Remotely Co-Designing Features for Communication Applications using Automatic Captioning with Deaf and Hearing Pairs

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ABSTRACT

Deaf and Hard-of-Hearing (DHH) users face accessibility challenges during in-person and remote meetings. While emerging use of applications incorporating automatic speech recognition (ASR) is promising, more user-interface and user-experience research is needed. While co-design methods could elucidate designs for such applications, COVID-19 has interrupted in-person research. This study describes a novel methodology for conducting online co-design workshops with 18 DHH and hearing participant pairs to investigate ASR-supported mobile and videoconferencing technologies along two design dimensions: Correcting errors in ASR output and implementing notification systems for influencing speaker behaviors. Our methodological findings include an analysis of communication modalities and strategies participants used, use of an online collaborative whiteboarding tool, and how participants reconciled differences in ideas. Finally, we present guidelines for researchers interested in online DHH co-design methodologies, enabling greater geographically diversity among study participants even beyond the current pandemic.

CCS CONCEPTS

• **Human-centered computing → Empirical studies in accessibility**; **Accessibility design and evaluation methods**.

KEYWORDS

Deaf and Hard-of-Hearing, Accessibility, Participatory Design, Automatic Speech Recognition, Videoconferencing

CHI '22, April 29-May 5, 2022, New Orleans, LA, USA

ACM ISBN 978-1-4503-9157-3/22/04…$15.00
https://doi.org/10.1145/3491102.3501843

ACM Reference Format:
Matthew Seita, Sooyeon Lee, Sarah Andrew, Kristen Shinohara, and Matt Huenerfauth. 2022. Remotely Co-Designing Features for Communication Applications using Automatic Captioning with Deaf and Hearing Pairs. In *CHI Conference on Human Factors in Computing Systems (CHI '22), April 29-May 5, 2022, New Orleans, LA, USA.* ACM, New York, NY, USA, 13 pages. https://doi.org/10.1145/3491102.3501843

1 INTRODUCTION

Research on the 20% of adults in the United States who are Deaf or Hard of Hearing (DHH) [9] has revealed how hearing ability correlates with employment success, e.g. DHH people have 34% lower wages and a rate of employment two-thirds that of hearing peers with comparable education [12, 50]. Prior research has identified a critical factor behind these inequities: DHH individuals often have difficulty communicating with hearing peers in the workplace [23], yet successful communication in small-group meetings is critical for the success of DHH employees [1, 31].

Professional American Sign Language (ASL) interpreters or real-time captionists, while ideal for communication, must be scheduled in advance, and are rarely available for impromptu workplace meetings. DHH individuals are not satisfied with alternative strategies for communication with hearing colleagues in small group settings, e.g., writing on pen or paper and gesturing, leading many DHH people to skip workplace meetings altogether [15].

Applications using automatic speech recognition (ASR) may benefit DHH individuals who find themselves in impromptu settings without access to an interpreter. These ASR-supported mobile applications, such as Live Transcribe [47], transcribe spoken words into text on a user's personal mobile device. Furthermore, due to the COVID-19 pandemic, many workplace meetings have become remote, using videoconferencing apps, e.g. Zoom [54], which further limits communication strategies like pen-and-paper and constrains gesturing. While many videoconferencing applications have integrated captioning into their interfaces, and while many DHH individuals have interest in mobile apps using ASR, both caption accuracy limitations and the lack of accessibility research on the user-interface/user-experience (UI/UX) design of these apps are challenges [16].

The pandemic has also disrupted in-person HCI research among DHH users, as mask-wearing interferes with both speechreading and sign language, for which mouth and face movements are important linguistically. Co-design methods that bring together DHH and hearing individuals would be invaluable for addressing the lack of HCI research on designs for both ASR-supported mobile applications and ASR-supported videoconferencing; however, no prior work has explored such methods in an online modality. Bringing together both perspectives may more appropriately address DHH users' needs, leading to designs that account for accuracy limitations in transcriptions. To address this gap, we conducted 18 two-hour co-design workshop sessions over Zoom with DHH-hearing pairs to investigate the efficacy of remote mixed-ability design activities to create accessible designs for ASR-supported communication technologies. Half of our 18 sessions focused on ideating for ASR-supported mobile applications to be used in-person (post-COVID), and the other half focused on ASR-supported videoconferencing applications to be used in remote settings. In our online workshops, we focused primarily on two dimensions: First, how errors in ASR-caption output should be fixed, and second, how to implement a notification system to influence hearing speakers' behaviors, notifying them to, e.g., speak more slowly or speak more loudly.

Our primary contribution is methodological: We describe entirely virtual co-design sessions with both DHH and hearing participants in which participants collaborate and create sketches of prototype designs. We provide evidence of its efficacy through qualitative analysis of our video recordings of these workshops and the feedback obtained from workshop participants. We additionally provide guidelines with recommendations for future researchers interested this methodology. **As a secondary, empirical contribution**, we employ our virtual co-design method to investigate the design space of features for ASR-supported communication applications. We present some design prototypes that we obtained for both ASR-supported videoconferencing applications and ASR-supported mobile applications.

2 RELATED WORK

2.1 Co-Designing For Users with Disabilities

Co-designing is a process where all stakeholders are actively and equitably involved in the design process so that the end result is satisfactory. Since its early adoption in HCI [19, 40], it has become well-established across accessibility, e.g. [25]. Co-designing is especially common when designing for people who are blind or low-vision (BLV) [4, 13, 28, 52], with learning or cognitive disabilities [10], or with movement disabilities [48]. Researchers have also studied how to make design workshops themselves accessible for people with disabilities [11, 30, 37, 45].

In-person co-design research within the DHH community is active and ongoing, e.g. [35, 38]. For example, researchers have used possibility-driven co-design methods to develop new hearing-aid designs [14] or augmented reality books [53]. Co-design has also been used to develop CollabAll, a system designed to allow DHH individuals to participate more easily in conversations with hearing peers [34]. Wang and Piper conducted a co-design study where they analyzed strategies for communication and interactions between in-person DHH and hearing dyads [51].

COVID-19 has motivated us to identify new online methodological options, and beyond the pandemic, remote co-design workshops may address challenges in scheduling multiple participants, as they may be less likely to miss appointments if they don't have to be physically on-site. Further, in some geographic locations, it can be difficult to recruit enough DHH participants; an online study supports inclusion of greater numbers and more diverse participants.

There have been a few prior co-design studies with DHH participants in a remote context, e.g., researchers utilized co-design to implement an ASL-accessible health survey [5] in which users provide input through an online survey-like apparatus. Such remote co-design studies involving the DHH community are typically more limited in the scope of participant involvement, e.g. answering survey questions rather than actively collaborating and designing [5, 49]. More research is needed to examine how to best support collaborative design tasks, as it is unknown whether participants can efficiently collaborate and prototype remotely, given language barriers between DHH and hearing users and challenges DHH users face in working visually on a screen, e.g. in a drawing task, while communicating. Participants may not engage in discussion, negotiation, or design activities as readily in this virtual setting.

