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CommBo: Modernizing Augmentative and Alternative Communication

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ABSTRACT

For every 100,000 people, there are 536 individuals with speech impairments who can benefit from the use of Augmentative and Alternative Communication (AAC) devices (Creer et al., 2016). Existing AAC devices can suffer from the shortcomings of being difficult to adjust to the user's specific needs or simply being expensive to own and maintain. We aim to reduce the impact of these problems with CommBo: a web-based, speech-generating picture communication board meant to alleviate some major difficulties commonly experienced by AAC users. CommBo offers customizability beyond that of a physical picture board and leverages machine learning to provide intelligent suggestions. It supports heightened communication that can be brought to a multitude of computing devices, including those that are low-cost or have limited internet access. CommBo is designed for those with autism spectrum disorder (ASD) and patients suffering from any trauma that impacts the person's ability to communicate effectively, e.g., stroke-induced aphasia. Across two studies, target and non-target participants evaluated CommBo in terms of functionality and usability, and results showed significant benefits of the system.

1. Introduction

1.1. The need for assistive communication technologies

The United Nations Convention on the Rights of Persons with Disabilities defines communication as a human right (United Nations Department of Economic and Social Affairs, 2007). Lacking the means to communicate meaningfully increases feelings of isolation, social anxiety, and depression (Knutson and Lansing, 1990). These symptoms in turn are capable of further progressing to feelings of worthlessness, guilt, and suicidal thoughts and feelings (Taylor et al., 2016; Weeks et al., 2009).

Augmentative and Alternative Communication (AAC) solutions exist to promote and support communication for those who do not communicate verbally. AAC techniques have long been a topic of research. Studies have yielded exhaustive lists of those who could benefit from AAC technologies due to difficulties communicating (McNaughton and Light, 2013). These lists frequently include a variety of neurological and developmental conditions; according to the University of Sheffield and the Barnsley Hospital NHS Foundation Trust, AAC solutions are particularly applicable for those with the following six conditions: Alzheimer's disease, dementia, Parkinson's disease, autism spectrum disorder (ASD), learning disabilities, and cerebrovascular accident (often referred to as a stroke) (Creer et al., 2016). There are 475 individuals with these top six conditions for every 100,000 people; this number increases to 536 when considering the remaining 13 categories of conditions discussed in the study. Regarding autism spectrum disorder (ASD) as a specific example, experts have determined that 20–30% of individuals diagnosed with ASD cannot express themselves well enough to meet their own basic needs, with some estimating the number may be 50% or more (Anderson et al., 2007; Cafiero, 2001; Lorah et al., 2013; Wodka et al., 2013).

1.2. Types of AAC

While some can communicate through unaided means, such as gesture or sign language, others must rely on aided means. Aided AAC solutions fall into two major classifications (The American Speech-Language-Hearing Association, 2019a). The first is the low-cost, low-tech category which includes both homemade tools and commercially-available products. Such devices are typically considered to be cost-effective yet somewhat inconvenient. Manually created picture boards are very affordable, taking only time and few other resources to create. However, these systems inherit the limitations of whichever language

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representation method (LRM) they use, e.g., alphabet-based or image-based (The American Speech-Language-Hearing Association, 2019b). Alphabet-based methods that rely on spelling generally have higher time and motor requirements; word-based and image-based methods encounter a physical limitation on the number of concepts they can represent, resultingly restricting communication to broad concepts and ideas. The Picture Exchange Communication System (PECS) improves on this type of device by providing a mechanism to group phrases into sentences and communicate more effectively (Bondy and Frost, 1994). Overall, this category of tools can place a significant burden on a communication partner to interpret meaning from the AAC device.

The second category of solutions is high-tech AAC devices. Such devices aim to reduce issues common to manually-created instruments but carry an additional cost to the user. This category includes apps or hardware devices that offer some increased depth of communication through speech output or sentence generation. They may offer some dynamic control, but this customization is usually quite limited in scope. With the downsides of notably higher costs both fiscally and from time and energy spent on maintenance such as keeping the device charged and operational (Van der Meer et al., 2012), high-tech AAC solutions may not fit the needs of all individuals.

Inequities with respect to monetary situations, availability of consumer solutions, and internet access can bar people from using high-tech AAC devices. As such, these AAC users are restricted to low-tech devices that they often have to make at home. Low-tech devices, however, often lack expressiveness due to the physical limitations of the systems and can be cumbersome to personalize to the specific needs of the user. With that said, there is a critical need to make features associated with high-tech solutions available in a cost-effective, accessible manner. We present CommBo in an effort to combat these challenges.

1.3. CommBo

CommBo is a web-based, speech-generating picture communication board that offers a customizable interface and machine learning capabilities to provide intelligent suggestions to the user. These intelligent suggestions help mitigate the inherent physical limitations of picture boards by making the most relevant communication options more readily accessible. The utility of an adaptive and easily modifiable board layout and speech generation make communication more convenient and personalized. Evaluating CommBo with two individuals who use AAC devices showed that CommBo scored better than a traditional picture board with respect to physical demand, performance limitations, effort, and frustration.

CommBo leverages technologies compatible with virtually any smartphone, tablet, or other computing device. As a free web-based interface, users can save hundreds compared to most other high-tech tools which often have specific hardware needs or license costs (Alliano et al., 2012). This means that CommBo can be deployed even in developing countries where budget smartphones are widely owned. A 2018 survey determined that smartphones can be purchased in parts of Africa for as little as 30 USD, with continual adoption of smartphones growing across the world (Poushter et al., 2018; Scott, 2017; Wyche and Olson, 2018). This provides a low-cost entry to the use of our application and will potentially provide means for better communication for those who otherwise could not afford an AAC solution.

Additionally, CommBo's use of storage libraries and browser APIs allows it to cache itself on a user's device. This enables entirely offline operation, making the app accessible to those who lack consistent internet access. CommBo only requires internet for the initial setup. This design consideration further drives down operating costs.

The application improves upon traditionally inflexible interfaces by utilizing machine learning to suggest cards to the user. Information such as time of day and frequency of use are used to build a predictive model for an individual's needs. This allows operation of the application to be faster, easier, and more intuitive. This sensitive user data gathered to produce these results is appropriately hashed and stored on the server within a local MongoDB collection following at minimum the HIPAA (Health Insurance Portability and Accountability Act of 1996) guidelines.

2. Prior work

Aided AAC methods, i.e., tool-based solutions, enable individuals who cannot communicate effectively with unaided AAC methods, e.g., sign language, to have an independent means of communication. Without AAC tools, these individuals become dependent on their caregiver to convey their needs. Methods such as facilitated communication where the caregiver physically guides the individual's hand or arm toward the device as the medium for the individual to communicate have been discredited and decried by experts (Hemsley et al., 2018; Travers et al., 2016). Thus, it is paramount to enable users to independently express themselves, which is the primary motivation behind AAC technologies.

The greatest challenge in designing AAC solutions lies in ensuring that the method enables individuals with speech impairments to communicate in a meaningful way. Those relying on these methods need them to access vocabulary capable of meeting their needs. This vocabulary must be appropriate for the individual and be applicable to situational contexts while avoiding being overly complicated (Balandin and Iacono, 1998). As such, the selection of the available vocabulary is very important. It is important to provide choices that allow the users to discuss memories, values, life expectations, wants, and desires while making the vocabulary relevant to the users' skill levels (Hilari and Northcott, 2006). By doing so, this practice increases initial engagement and the overall actual adoption and autonomous use of the device (Ferreira et al., 2017).

