96].

Researches shows that it is difficult for Deaf individuals to manage their focus on multiple inputs [11, 68, 79]. To overcome these difficulties, deaf students are found to focus their attention on the interpreter or the slides and use their peripheral vision to monitor any changes in other inputs such as captions/ subtitles, lecturer or student discussions. Though, this strategy helps deaf individuals absorb as much data as they can, more time is spent on decision making rather than actually paying attention on the important information. In one research [67], Khushalnagar et al. compared the gaze pattern of hearing and deaf individuals and found that hearing students were able to focus more on instructors and slides compared to deaf individuals. They found that hearing students focused 74% of their attention on/around the instructor and 19% on slides whereas DHH students focused only 10% on/around the instructor, 14% on slides and they mostly focused on the interpreter. One of the reason emerges to be that deaf individuals spend a lot of time searching for the topic of concern. Many researches aimed to provide visual cues, sometimes called reference cues, to the DHH students in order to guide their visual attention effectively [66, 67, 96]. The reference cues were obtained through analysis of the point-of-focus from the eye-tracking data for the hearing and DHH individuals. These cues would help DHH students to directly focus on the slides or the lecture that is currently being discussed, rather than focusing on the interpreter first to know where to look at. This resulted in improvement of their gaze fixation on slides from 14% to 16%. Khushalnagar et al. in another research transcribe a classroom lecture in three different types of captions [68]. Here, data analysis generated from eye-tracking shows how real-time captioning for a classroom lecture is preferred more than the Automatic Speech Recognition (ASR) by both hearing and DHH individuals [68]. Similarly, in ClassInFocus, students get notifications about the changes happening in a classroom environment such as a slide or a speaker, helping them utilize their visual attention in a better manner [28]. Additionally, other research has focused on tracking a user's eye gaze to recognize their visual attention and to place the captions according to their gaze [30].

4.3.2 Attention management: Watching television produces a lot of information in the form of pictorial and textual content, the interpreter and subtitle text and the anchor or commentator, especially for the news and sports broadcasts. To comprehend so much information at one time, deaf users would have developed strategies in order to manage their gaze and along with that they can manage their visual attention. Motivated by this idea, an eye-tracking research [120] focused on understanding viewing strategies of DHH and hearing individuals when watching sign language interpreted news broadcast. They found that the deaf people focus primarily on the interpreters and secondarily on pictorial information, however, very little focus was given to subtitles and lip-reading. Hearing individuals, on the other hand, focus primarily on the pictorial information but also focus significantly on subtitles, interpreters and lip-reading. Surprisingly, DHH individuals looked only 7% of the text available whereas hearing individuals looked around 18% of the text.

Websites consist of a lot of visual and textual content together and each of us have different strategies to search for different types of content. Studies show that, when viewing a website with equal amount of text and pictures, DHH people focus more on pictures while hearing individuals focus more on text. One of the researches [55] focuses on comparing strategies used by the deaf and hearing individuals while looking for information on the websites. As predicted, they found that both the groups used different strategies to access content on these websites and that while going through a website, deaf people looked more at the textual content than the pictorial content while hearing people focused more on the pictorial content than the textual content. They classified 7 different strategies and tested it on 3 different levels of websites. Another research focuses on understanding the preference of hearing and DHH individuals when it comes to pictorial data and its hyperlink [91]. They found that both groups preferred labelled pictures.

4.3.3 Prototypes: We came across several papers that focus on prototyping new systems for the DHH individuals which included designs of mobile applications, websites, or entirely new systems.

Khushalnagar et. al. suggest one such system where they focus on a niche population of DHH engineering professionals and students to recognize that attention splitting causes more harm to the growth of the DHH participants than previously expected and provide a potential solution to solve this problem [11]. They created a prototype system which tracks a presenter and displays captions around them, minimizing the attention split and loss of information while making it easier for the DHH students to perceive and process maximum information with ease. The authors, in another research, focus on implementing the above-mentioned idea using real-time speech-to-text generated captions [69]. A system like this would not need a skilled captionist, a speech-to-text converting software would work just as well. Here too the authors focus on tracking the presenter and displaying the captions near them and they called this system Tracked Speech-to-text Display (TSD). Another research focused on designing a hearing aid using different input methods, called Attentive Hearing Aid (AHA), it analyses the input methods like pointing, button, or eye input [47] and amplifies the audio input based on the user's attention. The DHH individuals would look at a person they would want to hear from and the AHA would amplify their voice. According to the data analysis from the comparison of input methods, eye input was 73% faster than pointing methods and 58% faster than button selection, making it a better option to go along with hearing aid.

4.3.4 Future Directions. *Sports Broadcast:* Reference cues are helpful in guiding the DHH individuals' gaze to gain knowledge from the current context [66, 67, 96]. If we can extend the use of real-time eye-tracking technology, we can use reference cues in sports broadcasting. Sport broadcasts have multiple forms of information such as scores, advertisements, player information, the actual game and in case of DHH individuals, interpreters and captions as well. To reduce the cognitive load and help DHH individuals to gain information in an easier way, we can track the gaze of commentators in real-time and provide the reference cues as an input that guides the viewers on which player to focus on.