2.2 ASR-based Communication Technologies

Recent apps provide ASR-based captioning [2, 32], but research with DHH users has revealed that current systems do not yet provide sufficient accuracy [36] nor efficiency for conversation participation [26]. Compared to the rapid growth in such apps, how design factors affect usability has been relatively under-explored in HCI.

Prior research has investigated personal perspectives among DHH users on ASR applications. For instance, two studies [18, 22] found that DHH users are interested in ASR but frustrated by current designs and by inaccuracies in ASR output from the speaker talking in a way that was hard to understand, e.g. too quickly. Seita et al. had participants subjectively rate which behaviors they preferred to see from hearing speakers in both mobile ASR and videoconferencing contexts [43, 44], revealing significant differences in their preferences for specific levels of speech rate, voice intensity, enunciation, intonation dynamics, and eye contact [43].

Beyond understanding users' preferences and concerns, relatively little prior work has evaluated design options for ASR captioning among DHH users. Berke et al. [7] compared prototypes for how captions could visually indicate words that the ASR was not confident had been correctly transcribed during one-on-one meetings, e.g. by underlining. Participants expressed preferences among the options presented but were concerned that the visual indications would be distracting. While the prototypes in that work had been designed by the researchers, co-design approaches with DHH participants may have yielded other design options. Other researchers investigated augmented reality to display real-time captioning as speech bubbles [33]; however, the modality used, a HoloLens, can be cumbersome and is not widely available. We investigate designs for more ubiquitous mobile and computer platforms.

A recent study by McDonnell et al. conducted interviews and design activities with 15 DHH participants and discovered that DHH experiences with ASR-supported small group discussions are shaped by social, technical, and environmental factors [27]. In section 6.2.2, we discuss how these factors may have shaped how participants in our study designed their prototypes. McDonnell et al. additionally provided insight into users' initial preferences for ideas and potential design options for future ASR technologies, e.g., those for error corrections, displaying volume levels, and other features, and in this paper we investigate this further by obtaining concrete, co-designed prototypes for some of these capabilities.

Prior research in ASR-supported videoconferencing has not focused much on design benefiting DHH users. Motivated by work in ASR-captioning [7, 43, 44], we explore two design dimensions:

- **How errors in ASR output should be indicated and how to correct them:** Prior work has revealed DHH participants are frustrated when there are errors in output [22], and are interested in error correction features for ASR technologies [27]; so, the first design dimension we selected to explore in our study involves ways for the hearing user to identify and fix any mistakes.
- **Notification system for influencing speaking behavior:** Prior work [22, 43, 44] revealed that DHH users are frustrated when hearing conversational partners exhibit certain behaviors when speaking, e.g. too quietly or quickly, so our second design dimension involves notifying hearing speakers to change their behavior.

Prior work has investigated how to evaluate ASR output: Kafle et al. tested a novel method for evaluating caption quality that outperformed the standard word error rate metric [21], and Berke et al. [8] compared the efficacy of various probes for measuring DHH participants' perception of caption quality. Such measurements of caption quality would be useful when implementing real-world prototypes of error correction to indicate words that should be fixed.

Gugenheimer et al. advocated for assistive technology to shift some conversational burden from the DHH person to their hearing partner [20]. In this study, we make this a priority: Our two design dimensions both focus on shifting some of the responsibility to the hearing person: only the hearing person will be notified to change their behaviors and they will also be responsible for catching and correcting errors in ASR output.

Although ASR-based technologies are intended to support communication between DHH and hearing users, prior research has not investigated the experience of hearing participants in this context—despite how both DHH and hearing people are users of the system. A study by Seita et al. [42] highlights this need by revealing that the presence of ASR caption markup styles caused hearing participants to speak differently. Though DHH users are justifiably the primary focus of research in this area, the result of that study reveals why it is important, for DHH users, that the hearing perspective is also considered in design: They found that exposing a hearing person to various designs caused them, in some cases, to exhibit variations in speech patterns that were *harmful*. Prior work on mixed-ability focus groups has shown that they result in different ideas and insights than groups that include only hearing participants [3]; so, there is a clear benefit in gaining both perspectives. In fact, prior work has revealed such benefits, e.g., work on ASR-supported tabletop technology to facilitate communication between medical personnel and DHH patients [35] or investigation of social-networking apps with DHH and hearing users [39].

3 RESEARCH QUESTIONS AND METHODS OVERVIEW

Section 2.1 revealed that this study would be the first to combine three elements: (a) using participatory design to ideate new solutions for designing ASR-supported communication applications, (b) with DHH and hearing pairs actively collaborating, negotiating, and prototyping, and (c) the process occurring entirely virtually. Given potential communication or visual-attention barriers for DHH users while drawing and communicating with a hearing partner, it was unclear whether discussion or design activities would be successful. Thus, our **primary methodological research question** is:

RQ1: How well can pairs of DHH and hearing individuals participate in an entirely virtual co-design workshop session in which participants collaborate and create sketches of prototype designs?

The prior work in Section 2.2 guided our selection of design dimensions to investigate during our co-design sessions. Specifically, we investigated design solutions to address challenges faced by DHH users when they use ASR-supported communication applications in conversations and to evaluate design options from the perspective of both DHH and hearing participants, rather than conceived of by researchers. This leads us to our **secondary empirical research question** concerning the exploration of the design space of features for ASR-supported conversations:

RQ2: What exploratory design solutions emerge from pairs of DHH and hearing individuals remotely co-designing features for an ASR-supported communication application, along two design dimensions—firstly, how errors in ASR output should be indicated and fixed, and secondly, how the system should notify users to influence speaking behavior?

Prior work on ASR-supported communication applications had focused on mobile phones or tablets, but due to COVID-19, which moved many face-to-face interactions online, we decided that half (9) of our participant groups would co-design within the space of ASR-supported mobile applications, and the other 9 would co-design within the space of ASR-supported videoconferencing on computers. The data for all 18 are discussed throughout the paper.

To address RQ1, we performed qualitative analysis of our video recordings of these workshops. After conducting these workshops with 18 pairs of DHH and hearing participants, to address RQ2, we considered the design options suggested by participants as well as drawings produced during the sessions, which revealed several design options along each of the two dimensions investigated.

3.1 Participant Information

We recruited 18 hearing participants from the official RIT Facebook page, and we recruited 18 DHH participants from social-media posts on the "NTID Community" and "RIT Cross-Registered Community" Facebook pages. The former consists of individuals that are part of the National Technical Institute for the Deaf (NTID), and the latter consists of DHH students who are enrolled at the Rochester Institute of Technology (RIT) and benefit from NTID-supported services, e.g., captioning or ASL interpreting. Information for the study was also shared by word-of-mouth. Participants were required to have a computer capable of running the Zoom application, as a mobile phone or tablet would not be sufficient, due to our use of both Zoom and online whiteboarding activities.