Low-tech AAC solutions can be an appealing option since they are typically affordable and easy to make (The American Speech-Language-Hearing Association, 2019a). Low-tech can be as simple as pictures or objects placed in specific locations, such as the use of photos to increase communication with individuals who have dementia (Bourgeois et al., 2010; Yasuda et al., 2009). For those with ASD, one of the most prominent low-tech AAC methods is the Picture Exchange Communication Systems (PECS). PECS guides therapists and caregivers through the process of creating and using inexpensive picture boards for communication (Frost and Bondy, 2002). It is generally regarded as a promising system with demonstrated benefits for children with ASD (Flippin et al., 2010; Ganz et al., 2012; Magiati and Howlin, 2003), although one limitation may be the lack of expressive speech and the difficulty for some children to master PECS depending on their individual needs (Ganz et al., 2008).

High-tech AAC is more commonly associated with computing technology and can be seen as an emerging area thanks to the increasingly ubiquitous nature of mobile "smart" devices (Moffatt et al., 2017). High-tech solutions can offer benefits in the form of speech generation or adaptability but may be more expensive. To support those with various special needs, accessible design is an important consideration for computer systems. It is necessary to build flexible internal models (called ontologies) to represent users. A mapping between certain disabilities and user interface controls is established to promote a notion of "eQuality" and usability for each of the unique users on the platform (Karim and Tjoa, 2006). Various other user interface optimizations include page linearization, text enlargement, and page segmentation, each of which has proven to improve a user's understanding of the computer system (Lee and Hanson, 2003). In existing systems like Proloquo2Go (Sennott and Bowker, 2009) and TouchSpeak (van de Sandt-Koenderman et al., 2007), failures to optimize user interactions have resulted in a notable decline in quality of conversation (van de Sandt-Koenderman et al., 2007). Additionally, an oft-overlooked concern in AAC interface design is the relationship between a speech-impaired individual and their communication partner. While most AAC solutions focus on the experience of the primary user, efficacy in communication is dictated by the ability of both users to fully leverage the AAC device (Kent-Walsh and Mcnaughton, 2005).

User priorities for their AAC devices have remained largely the same over the last few decades (O'Keefe et al., 2007). Unfortunately, previous AAC research shows that most AAC devices, high-tech and low-tech alike, fall short of the needs of speech-impaired individuals (Hodge, 2007). As such, the decision to use a high-tech or low-tech AAC solution is based on prioritizing cost or expressiveness. Illustrating this, some researchers try to avoid using newer technologies in favor of using cheaper and more accessible solutions (O'Keefe et al., 2007). In the high-tech space, solutions often use applications on smart devices or physical computer-based solutions to aid the user in communicating. Examples include the widely-used Proloquo2Go (Sennott and Bowker, 2009) and the older but well-regarded TouchSpeak, a portable computerized device developed for aphasic people (van de Sandt-Koenderman et al., 2007). In the low-tech space, solutions such as picture board binders like PECS are popular. The technology is cheap relative to solutions requiring tablets or smartphones, but the physicality of the solution is cumbersome to transport (Ferreira et al., 2017). The largest cost for low-tech solutions comes from the losses in expressiveness available in high-tech solutions (Hill and Flores, 2014).

In a comprehensive review of available high-tech solutions, one study cited the importance for those who rely on AAC to work with speech-language pathologists to structure intervention plans that will both assist and advance communication (Alliano et al., 2012). No single AAC device will address all of the needs of every individual, and as indicated through previous AAC research that shows most AAC devices, high-tech and low-tech alike, fall short of the needs of individuals with speech impairments (Hodge, 2007). Similarly, researchers have shown that both low-tech and high-tech solutions can lead to similar performance and outcomes (Gilroy et al., 2018; 2017).

A detailed review of the field by Lorah et al. determined the market of high-tech AAC and speech-generating devices to be an important emerging space (Lorah et al., 2015). A notable system with this approach, "How was School today...?" (Black et al., 2012), uses data-to-text technology and natural language generation (NLG) to enable children to have detailed, personally-curated conversations about the events of their day. However, the foundational components of this system are voice recordings from caregivers and RFID location data, so this solution is not ubiquitous and requires significant aid. Thanks to advancements in NLG, the spirit of this system can be achieved in fashions that improve user independence and have more general availability.

Another example of high-tech solutions includes work by Hayes et al. which studied several different approaches for optimizing AAC: mobile devices, personal recordings, and collaborative display boards. One of their core contributions was the *Mocotos* mobile tool based on the concept of virtual picture cards (Monibi and Hayes, 2008). However, this was a comparatively early work in the mobile space, so it was difficult for the authors to robustly evaluate with end users. Overall, they report on the promises of high-tech AAC and highlight the importance of flexible designs that enable collaboration with caregivers and support for end-to-end programming and customization (Hayes et al., 2010).

With the increasing availability of smart devices such as smartphones and tablets, AAC researchers have investigated how to use mobile and web technologies to develop AAC solutions that are easy to transport and/or contain high-tech features. Many of these systems are interactive PECS boards such as AutVisComm (Sampath et al., 2012), Cboard (Gilroy et al., 2019), and CoughDrop[1]. As a speech-generating PECS board, Cboard is the closest to CommBo; their main difference lies in that CommBo uses machine learning to adaptively make relevant cards available to the user and allows for custom card generation instead of exclusively using the Mulberry Symbols (Mulberry, 2018).

One of the largest audiences for AAC devices consists of those with stroke-induced aphasia. This condition causes the individual to lose large amounts of speech comprehension or expression (Borthwick, 2012). They are often older individuals who have been previously used to living independently. Many can become frustrated with their AAC devices because the devices limit their communication or make it tediously slow. These problems make the user feel like a passive participant in their own care instead of an active one. Some have chosen to rely on paying personal caregivers to accompany them at all times since the caregivers might intuitively understand what they need based on experience (Morris et al., 2013). Furthermore, those who are deaf, hearing impaired, or mute, may be able to benefit from greater accessibility of AAC tools as a means of assisted interaction with those who do not understand sign language, the primary form of communication for these communities (Bird and Kusior, 2016).

Another sizable group that can benefit from the use of AAC are those with autistic spectrum disorder. It is estimated that 20–30% of autistic individuals experience limited capacity for speech or are completely nonverbal, while some experts estimate the number is higher (Ganz et al., 2013; Waddington et al., 2016; Weitz et al., 1997), and the prevalence of ASD has been increasing (Gilroy et al., 2017). In the case of ASD, the introduction of a picture-based communication system can significantly improve the individual's ability to communicate (Nunes and Hanline, 2007). For non-verbal autistic children, the most popular/commonly-used low-tech and high-tech solutions are the Picture Exchange Communication System (PECS) (Ferreira et al., 2017) and Proloquo2Go (Sennott and Bowker, 2009), respectively. PECS is a physical solution consisting of a binder with pages of Velcro strips. The children attach cards with pictures to the pages to build the phrases they wish to communicate (Hill and Flores, 2014). Proloquo2Go is an iPad, iPhone, and Apple Watch application with speech generation capabilities that allows users to build sentences using virtual cards. Proloquo2Go improves on its physical counterpart, but drawbacks of this solution include a high cost, $250, and an extensive training cycle in order for the children to use it effectively (Waddington et al., 2016). The efficacy and user preference of traditional versus digital PECS binders were tested in a prior study conducted by Dr. Jennifer Ganz. Results demonstrate that children with ASD were mostly able to independently and correctly use a traditional PECS board but not the digital one. However, two of the three children in the study drastically preferred the use of the app over the traditional PECS system (Ganz et al., 2013). An evaluation of a speech-generating iPad app against traditional picture exchange methods by Lorah et al. also found the majority of participants preferred the app, although preference varied by participant and familiarity with such devices (Lorah et al., 2013).