Virtual Learning: Our learning system is structured in a way which keeps the hearing individuals at the center [35, 41, 44, 79]. It is not uncommon to find that the DHH students get co-enrolled with their hearing peers and both get exposed to the same knowledge. However, the learning structure of our education system and criteria for success are highly favourable for the hearing individuals which could be the reason why DHH students seems to perform lesser than their hearing peers. As we move towards a remote learning setting, we should improve the technology so that our education system supports both the hearing as well as the DHH students. We can utilize the eye-tracking technology to provide reference cues based on the hearing individuals' gaze to help guide DHH individuals in online lectures. We can also perform real-time eye-tracking for the DHH students to video code the interpreters' stream in order to reduce data usage. As captions provide an important input for the DHH individuals, we can focus on improving these technologies to further help them. We can maintain a history of captions for the DHH individuals to refer in case of some information getting missed. Real-time eye-tracking can also help in making captions interactive. For example, if a DHH individual gazes on a particular caption then it can get highlighted which would help interpreters understand which parts need more clarification. Moreover, not all terminologies have a sign language translation, so maybe we can highlight the uncommonly used terms and mention their definition in order to help the DHH individuals understand the context better. However, this suggestion would require future research to understand the feasibility and design of such features.

5 DISCUSSION

This paper conducted literature review of 55 papers focusing on the understanding of gaze patterns of the DHH individuals and their connection with behavior patterns during different modes of communication. Throughout our research, we were able to see how DHH individuals have adapted different gaze strategies when compared to the gaze patterns of hearing individuals. In this section, we further summarize our findings.

DHH individuals focus on the face instead of the hand gestures or movements [119]. However, the region of focus varies between native DHH signers and beginner DHH signers. When looking at the signs and reading lips simultaneously, beginner signers focus on mouth region in order to gain more information from lip-reading and viewing signs in peripheral vision while native signers focus on eye region of the face providing feasibility to perceive hand gestures and lip-reading in peripheral vision [37, 57, 119] and in contrast, hearing individuals focus typically on the nose region [119]. The research also revealed that more information is gained with fewer efforts through multiple inputs such as the eyes, mouth, eye-brows, and overall facial expression [51, 57, 58, 122]. Other studies also suggest that DHH individuals have a wider perceptual span and show that they focus on the face, which helps them gain linguistic information and helps them to maintain the social norms while processing expansive signs, finger-spelling, and body movement in peripheral vision [57, 61]. These findings from previous eye-tracking studies can help us to strategically compress sign language videos saving storage and data processing [2, 27, 87, 89]. Eye-tracking research has also been used to investigate the video coding improvements that can be made for videos by observing the important regions that a viewer focuses on. Thus, the importance of face and facial expression in sign languages lead us to conclude that during video coding, the facial region requires the highest resolution in terms of temporal and spatial aspects, while the rest of the body can be compressed to give better temporal fidelity [2, 27, 87, 88].

Animation of sign language is another communication method adopted in different contexts. Adding facial expressions to the animation also provides a better understanding and enhances the accessibility benefits of the animation [51, 57, 58]. Moreover, if the animation is considered to be bilinguistic, where sign language and spoken language are used, they are more likely to be scored higher on naturalness and are capable to dissipate more information.

Deaf individuals tend to exhibit different viewing patterns in different scenarios. During a sign language conversation, maintaining eye contact with the signer indicates that the signer has the audience's attention while breaking the eye contact indicates a shift in turn-taking [6, 119]. Eye-gaze also indicates who would be the take the next turn to sign. Signer looks at their own hand gestures in order to emphasize on a particular sign and would look to a particular position to indicate location of the object/person in context [122]. During speech, the mouth region is an important source for information comprehension from spoken language [61, 120]. The findings from several studies suggest that the information comprehended by DHH individuals is as accurate as their hearing peers, suggesting that DHH individuals have formed various strategies to eliminate the barriers of auditory impairment [61, 106].

In classroom environments, DHH students were observed to primarily focus on the interpreter, and secondarily on text content provided in slides, and demonstrations if available. This could typically lead to reduced attention towards the instructor or other visual information. Most of the time, the DHH individuals first looks at the interpreter to understand the topic of focus while monitoring the slides and instructor in peripheral vision. This, though allows them to monitor maximum aspects at one time, adds up to the cognition load of making decision to shift their gaze and attention to changes happening in their peripheral vision. We can use the findings [66, 67, 96] to help guide the attention of DHH individuals to focus on and gain the same information as to their hearing peers.

Sign language and spoken-language were observed to have the same processed neurological effects [40]. However, it is important to identify the limitations of deaf individuals' lack of phonological awareness for a given language. This notion makes it difficult for them to understand the relation of a word (orthography) to its sound (phonology) [21]. To overcome this lack of orthography-to-phonology connection, research has shown that deaf individuals built orthography-to-semantic connection [20, 116]. This suggests the unique adaptation embraced by them to overcome auditory impairment. The difference between a skilled and a less-skilled deaf reader is also observed, however, the fact that overall deaf individuals have better perceptual span with fixation up to 18 letters compared to hearing individuals with up to 14 letters is concluded [20].

Eye-tracking has proved to be a helpful research methodology to gain insights into human behaviour, hence, helped Human-Computer Interaction (HCI) community to developed technologies accordingly. These findings help us understand that there is a need for new technologies as a substitute for lack of auditory input spoken language. However, current researchers that focus on improving different factors like video coding, animation, captions, and subtitles would contribute in improving the experience of DHH individuals in the future.

6 CONCLUSION

The findings from a database of over 55 literature studies have helped us to understand how gaze patterns of DHH individuals can help us gain insights into their behavior and strategies adopted by them to comprehend information from different communication methods. We were able to analyze the findings from this literature and answer some of the targeted questions. Moreover, these findings helped us gain insight into issues that DHH individuals face and their attempts to tackle these issues. We have also presented some design recommendations based on the findings of the literature review.

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