ASR-Supported technologies for small group meetings between DHH and hearing users:

Error Correction Capabilities: Imagine the ASR technology is inaccurate in transcribing some words.

- How would you visually indicate this to participants?
- How will participants be able to correct any errors in ASR output? Clearly detail how this would happen; what do users have to do?
- How would any indications that errors were corrected appear visually on the screen of the device?

Notification Systems for Influencing Speaker Behaviors: Imagine in conversation that hearing speakers are speaking in a way that is difficult for the technology to understand and transcribe accurately.

- How would you implement a system to notify the user to speak slowly, more loudly, or more clearly, etc.?
- Would the notification be only visual or would it incorporate other modalities?
- In your prototype, clearly explain how the notification would work, how it would look like, and any other details.

Figure 1: The design prompt we provided participants for their co-design activity.

We submit a complete participant table as a .csv file in an electronic supplement to this paper, and provide a textual summary below. We recruited DHH participants who had experience working with hearing colleagues in a workplace sometime in the past five years. Of 18 DHH participants, 10 were female, 7 were male, and 1 was non-binary. Seven identified as Culturally Deaf, 5 as deaf, 5 as hard-of-hearing, and 1 did not disclose. Ages ranged from 19 to 32, with median 25.5. All became d/Deaf at or before age three. Seven wore hearing aids or cochlear implants during the study, and 11 did not. For hearing participants, we recruited people who did not know any sign language and who had experience working with DHH colleagues in the workplace or academic environments sometime in the past five years. This criterion was included to facilitate discussion of ideas between pairs as the hearing participant could use prior experiences to guide their decisions. Of our 18 hearing participants, 12 identified as male and 6 as female, and ages ranged from 20 to 28, with median 23.

3.2 Design Workshop Procedure

In our IRB-approved study, one DHH and one hearing participant met with two researchers (one DHH and one hearing) via Zoom, and ASL interpreters were present to mediate conversation. Before the appointment, participants were instructed to sign up for an online whiteboarding application called Miro [29]. While alternatives had been considered, e.g. Scribble [41] and Lucidspark [24], we selected Miro due to the built-in chat function, range of drawing features, no paywall, overall ease of use, and popularity in the HCI and design fields. Furthermore, during the pilot sessions of our experiment, participants commented that they were satisfied with Miro, which validated its selection.

Each session took up to two hours to complete and all participants were compensated $60 for their time. To begin, the researchers introduced themselves and screen-shared a PowerPoint explaining the agenda, briefly introducing ASR technologies, and explaining the goal of the study—i.e., for a DHH and hearing pair to work together to create new ideas to augment either mobile-based or videoconferencing applications with ASR features. We gave participants a design prompt, which was conveyed verbally, through ASL, and in written form (Figure 1).

Participants were told that throughout the co-design session they could choose and decide among themselves to utilize the interpreter, chat, or some other method for communication. They were also free to switch communication methods at any time. During pilot testing of our study with a few participants, we originally had participants directly engage in discussion and prototyping from the beginning. However, some participants struggled with the whiteboarding application or had difficulty expressing their ideas in prototype form. Thus, for our actual study, we added some short preliminary activities before the collaborative prototyping session, with the session partitioned as follows:

- During **brainstorming**, participants had 10 minutes to work independently in a Google Document to brainstorm possible solutions for each design dimension—intended as a starting point for ideation, to help participants quickly create a list of many ideas for later reference when discussing and creating their prototypes.
- Next, to give participants time to explore the different features on the whiteboarding application, we set up an **icebreaker** where participants were given 5 minutes to draw their own favorite dessert. This activity also served as a get-to-know-you activity and build rapport.
- During the subsequent **sketching** phase, participants were instructed to select a few ideas from their brainstormed list and to spend 15 minutes independently creating quick sketches on Miro. The goal of this phase was to help participants quickly visualize some ideas and make it easier for them to discuss and share ideas with their partner during the prototyping phase, discussed next.
- Finally, participants engaged in collaborative **prototyping**. They were asked to work together to create their final designs: a prototype incorporating all required design elements. This prototyping activity was allocated 50 minutes. Before jumping into drawing, participants were directed to first discuss their own brainstormed and sketched ideas with each other, reconcile any differences in opinion, and agree upon a final set of features for the prototype.
- After participants finished prototyping, we wrapped up with breakout rooms for individual semi-structured **exit interviews**, where we asked about their experiences during the workshop and demographics. We started with several brief questions: "What worked well during the co-design session?", "What did not work well?", "How effective was communication with everyone involved?", and "Any feedback or suggestions?" The exit interviews lasted at most 10 minutes.

During each design activity, participants were instructed to open both Zoom and the software being used for the current activity (e.g. Google Docs for brainstorming or Miro for prototyping) in two separate windows, set side-by-side. Alternatively, if the participant had two screens, they were asked to display one on each screen. Participants were instructed to avoid obstructing the Zoom window; this way, DHH participants in particular would be less likely to miss information by ensuring that one window is not overlaid over the interpreter. During collaborative activities, this set-up allowed DHH participants to quickly shift their gaze horizontally to view either the workspace or Zoom.

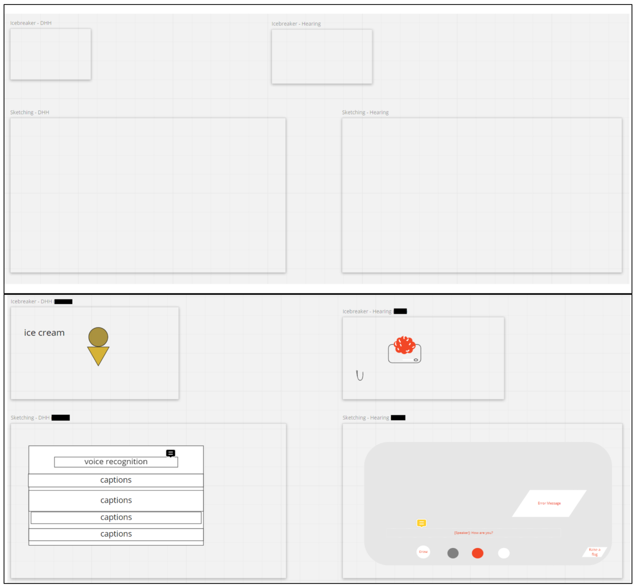

Figure 2: The top image shows a portion of an empty workspace, with pre-labelled ice-breaker and sketching frames for both DHH and hearing participants. The lower image shows the same workspace but with the frames filled in by one of our participant groups.