3. Implementation

The idea for CommBo was initially motivated by first-hand experience with the difficulties experienced by a nonverbal ASD child. The child could not communicate efficiently with existing tools likes PECS. However, the child did engage with an iPad as evidenced by using it to watch videos and play games. After learning that the child's family could not find an affordable AAC solution that ran well on the iPad, the team began work on a simple picture board interface to address this need. Rather than using static images, the effort evolved into a project built around standardized web technologies with low system and connectivity requirements.

This section will discuss the technology stack behind CommBo and covers both basic and advanced features that have been integrated into the interface. In particular, the use of versatile web languages such as Javascript enables flexible interface settings like custom sizes, categories, high-contrast mode, and smart suggestions which leverage machine learning algorithms to adapt to the user. All of these features are

[1] https://www.mycoughdrop.com/

optional, and the user or caregiver can control them as desired or appropriate for their situation. For example, certain low-powered devices like cell phones may benefit from using only basic features while leveraging the local caching mode, which removes the need to be connected to the internet. This unique combination of cost, requirements, and optional settings is intended to make CommBo a high-tech solution with the appeal of low-tech simplicity.

3.1. Technology details

Creating CommBo required careful consideration in the program design and implementation. In order to expedite the development of the project, the basis of the web application uses a MEAN stack as the selected combination of external libraries and APIs. The MEAN (MongoDB, ExpressJS, AngularJS, and Node.js) stack consists of technologies sourced in JavaScript, simplifying development by having one sole language across all components of the application.

MongoDB is a document-based, "NoSQL" database capable of storing non-relational modeled data in a binary JSON format. Simply, this means that there is no required schema for each record in the database in contrast to highly-structured "SQL" databases. This aspect compliments the application's intended dynamic design with the many options offered to its users. MongoDB was also selected for its compatibility with the Mongoose driver as well as its horizontal scalability (Kaur and Dhindsa, 2017). All user information such as login information, user boards, cards, and customizations are stored securely within the database.

AngularJS is a front-end framework which allows for dynamic web pages and complex functionality built on decorated HTML and JavaScript (Aggarwal and Verma, 2018). The application is served by a Node.js backend which uses ExpressJS middleware to handle routing for various static resources. ExpressJS is also responsible for serving CommBo's API which securely handles requests from the front-end.

CommBo makes use of other open source libraries for various purposes throughout the application. For example, CommBo uses bcrypt to protect the users' passwords. bcrypt is a password hashing tool with capabilities in place to mitigate against both (1) rainbow table based attacks via implementation of salting and (2) brute force attacks via increasing iteration counts in order to combat the increasing power of computation. CommBo uses ResponsiveVoice.JS to provide the text-to-speech (TTS) functionality for reading out each card. ResponsiveVoice is a relatively lightweight HTML5 based TTS library capable of reading through virtually any web enabled device using 51 different languages with 168 voices and dialects. The language options will allow CommBo to serve as an AAC device globally.

3.2. Features

CommBo strives for high customizability while maintaining a simply, easy-to-use design. As such, users have full freedom on what text they wish to use for their cards' displayed titles and texts to be read by ResponsiveVoice. Furthermore, the user has a variety of options for selecting the image for the card. As a completely offline option, CommBo supplies a selected set of images consisting of open-source, royalty-free images stored in the CommBo app. To personalize their cards, the users can also choose to upload an image from the device's memory or camera. CommBo also provides the option to import images from the internet through the use of a Google Custom Search Engine API.

To be accessible to users in the developing world with potentially limited internet access, CommBo utilizes caching to store the web application on the user's device. As a result, though the user needs internet access to install the app, the user will be able to use CommBo entirely offline.

3.3. Machine learning

CommBo offers users context-driven card recommendations based on frequency and time of use. This numerical data is driven and collected within the application itself and is fed into a custom machine learning system to generate predictions. To accommodate the needs of users with ASD, the machine-learning suggestions occupy the top row of each page. This consistency in location avoids needlessly challenging the user's ability to effectively use the application (Tang and Winoto, 2018). This feature can be turned off according to the preferences and needs of the user.

To provide more detail, CommBo includes a recommendation engine based on nearest-neighbor clustering, similar to click-based (Adeniyi et al., 2016) or active learning (Bu and Small, 2018) recommender systems. Each time a card is clicked, the interface triggers a call to the backend engine to update its internal "ranking" of cards for suggestion. The ranking is determined using clusters based on the time of day and number of clicks. Fisher–Jenks algorithm (Fisher, 1958; Jenks, 1977) partitions these features into ideal clusters so that an optimal collection of relevant cards is available for any given time of day. Then, the final selection, or rank, of cards is based on their minimum distance to the current time of day, considering their frequency. If the suggestion feature is enabled, they will appear in order of rank along the top row of the interface. In addition to proximal separation by being along the top row, a black underlay is applied to visually delineate these cards from the standard ones.

Fig. 1 demonstrates a greatly simplified example of how the suggestion feature works. Each time a user clicks a card, it is updated internally to reflect the appropriate frequency for that time of day. These values can be thought of as a scatter plot, which is optimally divided into regions of the day based on Fisher–Jenks algorithm. As Fig. 1 shows, some parts of the day may be less active than others, so the resulting "breaks" will window the recommender to select appropriate cards close to the current time. In this case, the *snack* card may be added to the suggestion for this time of day.

Suggestions can be more or less important depending on screen size and number of cards. For instance, if the user is on a phone or if the categories are using multiple tabs, the suggestions row along the top can be very useful and save time and effort.

4. System Walkthrough

CommBo is designed to be a universal product. Capable of being deployed in both the home and medical environments, the application is designed with several user classes: independent users, dependent users, and caregivers. Independent users (IUs) comprise those users capable of managing their own information and communication boards. In contrast, dependent users (DUs) are incapable of managing their own accounts, usually due to a form of motor or cognitive impairment, and therefore rely on a caregiver to manage their communication boards for them. Caregivers may be parents, guardians, or medical professionals responsible for one or more DU. Based on initial setup, the user designates themselves as an independent user or a caregiver.

CommBo is relatively intuitive to use and easy to navigate. On the initial screen of the application, the user will presented with the login screen where the user can choose to create an account or log in to an existing account. This page has the features of detecting incorrectly formatted inputs as well as missing data fields. During account creation, the user is asked to designate themselves as a caregiver or an independent user.

A caregiver will be prompted to enter their name, then enter their dependent user's name, and lastly have their user complete an onboarding assessment. An independent user will immediately be taken to a board with preset images and tabs. This allows for quick and easy access to a fully-functional picture board (Fig. 4).

The on-boarding assessment determines the size of the cards and

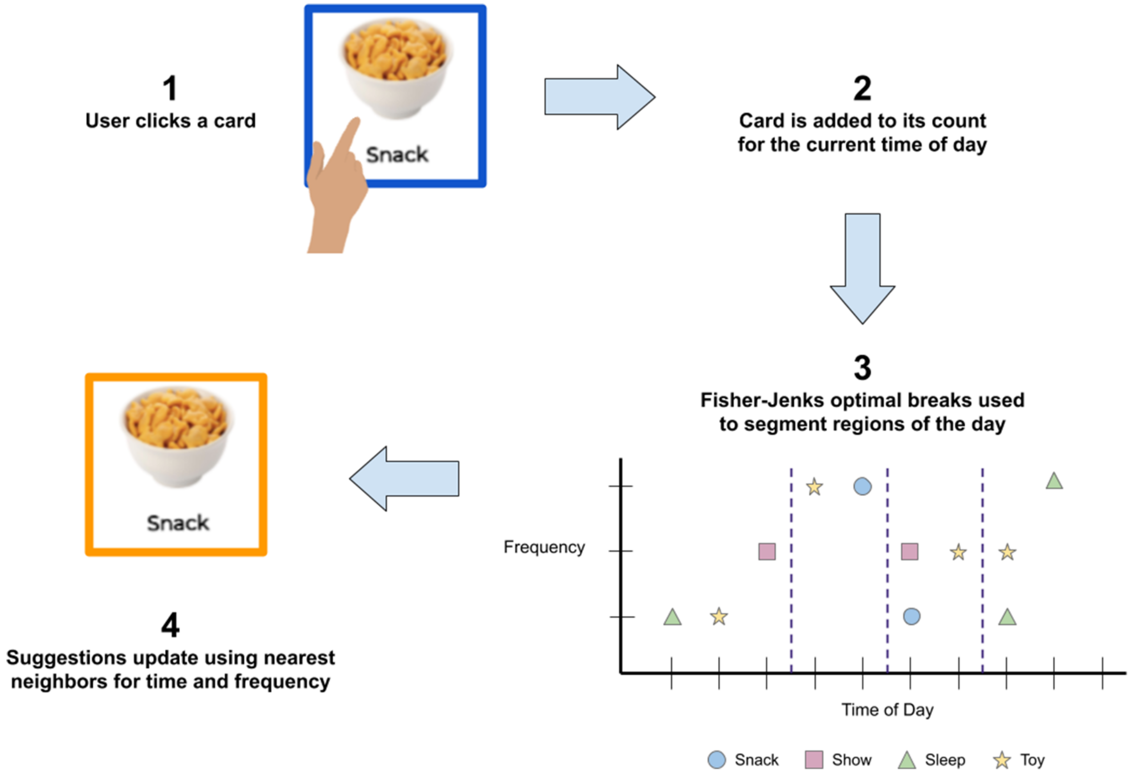

Fig. 1. A very simple flow chart showing how the user click generates an updated representation of the time and frequency features used to determine a card's rank.

which card organization features to use based on the user's abilities. The cards will be the smallest size that the user can adequately and consistently select and identify in order to maximize the options available. The first step of the assessment consists of the user selecting the highlighted card (Fig. 2). With each successful attempt, the cards get smaller and more cards are added. This phase tests the user's motor skills and ability to identify a card in various positions. If the user cannot successfully and consistently locate the cards, then the card suggestion feature is turned off. The next step of the assessment tests the user's categorization skills (Fig. 3). If the user cannot successfully categorize cards, then the category tabs feature will be turned off. When categories are disabled, all of the cards are displayed on a single screen that the user will navigate via scrolling.

Often, the preset options will not suit every need of the user. As such, the user can change the available options in the board settings. To access the board settings, the user presses and holds the settings gear icon in the lower right corner for 2 s. This is designed to protect the board from unauthorized changes and accidental access.

Once in the settings menu, the user is able to toggle various settings like enabling intelligent suggestions, high contrast mode, or simply editing the cards or tabs on the board (Fig. 5). In edit mode, the user can click and drag a card to its new position. Furthermore, a user can click on the pencil icon located at the top right of the card (Fig. 6) and change the card title/card image/card phrase (Fig. 7). The card image can be changed by simply clicking on the image and selecting the mode of change: take photo, select from library, or browse. Additionally, the spoken word or phrase for each card can be customized (Fig. 8).

When the *speak cards when pressed* setting is turned off in the settings menu (Fig. 5), the card queue feature is turned on. Instead of cards immediately sounding when pressed, the user can queue a sequence of cards at the bottom of the screen. When the user presses the play icon, CommBo will read the sequence of cards in the specified order. The user can remove queued cards by pressing the exit icon.

5. Design validation

Before evaluating CommBo in user studies, we collected feedback on the initial design from professionals such as teachers, physicians, and

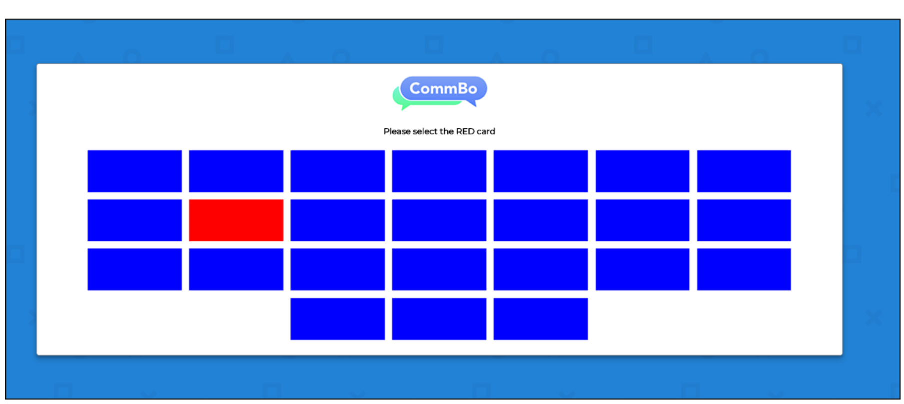

Fig. 2. User onboarding tests for cognition and motor impairment.

Fig. 3. User onboarding tests for cognition and mental impairment.

speech-language pathologists who have practical experience working with communication boards and other AAC systems. Specifically, we worked with Erich Rainville, a seasoned user experience designer; and Dr. Julie Thompson, an assistant professor and researcher of Educational Psychology with an emphasis in special education. With their aid, we were able to refine the user interface and experience. We improved our methods for evaluating an individual's tolerances to font size and the minimum card size, redesigned the manner in which the intelligently selected cards were displayed, and made sure that CommBo was capable of meeting their specifications as professionals who work with AAC devices.

5.1. User study design

To ensure that CommBo improves the communication skills of those with learning disabilities and communication impairments, we conducted comprehensive user studies. Participants were recruited via word-of-mouth and email advertising. We tested CommBo with three individuals who have one or more of the following conditions that impede verbal communication: ASD, stroke-induced aphasia, deafness, muteness, or a learning disability. The study consisted of six different phases: a pre-testing phase, an observation of the participant's current methods, a mid-study interview phase, a CommBo learning period, an observation of using CommBo, and a final interview. This design gives opportunities for breaks to help avoid user fatigue during the study; additionally, always evaluating CommBo second puts CommBo at a disadvantage with respect to frustration evaluation.