Audio and visual was recorded of the entire co-design session, from beginning to end, with all activities and interviews. These audio-visual recordings also included the ASL interpreters, our researchers, both our participants, as well as a view of the Miro workspace and any text-based chat or activities that occurred. These recordings serve as our primary source of data for our analysis.

For all activities that required drawing on Miro, we pre-created labelled frames (e.g. "Icebreaker - DHH participant") in the Miro workspace, so that participants would know where to draw during each activity. For an example of a labeled frame, see Figure 2.

3.3 Analysis of Workshop Data

Two researchers performed a qualitative analysis of our recorded data, beginning with an independent review pass during which we noted several possible emergent themes relating to how participants interacted with each other, with the interpreters, with the text-chat, and with the online collaborative tool. In a subsequent review pass, we performed a more in-depth coding, while focusing on learning more about the interactions noticed in the initial pass. After this, our researchers came to an agreement on a list of categories based on inductive coding. Finally, we readjusted our list of emergent themes from the initial review pass to align with the categories we created to refine our list of final themes, shown below:

- Communication modalities: How did participants utilize interpreters and text-chat?
- Use of collaborative drawing tool for co-design: Was the use of it effective? Were there any challenges?
- Conversation flow: What strategies for communication did participants employ?
- Reconciliation of ideas: Was there any negotiation between participants?
- Participant feedback on the workshop: How did participants react to our workshop methodology?

4 FINDINGS: REMOTELY CO-DESIGNING ASR-SUPPORTED COMMUNICATION APPLICATIONS

This section presents our qualitative analysis findings, and Section 5 presents prototypes our participants developed. Throughout, we refer to participant groups 1 through 18 as G1, G2, ..., G18. Groups G1 through G9 focused on designing for mobile applications, while G10 through G18 focused on designing for videoconferencing. Specific participants will be referred to using group nomenclature with a D or H suffix for DHH or hearing, respectively, e.g. G1-D or G1-H.

4.1 Communication Modalities

We had informed participants they could use any of the following three communication modalities as needed: interpreters, text-based chat, and the online drawing workspace itself. We then observed how our participant groups communicated with each other:

- Four pairs were relatively comfortable communicating orally (G1, G4, G11, G12) and the DHH participants in these pairs used their voice to communicate and were able to understand most of what their hearing partner said using their residual hearing alongside speechreading. However, the interpreter provided occasional support at times when the DHH participant had difficulty understanding their partner.
- Eight pairs (G2, G3, G7, G9, G10, G13, G16, G18) relied primarily on the interpreter for communication.
- Four pairs (G5, G6, G14, G15) relied primarily on using text-based chat on Miro.
- The remaining two pairs (G8, G17) utilized both interpreter and chat relatively equally.

4.1.1 The Role of ASL Interpretation in Remote Co-Design Workshops. ASL interpreters played a necessary role during the study, which had a complex communication setting, with multiple shifts in activity and DHH participants needing to split their visual attention across the collaborative drawing space, the ASL interpreter, the text-chat, and the researchers. Frequently the interpreter needed to make significant effort to visually capture the DHH participant's attention when the hearing participant wanted to communicate. Also, our hearing participants were not completely familiar with the etiquette and best practices for ASL-interpreted communication [17], e.g. with multiple instances in which the DHH participant began to sign, but before the interpreter could speak, the hearing participant interrupted. In the exit interview, G18-H discussed this challenge: *"I'm not used to this process, so sometimes when [my partner] was telling, like trying to say something to me, I think I was cutting it in between. So that was a good learning experience for me that I need to become patient."* In a multi-party videoconferencing context with both DHH and hearing individuals, it is best practice for participants to not only wait for their turn to speak but also identify themselves by name before doing so, which helps the interpreter keep track of who is speaking.

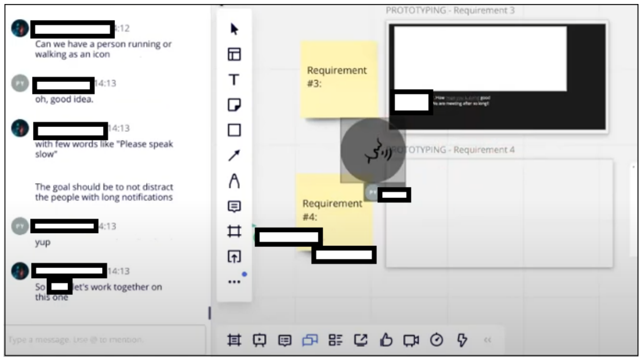

Figure 3: A snapshot of a Zoom recording capturing the DHH and hearing participants communicating via text chat and working on creating icons for notifications.

4.1.2 The Role of Text Chat in Remote Co-Design Workshops. Several pairs preferred interacting using text chat rather than interpreters for co-designing. One reason was quicker communication, as G6-D mentioned: *"Our ideas were able to be discussed quicker. And it is more visual so i can see and capture them with my eyes."* G6-H said chat, *"feels more personal. Like I can directly communicate with that person, rather than being dependent on an interpreter... It feels like I'm talking to a person directly."* Participants also mentioned how chat became more commonplace when working from home during COVID-19. Participants also liked how chat was useful in referring back to things discussed prior, in contrast to the ephemeral nature of ASL interpretation: *"I was able to refer my old conversation like what he told me five minutes ago."* - G14-H.

We observed that many pairs switched back and forth between chat and interpreter-mediated conversation, based on their needs in specific contexts. Many pairs switched to chat when working together on the collaborative drawing platform, especially if they wanted to open the drawing application in full-screen mode on their screen. As the drawing tool contained its own text-chat functionality, pairs naturally shifted to the chat modality. Figure 3 shows a snapshot of one participant group communicating via text chat. Additionally, interpreters and DHH participants may have difficulty understanding each other if they are not used to each other's signing style, as G8-D explained: *"It felt like the interpreter had a hard time understanding me [my ASL signs] so I felt our communication suffered a little bit so I typed in chat which was easier. Additionally, some of [the interpreter's] signs were ambiguous to me."*.

However, participants noted there are some drawbacks to relying on text-based chat for communication, such as the conversation being less synchronous and thus the communication less fluid, as compared to using an interpreter.

4.2 The Use of an Online Collaborative Whiteboarding Tool

The online drawing platform not only provided a workspace for the joint creation of design sketches, but it also enabled participants to draw and insert text boxes, thereby serving as an additional communication modality. In this section we discuss how participants interacted with the platform and any challenges that arose.

4.2.1 Our Approaches for Incorporating Collaborative Drawing. Participants commented how the icebreaker drawing activity was enjoyable and lifted the mood, while providing practice in using Miro. Our pre-arranging of locations for sketching within Miro (Figure 1) helped participants stay organized. It was also effective to insert text instructions for required design elements into the shared drawing workspace itself so that participants did not have to switch windows as often, e.g. to refer to the design prompt.

At times, moderators had to intervene during prototyping, e.g., to encourage participants to add more detail to a drawing or ask for more explanation from participants about their sketch. For example, one pair (G13) had ideas about a design for enabling users to fix errors in automatically generated captions; however, after creating a drawing, the pair simply explained that "users can change the incorrect words." The drawing itself did not indicate how they intended this to occur, and as moderators, we had to ask questions to draw this out. In this case, we found that the capability provided by the collaborative drawing tool to insert text-box annotations into drawings was helpful for enabling users to describe their designs in words, if they did not know how to express it in a drawing, e.g. in this case, the pair (G13) added a text box explaining that users of their proposed design can "click the word and type" to fix an error.

4.2.2 Challenges from Lack of Familiarity or Comfort. Neither member of G15 was particularly comfortable drawing on Miro. As a result, the designs they created were smaller and simpler than those of other pairs. In exit interviews, a few other participants expressed similar sentiments on their lack of skill: *"Miro is interesting maybe I needed some more time to learn Miro. better instructions for drawing."* - G16-D, or their desire for a more in-depth tutorial session for Miro use: *"I think a quick briefing session about Miro and how to use it would have made the diagrams more illustrative."* - G10-H.

4.2.3 Challenges from Divided Visual Attention. Overall, there were some challenges with getting the attention of the DHH participant, because they often had to split their visual attention across three communication modalities: interpreter, chat, and drawing tool. Before prototyping, we reminded participants to check the interpreter frequently, but participants often forgot while busy sketching. Two groups (G10, G11) in particular had difficulties because their strategy was to have each person work on Miro and discuss ideas simultaneously via the interpreter. With each person discussing while drawing and having both concurrently draw on the same prototype, it was a challenge to follow their thought process and to catch the attention of the DHH participant. One additional participant group (G1) had both simultaneously discuss and draw, but since the DHH participant was skilled at communicating orally, they did not encounter the same issues.

Several groups (G7, G8, G9, G18) decided to first discuss and agree upon features then had the DHH person sketch most of the prototypes afterwards. While in theory this would reduce conversation while drawing, in reality, communication issues persisted. Multiple times the hearing participant had a spur-of-the-moment thought or real-time feedback on the sketches the DHH participant was making, and communication stagnated if the DHH participant was actively drawing and did not look at the interpreter. Interpreters often had to wave at the screen until the DHH person noticed, disrupting the flow of the co-design activity.

4.3 Successful Communication Strategies

In this section we describe a few successful communication strategies that our participants employed.

Hearing Draw and DHH Reinforce and Critique: Five pairs (G2, G3, G4, G12, G13) adopted this strategy, in which the hearing person spoke while drawing, to describe in detail what they were drawing and what each feature does. Meanwhile, the DHH participant set-up the ASL interpreter and Miro side by side on their screen, in order to rapidly switch attention between them, which better enabled them to contribute, e.g. giving feedback as the hearing participant drew. This strategy took advantage of the hearing person's ability to speak and draw simultaneously. G2-D expressed: *"Hearing person was doing more of the drawing because its easier for them to multitask draw and conversation while DHH has to shift attention between interpreter and Miro."* This strategy has the added benefit of the hearing participant being able to share their screen on Zoom, so the DHH participant would only need to have one window open (Zoom); with the DHH participant viewing the Miro workspace through the shared screen. One group (G2) shifted to the DHH person drawing in final third of the session, but communication issues started becoming apparent, e.g. the interpreter having difficulty capturing the DHH participant's attention.

Agree First then Divide Responsibility: Three groups (G14, G16, G17) adopted this strategy, in which participants discussed each design dimension extensively until reaching an agreement about what features should be included. Then, they split up the prototyping responsibilities, e.g. with one person sketching for the error correction design dimension and the other focusing on notification systems design dimension (G14). Since two groups (G14, G17) relied significantly on the text chat, it was easy for them to refer to any agreed-upon features in the chat history. G14 included a text-based note within the Miro workspace itself, where they listed each agreed-upon feature, for easy reference, and where it could be updated as they made new decisions while prototyping. Since these pairs generally did not discuss ideas while someone was actively drawing, DHH participants missed less information.

Simultaneous Prototyping Alongside Text Chat Communication: Unlike the previous strategy, two groups (G5, G6) decided to have both participants jump into prototyping without dividing up responsibility beforehand. However, they were successful in communicating and co-designing because they relied on asynchronous text-based chat to communicate ideas without missing information. One participant said: *"Using the text squares in Miro was good to communicate ideas and type back and forth and easier than interpreter. Our ideas were able to be discussed quicker" - G6-D.* However, this communication strategy, while successful, comes with a caveat: since participants would constantly type throughout the session to communicate while simultaneously drawing, it relies on both of them having quick typing and reading skills.

4.4 Negotiation and Reconciliation of Ideas

In general, all 18 pairs behaved in a respectful, cooperative manner with each other, e.g. frequently asking each other "Do you agree?" or "What do you think? Do you have any suggestions for my idea?" In addition, participants were very vocal when they liked their partner's ideas, e.g. commenting "I think that is a very good idea!" This level of cooperation and openness between our participants contributed to the success of our design workshops. While pairs often agreed on concepts or were flexible, sometimes DHH and hearing pairs had to engage in negotiation—typically when one participant suggested an idea but the other had critiques based on their personal experience. We noticed this occurred most often during the discussion of our second design dimension (notification systems), and we provide three examples of reconciliation of ideas that occurred along this dimension:

- Group G15 had a disagreement about a notification system; the hearing participant originally suggested flashing lights that change colors with a key in the corner showing what action to take, e.g. red means speak slower. The DHH user said *"lights may be distracting for the DHH user and make it difficult for them to understand what is happening, especially if there are multiple colors and backgrounds in the layout."* They discussed further and eventually reconciled their ideas: They made the lights visible only to hearing users.
- In group G6, the DHH participant suggested that a notification to change behavior should be done through sound only. The hearing participant disliked that idea, saying that sound prompts would be distracting and possibly easy to miss in noisy environments. The DHH participant considered this and agreed, and they decided to accompany the sound with a pop-up text flashing on the screen.
- Before sketching prototypes, group G12 discussed various ideas for a notification system, and the hearing participant suggested a large pop-up appear in the middle of the screen. The DHH participant advised against this, saying *"A pop-up in the middle of the screen would block the captions."* The DHH participant instead suggested a smaller, circular pop-up to the side of the screen. The hearing participant agreed, and they decided to not cover the middle of the screen. However, when it was time to sketch the prototype, the hearing participant drew a pop-up that still potentially blocked the screen of another speaker. The DHH participant noticed this and advised, *"I think you should move it further out of the way. It would be difficult to lipread if anything is blocking the view."* The hearing participant countered, saying *"Placing the notification in the corner may make it difficult for the hearing speaker to notice it."* The DHH participant took this into consideration, and ultimately they agreed that the pop-up would be reduced in size and moved to the corner—but now a "ding" sound would accompany the notification, to help hearing participants notice it.