The study pre-test phase asked users and caregivers about their experiences with individuals with speech impairments as well as AAC systems they have interacted with. This was accomplished through a combination of a written survey and a semi-structured interview. The user and/or caregiver began with the survey to gather information about their demographics and use of AAC devices. Questions included what features they look for in an AAC device, the length of time needed to communicate and levels of frustration with their current AAC methods. Most of these questions were open ended and qualitative, but frustration with past experiences with AAC systems was defined quantitatively through the NASA Task Load Index (TLX). The TLX measures the burden of a task on a user on the scale 1–20 in 6 different areas of interest. As such, TLX serves as a method to compare various AAC solutions. To a similar effect, the semi-structured interview was used to discern what kinds of AAC devices the participants had used,

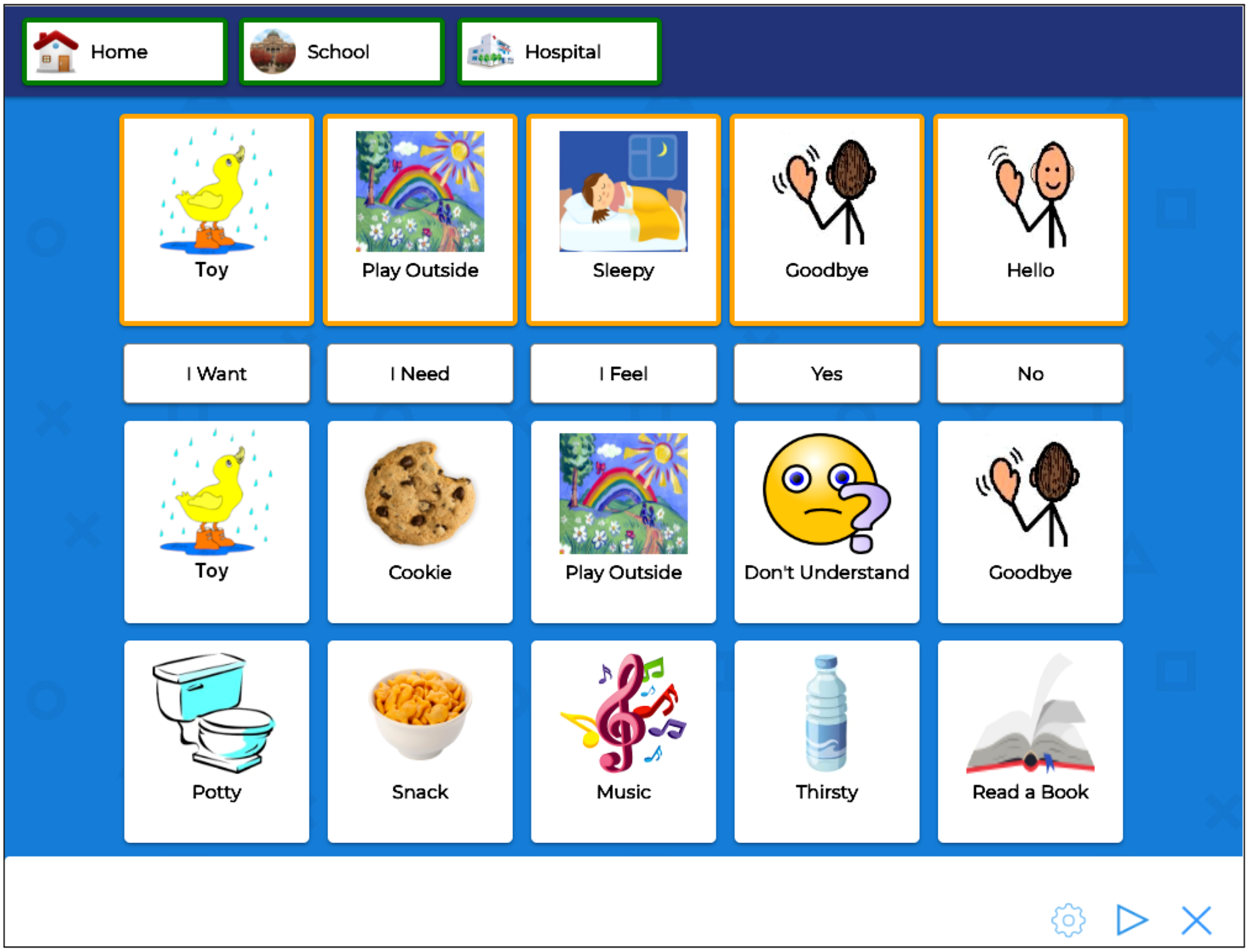

Fig. 4. Example user board.

how effective the devices were, what the participants liked and disliked about them, and whether there were any conditions with regards to their abilities that we should be aware of during testing.

After the pre-test phase, the study progressed into the first observational phase. Participants were instructed to select the communication methods they use on a daily basis. Their selections served as a baseline for the remainder of the study. This observational period, performed over the course of several hours, measured key indicators of the AAC devices' efficacy. These included time to communicate each idea, the number of incorrect or otherwise unintelligible communications made, and the level of frustration experienced by either party as perceived by the observer.

Following this session, participants entered the mid-study interview phase. This semi-structured interview gathers information on specifically how long the user and/or caregiver perceived the communication took, their levels of frustration, and other details about their experience in the observational phase (i.e. whether anything was abnormal). This format gave us the freedom to discuss the users' experiences and factor the results into the design of CommBo.

In the next phase, participants were introduced to CommBo. Caregivers and independent users were guided through the process of creating their accounts and, where necessary, setting up profiles for dependent users. The demonstrating researchers showed them the board's capabilities and features such as speech generation, card content and size manipulation, and the intelligently suggested cards. The researchers remained as a resource and observed the interactions users had while personalizing the board for themselves or their dependent user. Once the profiles and boards had been set up, a period of at least one hour was given for the users to learn how to interact with and use the boards as a communication tool. This provided time for the participant to better understand how the product works and how effectively it would work for them. Participants received more time based on their needs to guarantee that they had ample time to understand the device.

Once the user had gained sufficient familiarity with CommBo, we proceeded into the next observational phase. This observational exercise used the same format as before with regards to time frame and collected metrics, but this time the participant's used CommBo instead of their device of choice. This allowed the resulting observations to be directly compared against the individual's previously established baseline.

Lastly, we moved into a concluding interview. This interview gauged the participant's experience with and attitude towards CommBo to establish whether the application improved over the other devices they use. Furthermore, the interview allowed the participant to express any shortcomings or deficiencies in the application for the purpose of improving it in later iterations.

5.2. Preliminary user studies

Before conducting user studies with members of the target population, the design of the interface needed to be tested to ensure that there were no functionality bugs. The results of these user studies do not indicate the effectiveness of CommBo as an AAC device: they only validate the design from an HCI perspective.