4.5 Participant Feedback and Suggestions

In exit interviews, participants indicated that the workshops were effective, and that they had a satisfying co-design experience, e.g. G14-H commented *"It was actually very fun collaborating and working. So usually, I've worked with a person who is like sitting right behind me or right on my side, but working remotely as it was very collaborative and interesting."* G18-H agreed, commenting *"everything was very smooth. I wouldn't want to change anything."* G13-H echoed this sentiment, saying *"it was very, a very smooth run,...I feel* *like we're able to really come up with some really good ideas. And yeah, I think it was really fun. There was really no confusion."*

Participants indicated that the four-phase structure (individual brainstorming, ice-breaker session, individual sketching, and collaborative prototyping) facilitated the co-design activity. The brainstorming and sketching sessions were found to be effective prep work for co-designing, e.g., G5-H said, *"My initial sketching session essentially was like a visualization of the brainstorming points that I jotted down earlier. And what that did was essentially served as like a reference point for me to go back and refer to it when I was discussing things with [my DHH partner]"* Participant G2-D shared: *"I liked working alone in the beginning ... so I can focus on what I like first then compromise later."*

Hearing and DHH participants commented they benefited from the integrated drawing and chat features of the workspace, for example, G14-D mentioned that the tool helped them feel more engaged, *"Miro for collaboration is very good more involvement and action."* In fact, G13-H believed the drawing and chat interface was so effective that, *"if the interpreter wasn't there, I still feel like we could have accomplished something as close to what we did."*

Both hearing and DHH participants discussed how they appreciated that the design they had created took into consideration both perspectives, as G12-D explained, *"I liked having the different perspective of the hearing participant and met halfway."* Hearing participants in particular commented on their new insight into the experience of DHH individuals, e.g. as G14-H shared, *"the thing that really stood out for me with this whole exercise was the fact that I don't really think about things from the perspective of someone who isn't able to utilize his hearing...I was forced to actually think of this particular scenario from the point of view of a person who would use this app."*

Participants also suggested improvements, such as a desire for more training to know how to use the tool. G16-D commented *"Miro took a little bit to get a hang of. The only thing I would suggest to send information about Miro to get that ahead of time."* Participants also wished that they had more time to get to know one another at the beginning of the session, e.g. G18-H said, *"I'm interacting with [G18-D] for the first time, right? So you can also have an informal session when in which I can also get to know [G18-D] a little more. And [G18-D] also get to know me a little more before we start collaborating,... I think the collaboration process becomes more smooth."*

5 RESULTING PROTOTYPES

In this section we provide examples of the design prototypes participants created during our virtual co-design sessions, along the two dimensions outlined in the design prompt we provided: *Correcting errors in ASR output* and *Notification systems for influencing speaking behavior* (RQ2).

5.1 Correcting Errors in ASR Captions

All but one pair agreed that any text likely to have been mistranscribed by ASR should be indicated to users, but there was no clear consensus on how. Some ideas included a red squiggly line underneath (G9), colored boxes (G1), a triangle with exclamation point icon next to the word (G4), different colored text, e.g. orange or red (G6), highlighting the word (G8), and boldfacing (G9). The one pair

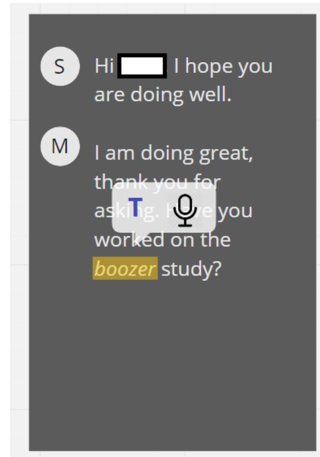

Figure 4: One participant pair (G8) included a small pop-up with options for repeating verbally (microphone icon) or fixing manually (T icon).

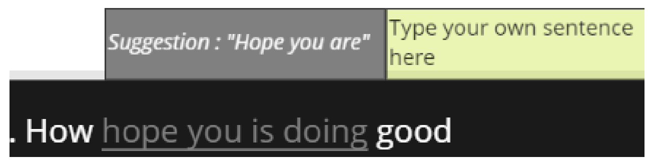

Figure 5: One participant pair (G5) included a pop-up with suggested words as part of their error correction feature.

(G15) who decided not to modify word appearance simply wanted the hearing participant to watch for errors and fix words if they noticed anything wrong.

To fix errors in text, participants suggested several methods, including: re-recording it verbally (G8), physically touching or clicking it (for mobile-app versus videoconferencing modalities, respectively) then typing to fix it (G5, G15), providing auto-correct options (G7), providing a built-in dictionary (G8), or displaying a pop-up of suggested words (G5, G14). A design with text pop-ups for correcting errors is shown in Figure 5, and an error correction prototype created by G8 is shown in Figure 4 with both spoken (microphone icon) and typing (T icon) fixing options.

To indicate the word had been changed, post-correction, again there was no clear consensus. Some groups suggested displaying asterisks next to a modified word (G2), colorizing it in green (G6), or inserting "*[CORRECTED]*" immediately after the word (G16).

5.2 Notification Systems For Influencing Speaking Behavior

All groups suggested a visual alert to influence speaking behaviors of a hearing conversation participant, with one-third also wanting an audio alert. In the mobile-app modality specifically, four groups also wanted the device to vibrate (G6, G7, G8, G9). Overall, groups were divided on whether notifications should be shown to all participants or just the current speaker. All pairs wanted text to appear

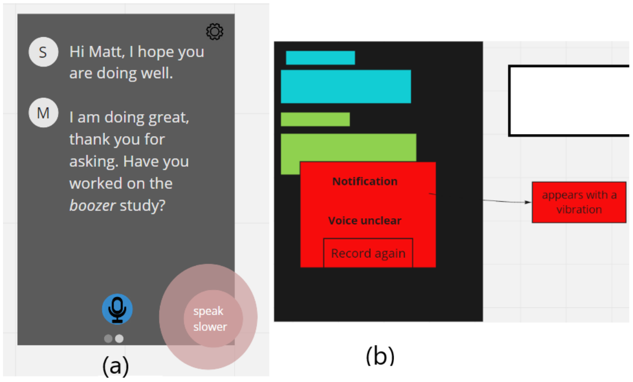

Figure 6: This figure shows two notification styles, with an Icon representation on the left (a) and a Pop-Up representation on the right (b).

with any notification, with instructions for what to do next, e.g. "Speak more slowly." Suggestions for appearance varied:

Some groups (G3, G4, G8, G11, 13, 14, G15) suggested using **Icons**. These icons would be small in nature, as to not obstruct view of the application, and appear on the screen when an action is needed. Suggestions for icon appearance varied, ranging from pictorial representations, e.g. a turtle to indicate "slow down" (G3), to textual reminders, e.g. circles containing instructions for behaviors (G8).

Other groups (G5, G9, G10, G12, G17) wanted a **Pop-up** bubble to appear on the phone screen, with instructions for improving speech, if that person began to speak in a way that was unclear. These pop-up bubbles typically were more visually prominent than the icons suggested by other groups. Figure 6 shows two designs our participants created, one using a small icon and the other a larger pop-up.

Finally, other groups (G2, G6, G7, G16, G18) wanted to notify the speaker to change their behavior by partially or fully covering the speaker's video with a transparent colored screen **Overlay**, with text-based instructions in the middle. There were some variations in color, e.g. red or gray, but these overlays were distinct in that they covered most or all of the screen.

We noticed that our participants' ideas naturally aligned along three levels based on visual salience. Of the three notification types, Icons were the least visually prominent, Pop-Ups had medium prominence, and Overlays were most likely to be visually disruptive. Examples of all three concepts appear in Figure 7. This reveals a tension between DHH and hearing perspectives, trying to attain a balance between being minimally disruptive (for DHH users) and ensuring it is easy enough to notice (for hearing users).

6 DISCUSSION

6.1 Discussion of RQ1: Remote Co-Design Methodology

6.1.1 Effectiveness of Our Remote Co-Design Method. Our findings provide empirical evidence of the effectiveness of participatory design workshops in this remote context, with pairs of participants of differing hearing ability engaging in collaborative drawing and

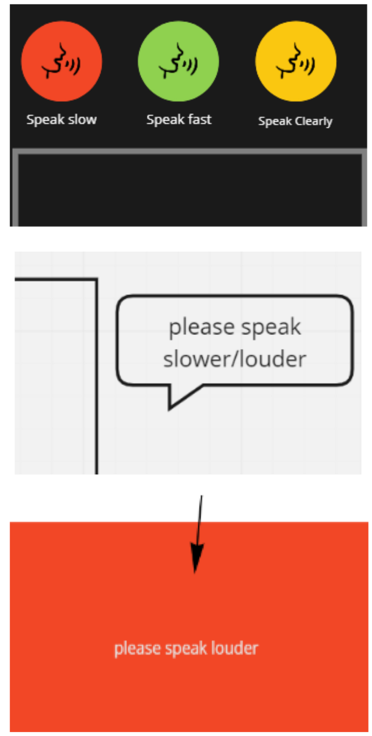

Figure 7: Three distinct notification styles resulted from our workshops: (a) Icons (pictured top) that persist on the screen and enlarge to notify the speaker to speak slow, speak fast, or speak clearly. (b) A pop-up bubble (pictured center) next to the speaker's video with text-based notification. (c) A screen overlay (pictured bottom) atop the speaker's entire video with text instructions to speak louder.

prototype design. Participants' discussions during ideation, in particular, highlighted the effectiveness of our workshop in facilitating negotiation and reconciliation of ideas. Our findings indicated the collaborative drawing workspace with integrated text chat functionality allowed participants to easily visualize their partner's ideas and designs. Finally, our use of this methodology resulted in development of ideas that were influenced, and enriched, by incorporating perspectives of both the DHH and hearing participants. Our participants generated design solutions of good quality, detailed enough to implement, and representing a range of feasible ideas. The workshops consistently and effectively elicited design work such that solutions coalesced around similar ideas and tensions (e.g., the icons, pop-ups and overlays of the notification solutions).

6.1.2 Providing Options for Communication Modalities. As we described in section 4, participants communicated in a variety of ways. Our main take-away was that participants should be given the option for both using ASL interpreting or using the chat function (or neither, if they prefer communication to be completely oral). The decision priority, however, should be given to the DHH participant, whose attention is dispersed between the interpreter and workspace. As the more disadvantaged conversation partner, communication should occur in a way that is most comfortable for DHH users, as discussed in greater depth in by Bennett [6]. In fact, prioritizing DHH participants' communication preferences appears to not disadvantage hearing participants, as they were able to co-design effectively and indicated general satisfaction regarding communication dynamics in exit interviews.

6.1.3 Encouraging Engagement From Participants. Our findings reported how some participants felt uncomfortable or uncertain in how to engage in brainstorming and prototyping, which highlights the important role of the research moderator in engaging each participant, asking leading questions to facilitate discussion, and encouraging participants to try the collaborative drawing tool. Moderators must ask for more details if the sketch does not fully encapsulate participants' ideas. To alleviate some artistic pressure, a dedicated graphic designer could be added to the session. This way, the DHH and hearing pair would be free to devote their energy to discussion and not drawing, and the sketcher would ensure each prototype has sufficient detail. This would especially benefit the DHH participant since they would no longer need to devote as much attention at the drawing region. Studies utilizing dedicated designers have been investigated with success, e.g. with blind and sighted users [46], but it remains to be seen how effective such a solution would be in virtual collaborations among DHH and hearing participants. Further investigation with DHH participants is especially critical, since addition of a sketcher could introduce a new power imbalance in favor of the sketcher, who might not accurately convey the desires of the participants.

6.1.4 Importance of Participant Characteristics. Many of our participants were relatively young, tech-literate, and familiar with communicating on Zoom, and several had prior experience with ASR technologies. Furthermore, as reported in the demographics data tables included in our electronic supplementary files, many of our hearing participants, and some DHH participants, were in school studying computing-related fields. Perhaps this resulted in these participants being more quick in acclimating to a new tool like Miro. In addition, as part of our screening process, we recruited people with prior experience working with others of different hearing ability within the last 5 years; naturally these people might be more receptive and open-minded when it comes to discussions and negotiations due to their past experience.

6.1.5 Recommendations for Future Studies.

- **Schedule of Activities:** For future researchers designing studies with this methodology, we recommend the same phases: individual brainstorming, ice-breaker with drawing tool, quick individual sketching, and collaborative prototyping. Individual brainstorming was effective at encouraging participants to formulate some ideas from their own unique perspective. The ice-breaker gave participants practice with the drawing tool and supported building some rapport. However, we recommend giving participants more time than in our sessions to introduce themselves to each other and engage in some conversation. The individual sketching activity was useful in encouraging participants to visualize some concepts from their brainstorming and facilitated the transition to prototyping.
- **Setting up the Workspace:** To keep sessions organized, moderators should pre-assign and label locations within the drawing canvas of the online collaborative drawing workspace, as we did, to organize the data and ensure participants are clear on where to prototype within. This is especially critical with mixed-ability groups as more people are involved, e.g. interpreters, and could increase distractions for DHH users. Moderators should encourage participants to add text boxes to their drawings of each design, to add explanations of features.
- **Responsibilities of Moderators:** If any participants are uncomfortable sketching, e.g. due to shyness about drawing or lack of familiarity with the prototyping tool, moderators should remind them that the prototype drawings do not have to be of high quality and they can relay their ideas through simple images and shapes alongside a textual label or description. Participants should have the option for both ASL interpreting and using the text chat function, and during the study, the moderator should ensure that it is the DHH participant who has priority in shaping the decision for how to use these options. Early in the session moderators should suggest that pairs of participants consider the two strategies that worked particularly well for prototyping with DHH and hearing pairs in our study: *Hearing Draw and DHH reinforce* and *Agree First then Divide Responsibility.* Finally, moderators should encourage reconciliation of design ideas between participants, especially when DHH users offer unique insights.