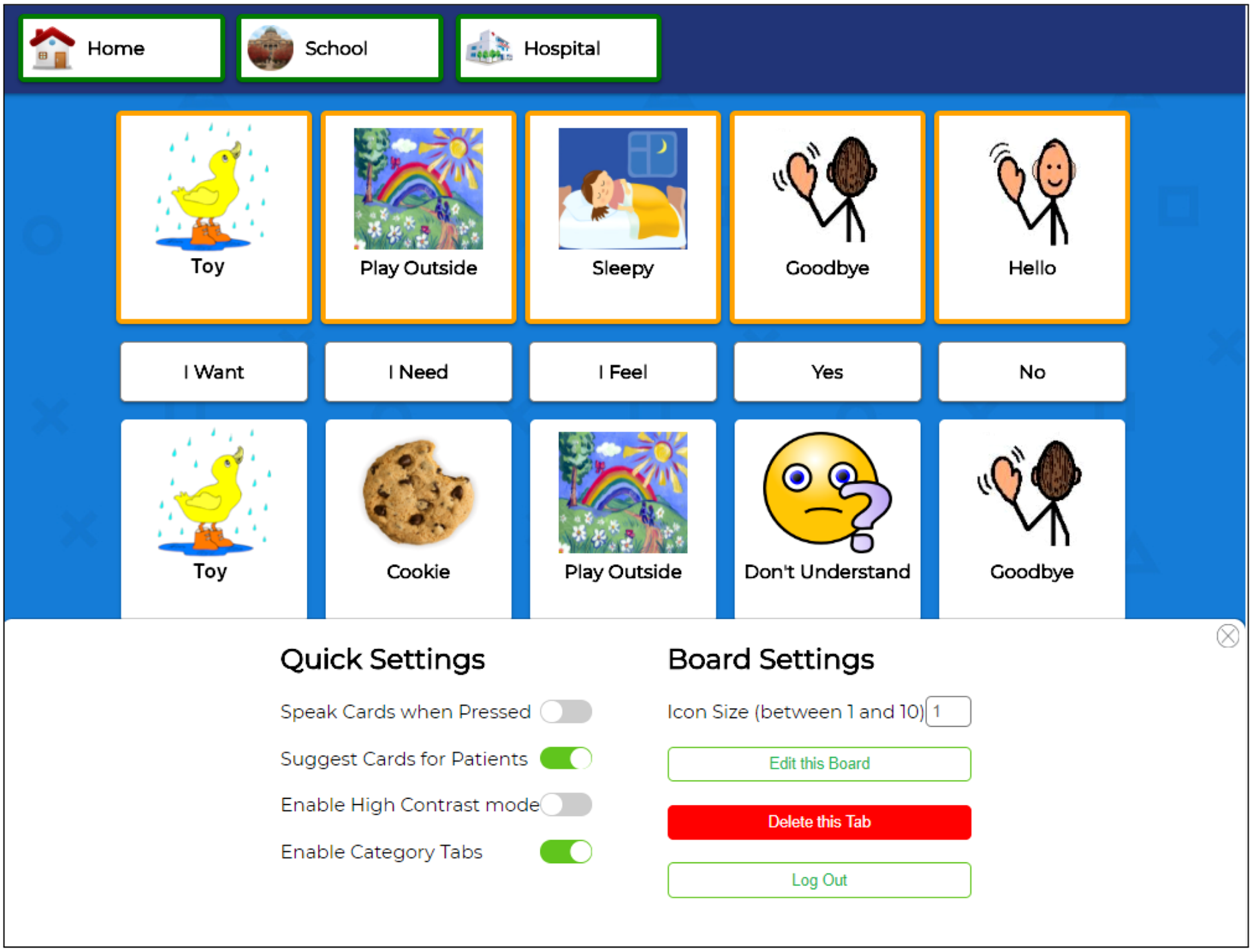

Fig. 5. Board settings.

5.2.1. Scott

Scott is a non-disabled male, and his name has been changed at his request. He has experience with communication technology and three different types of AAC devices: Dwell-click, Teletypewriter (TTY), and brain-computer interface. For this reason, he was asked to perform a user study to give feedback on CommBo's design.

For the sake of comparison, Scott was consulted on the frustration levels of the AAC methods he was familiar with. He scored them at a 4 on a scale of 10. Explaining his score, Scott describes the interactions as slow but effective: it takes roughly one minute for the user to convey a need. He also commented that frustration in communication most often occurs when the user tries to convey uncommon needs as those needs often are not represented in AAC devices with limited expressiveness.

During the first observational phase, Scott was asked to convey three needs with a traditional picture board. He found the communication process to be difficult, frustrating, and slow. He attributed this to the small images and the lack of categorization. Additionally, he pointed that some of the cards' images did not adequately correlate with the cards' titles, causing ambiguity.

After Scott familiarized himself with using CommBo, the study moved onto the second observational phase, and Scott was asked to convey three new needs. In the post-study survey and interview, Scott expressed that he felt less frustration using CommBo than any of the prior communication devices he had experience with, scoring it at a 2 on a scale of 10. Furthermore, he emphasized how it took just seconds to convey a single need as opposed to the one minute timeframe he gave in the pre-study interview. He praised the systems text-to-speech API and adjustable card size. On the contrary, he expressed concern for wasted space around the edges of the screen as well as the lack of uniformity in the organization of the cards. Lastly, Scott suggested offering a wider selection of text-to-speech voices to accommodate age and gender of users.

5.2.2. Additional participants

To fully vet CommBo's design, eight non-disabled individuals were asked to participate in the user study. The ages of the participants ranged from 21 to 27 years old. The majority of these participants had no experience communicating with people with speech impairments. These participants were asked to simulate a non-verbal user by refraining from speaking and each was paired with a communication partner. To emphasize, these results do not reflect how effective CommBo is for an actual non-verbal user; this request is to ensure that the participants communicate only using CommBo.

The participants were asked to convey three ideas with a traditional picture board and three new ideas with CommBo. For these studies, each participant received the same set of six ideas in different orders. These ideas consisted of the following: *ball, bathroom, cold, cookie sleepy*, and *thirsty*. To illustrate the method, one participant could be given *sleepy, cold*, and *ball* for the traditional picture board and *cookie, bathroom*, and *thirsty* for CommBo. In contrast, another participant could be given *bathroom, thirsty*, and *cookie*; and *cold, ball*, and *sleepy*. This method makes the results directly comparable while avoiding ordering bias.

The mid-study interviews revealed that the hardest part of communicating with a traditional picture board was finding the right corresponding image. 87.5% of the participants explicitly stated that the size of cards made using the picture board difficult. Furthermore, 50%

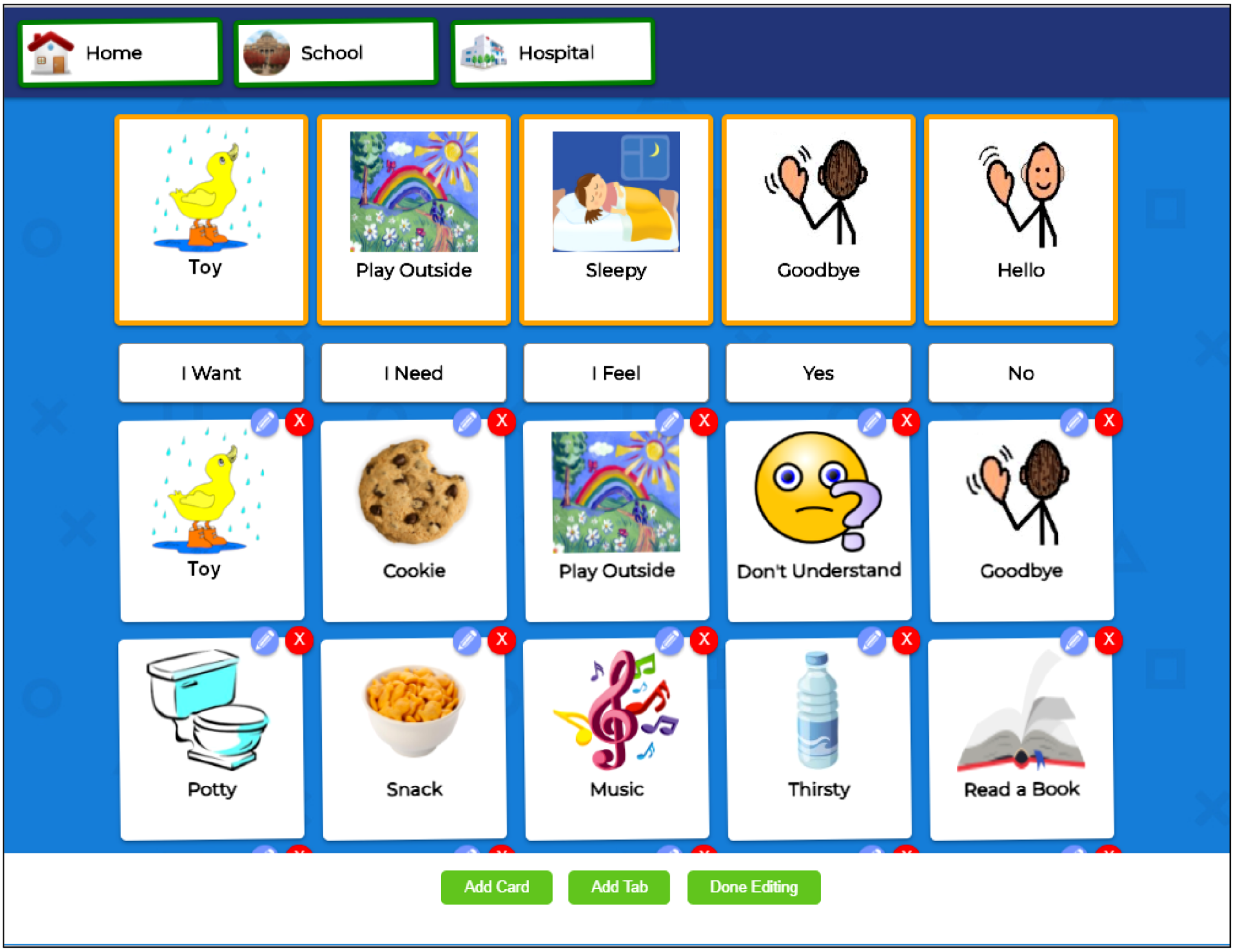

Fig. 6. Edit board view.

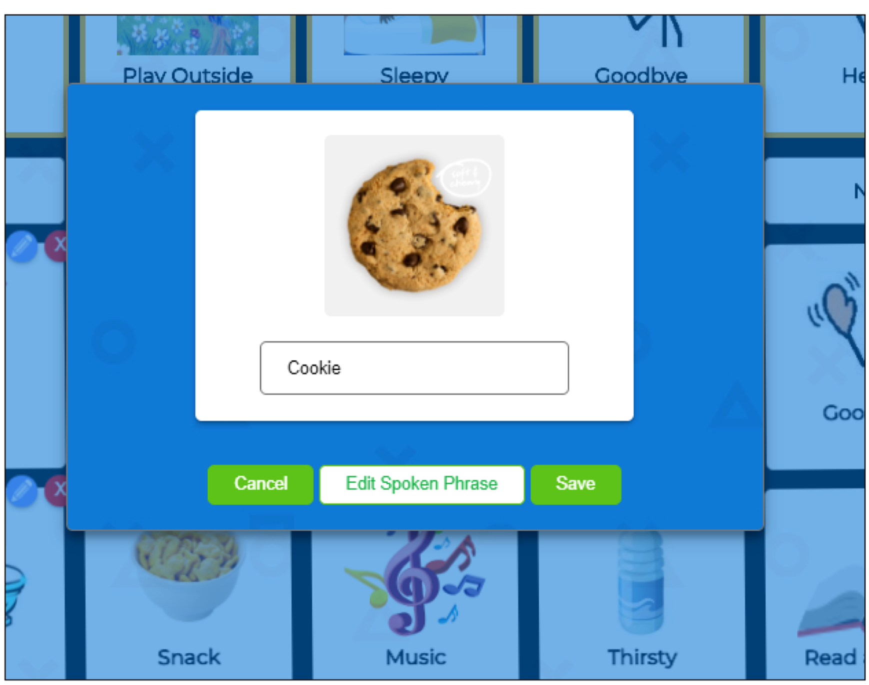

Fig. 7. Add/edit card.

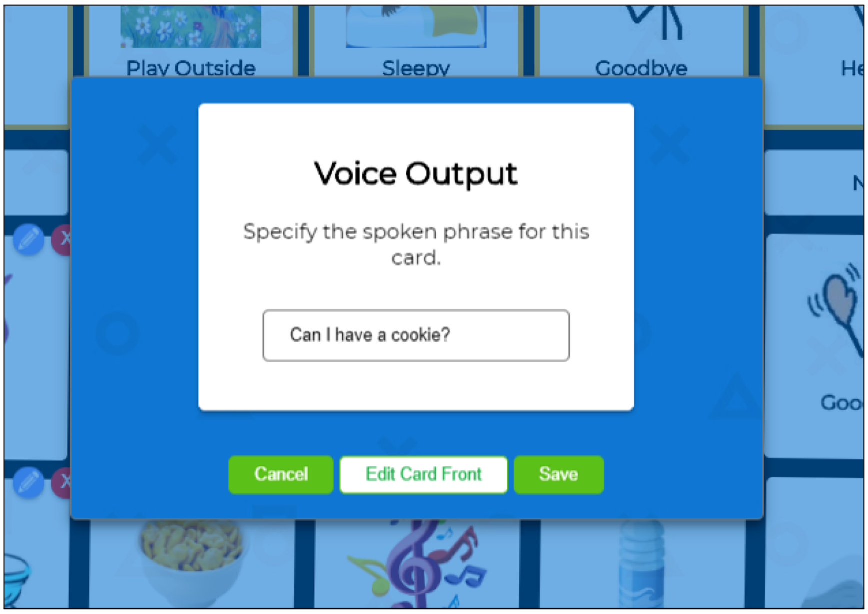

Fig. 8. Adjusting a card's spoken phrase.

of the participants stated that the lack of categorization complicated the communication process. Out of all of the participants, only one expressed a lack of frustration when using the traditional picture board.

At this point, the participants familiarized themselves with CommBo and moved onto the second observational phase to communicate their other three ideas. The post-study interviews indicated that 100% of the participants found CommBo to be an effective mode of communication, preferential to a traditional picture board. With that said, 62.5% of the participants stated that the text-to-speech API and the customizable design were amongst the main reasons they preferred CommBo over the alternative. Only one participant had a major dislike about the system: trade-off between icon size and the need to scroll. This is a design problem inherent to this type of system: small icon size allow more options to be displayed on-screen at once at the cost of the size reduction. CommBo tries to mitigate this issue with its tab system to maximize size and minimize the need for scrolling. In the post-study survey, the average frustration level using CommBo was a 1.5 on a scale of 10. 75% of the participants indicated that they felt they could express their needs within five seconds. Every participant agreed that CommBo resulted in quicker communication than the alternative. Feedback for the design of CommBo included a color-blind mode and a keyboard option for the user to type a message to be spoken by the text-to-speech API.

6. Target user evaluation

CommBo was evaluated with an autistic child, Briana; an adult with autism spectrum disorder, Charles; and an adult with stroke-induced aphasia, Todd. Briana and Todd use AAC devices while Charles does not. Note that participant names have been changed to protect their identities.

6.1. Briana

Briana is a 16-year-old female child who is completely nonverbal and incapable of communicating thoughts or needs to those around her. Briana has a moderate motor impairment and a high cognitive impairment. The study was conducted in her home with her parents who are her caregivers and communication partners. In the pre-test survey, her mother stated that her closest diagnosis is autism spectrum disorder, but her school has labeled her as having a cognitive disability due to her low IQ. Briana and her parents have some experience with traditional picture boards as well as the PECS system. However, they did not experience success with either system due to the system's respective limitations. Although Briana was capable of comprehending the use of the PECS system, it was difficult for her to manipulate and keep track of the many physical cards. Furthermore, the binder was cumbersome to carry around, making consistent use difficult. Briana's school implements traditional picture boards, but Briana has not found much success with them. This in turn hinders the progress Briana had previously made: she still struggles to express intended ideas. With that said, Briana and her mother do not currently use any type of AAC communication device. Briana's mother must periodically take measures to effectively care for Briana (e.g., she must take Briana to the bathroom every couple of hours). Because she is completely non-verbal and utilizes no signs or gestures to communicate anything, the investigator and her parents felt that the initial observation period and mid-study interview would yield no results. For this reason, the average time to communicate and number of communication errors were taken to be infinite, and Briana went immediately into the CommBo learning phase from the pre-testing phase. Notably, Briana's mother rated the perceived frustration of communication at a 5 on a scale of 10. This is due to the tedious nature of needing to periodically complete tasks even though Briana did not currently need to partake in the associated action.