6.2 Discussion of RQ2: Prototypes Created

When reviewing resulting prototypes, it became apparent that although we had obtained a wide range of designs and features, the suggestions from groups who considered the mobile-app modality were very similar to those suggested by groups who discussed the videoconferencing modality. The differences between modalities were relatively minor and generally platform-specific, e.g. clicking for videoconferencing using a computer mouse vs. pressing on a phone screen for a mobile app. This similarity in what our participants imagined and desired across modalities motivates future research, e.g. with working prototypes evaluated in real conversational settings, to investigate just how much consistency could be possible in the design of error-correction and behavior-notification features in communication applications across these modalities.

6.2.1 The Significance of Visual Salience In Prototype Designs. A major point of disagreement among groups (and between the two participants within some groups) in their prototype designs was how visually prominent features should be. For notification systems in particular, in a broad sense, three different implementations of notifications emerged (Icons, Pop-Up, and Overlay), as shown in the results section. These different implementations can be thought of in terms of visual prominence: Low, Medium, and High, respectively. Each has benefits and drawbacks: While notifications with lower visual salience would be less distracting it would also be harder to notice. Based on our observations of the discussions of participants in our workshops—as well as the wide range in the sizes of notifications in our prototypes—we speculate that users may have individual preferences about the optimal salience. This may motivate future research on designs that enable users to individually customize how notifications should appear.

6.2.2 Influence of Social, Environmental, and Technical Factors on our Protoypes. Prior work [27] interviewing DHH participants found that their experiences with ASR technologies are influenced by three major factors: social, environmental, and technical, and that each of these three factors are perpetually intertwined. This was reflected in prototype designs that emerged in our study: For instance, the design choice of what specific technical process would be used for fixing errors (e.g., directly and manually correcting textual errors in output) may have social implications (whether it causes noticeable lapses in communication) and environmental implications (whether the process would be more easily implemented and used in mobile or videoconferencing contexts). The co-design methodology in our study, with both DHH and hearing participants engaging in design simultaneously, may naturally encourage some consideration of social factors, and participants discussed environments of usage and potential technical capabilities of the system during the study. In subsequent studies to evaluate candidate prototype designs that have emerged, it would be important for all three of these factors to be specifically considered in the study design; for instance, while participants may report that a particular error-correction strategy is technically clear and easy to use, if the study also asked about potential social implications, then it could be revealed that a particular design might lead to awkward social interactions.

7 LIMITATIONS AND FUTURE WORK

A limitation of our study was that COVID-19 prevented us from investigating the effectiveness of our remote co-design workshops in comparison to workshop on the same topic conducted *in person*—such a future study could contribute further methodological insights about what is unique from the modality.

While engaged in a videoconference, some groups in our study were actually discussing videoconferencing designs. As such, there is a risk that the specific videoconferencing platform used (in our case, Zoom) may have influenced the designs that participants proposed. A future study, conducted using a different videoconferencing platform, could reveal whether there was such an effect on our findings.

Another limitation of our study was that our design workshops were relatively short at only 2 hours long, and a longer session may have given participants more time to flesh our their ideas during prototyping. A longer session may have also given participants an opportunity to both get to know each other, and to become familiar with the collaborative drawing workspace used in the study—both of which were concerns raised by participants in our findings.

The scope of our design dimensions is relatively specific and well-defined, and our participants were given clear instructions and tasks to complete sequentially. As such, we were able to keep them focused and on-topic without difficulty. However, it is possible that co-designing within broader topics could pose new challenges, e.g., due to the expanded scope and possible changes in dynamics between participants. We expect that our strategies for successful communication and workshop structure would still apply, in order to facilitate discussion, if the design prompt were appropriately tailored to the new topic of discussion. Our methodological findings would be most generalizable for co-design within areas adjacent to the focus of our current study, e.g., communication and engagement during one-on-one interactions between DHH and hearing individuals. Future work could confirm whether our method would be successful in a more open-ended context.

Our sessions did not include particularly large numbers of DHH or hearing participants, so, while the designs participants created can serve as valuable starting points for further empirical research, the preferences of these few participants should not be taken as representative of the DHH or hearing communities as a whole. In addition, co-designing with groups larger than two individuals could exacerbate some tensions between participants, e.g., in obtaining consensus for design ideas among the whole group, and it would be more challenging to keep larger groups of participants focused on each task and discussion. Future work would be necessary with larger groups of both DHH and hearing participants, with a focus on recruiting participants with a wide range of demographic characteristics and experiences, to gain a better understanding of how these results would generalize to the overall population. Such studies of a methodological nature could focus on whether online co-design workshops like this are also effective when conducted with a more diverse range of DHH and hearing participants.

8 CONCLUSION

In this paper, we present our findings from a set of 18 entirely virtual 2-hour participatory design workshops, each with one DHH and one hearing participant, to evaluate the feasibility of remote co-design sessions with mixed-ability groups. Our sessions explored new accessibility features for communication applications incorporating ASR-based captioning, in particular on the design dimensions of *Correcting errors in ASR output* and *Implementing a notification system to influence speaking behaviors*, which had been motivated by prior research on preferences of DHH users in this context. Our primary contribution was methodological: We report on our experience using this novel method and show it was effective at generating new designs and supported participant engagement. Our analysis revealed how participants used the online collaborative tool, what strategies for communication participants employed, how our co-design process facilitated negotiations between DHH and hearing partners, and how communication needs of DHH users were met—so that both DHH and hearing participants could equitably engage in design activities together. Finally we have contributed recommendations for future researchers who wish to utilize a similar online co-design workshop methodology in their work.

ACKNOWLEDGMENTS

We thank the Department of Access Services at the Rochester Institute of Technology/National Technical Institute for the Deaf for scheduling and providing interpreters, and the ASL interpreters for supporting communication during all of our co-design sessions. This material is based upon work which is generously supported by the National Science Foundation (NSF) under award No. 1954284 and the NSF Graduate Research Fellowship under award No. 1746056.

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