Due to the nature of Briana's condition, the CommBo learning phase underwent minor modification so that Briana could be be trained on how to use the application. The investigator turned off the machine-learned suggestions and the tabular format as Briana's mother and the investigator felt that Briana would benefit most from the system if only the necessary features were turned on. Additionally, Briana's mother engaged her in learning how to use the application while the investigator simply observed instead of the investigator providing discrete suggestions to Briana.

When Briana could effectively interact with the application, her mother and the investigator used her response to the pressed cards as the signal on whether Briana had successfully communicated her need with CommBo. That is, positive responses were taken as indication that she had effectively expressed her need and negative responses meaning that she expressed something other than the intended need.

At the beginning of the CommBo instructional period, Briana was asked by her mother to identify various objects on the screen. Briana identified the first object with ease. From there, Briana's emotional state fluctuated and inhibited her ability to consistently identify the object. With time, Briana had improved to the point where she could consistently identify objects her mother had asked her to identify. This whole process took approximately ten minutes.

The next step in the instructional period was to have Briana click on cards associated with objects that she wanted. For the purpose of the study, a bowl of Goldfish crackers was used as an incentive. When Briana clicked on the *snack* card, her mother would give her a single Goldfish cracker. It took approximately fifteen minutes for Briana to effectively express a single desire. This same process was repeated with the *ball* and *drink* card. At the end of the instructional period, Briana was able to communicate a single desire by clicking the corresponding card in approximately two seconds per attempt. That is a huge improvement considering that she was unable to communicate any desire before-hand.

During the post-test survey and interview, Briana's mother expressed very positive results. She indicated that Briana's perceived frustration of using the application was a 1 on scale of 10, 1 being the lowest level of frustration. During the interview, she expressed that the low perceived frustration was due to Briana's willingness to learn and use the system. Briana's mother went on to praise the system's customizability as well as the text-to-speech feature. She believed that the text-to-speech was a primary contributor to Briana's willingness to use the application. Briana's mother went on to praise the portability of the system as CommBo can be used on any of the electronic devices that they currently own. On the other hand, Briana's mother expressed the need for adjustable icon sizes. This feature was later implemented. The results of Briana's TLX surveys can be seen in Fig. 9.

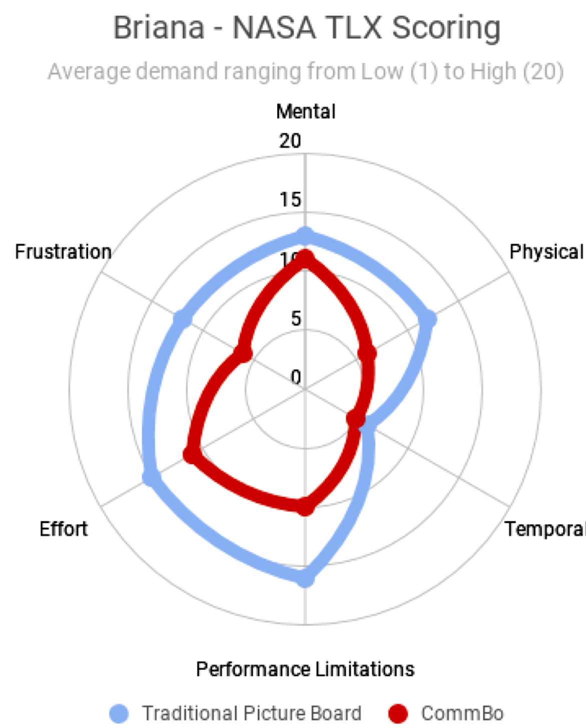

Fig. 9. Briana's NASA TLX comparisons. Lower is better.

6.2. Charles

Charles is an 22 year old male with autism spectrum disorder. Charles is an independent individual capable of speech, and he does not currently rely on AAC methods. However, his user study was highly beneficial in gauging cognitive understanding of the application in the realm of ASD. He was asked to refrain from speaking in order to simulate a non-verbal user.

For the first task, Charles was paired with another individual to communicate with using a traditional picture board. Charles secretly was presented a set of three ideas to communicate: *sleepy, bathroom*, and *cookie*. These ideas represent standard needs or desires for an individual to communicate. The *cookie* idea highlights the lack of expressiveness of the board as it lacks that specific card. Charles first chose the *eat* card to communicate *cookie*, but trying to bridge the gap between the two ideas made the communication effort confusing to both parties.

The mid study interview revealed that Charles felt unsuccessful in his communication attempts with the traditional picture board. The lack of categorization of the picture board made communication difficult for him. Furthermore, he felt hurried in communicating each idea despite the lack of time-keeping during the task. Despite these negatives, Charles felt that the mental and physical demand of the test was relatively low.

Charles moved onto the CommBo instructional phase and gained insight to how the application works and the corresponding features. He was given a new set of ideas to communicate: *cold, potty*, and *ball*. Charles's experience with CommBo was immediately less frustrating than using the picture board. In fact, he scored his frustration at a 1, the lowest level, during the post-study survey. Supporting this, he also found the communication process to be faster with CommBo. During the post-study interview, Charles expressed his admiration of the machine-learned suggestions, tabular format, and text-to-speech API. He criticized how some of the cards overlapped with each other, but this can be easily avoided with the customizable interface of the system. The results of Charles's TLX surveys can be seen in Fig. 10. With the exception of physical demand, Charles felt that CommBo was superior on all scales.

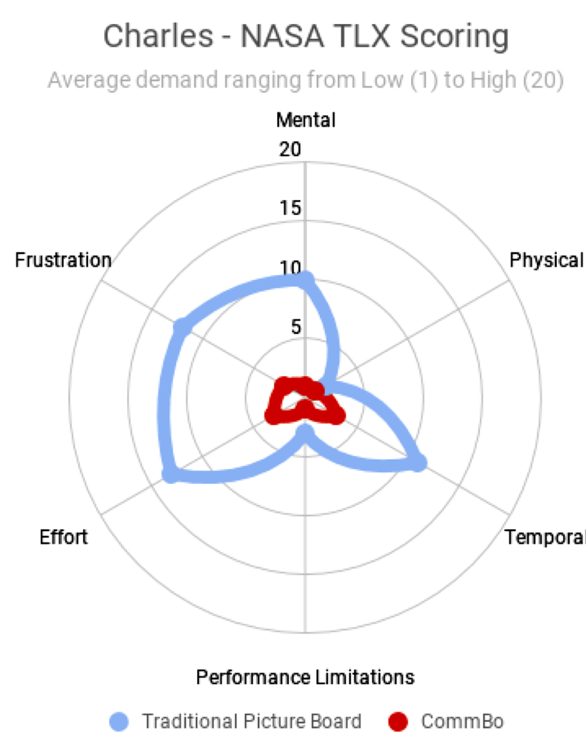

Fig. 10. Charles' NASA TLX comparisons. Lower is better.

6.3. Todd

Todd is a 70 year-old male who has suffered from two strokes in the last couple of years. Todd possesses high motor impairment and little cognitive impairment. Although he can communicate simple ideas verbally, he struggles extensively to articulate words and phrases. Because of that, he currently uses a traditional AAC picture board to communicate. This device has been an essential tool for him since he began rehabilitation after his first stroke. He lives with his wife who also serves as his caregiver. The pre-test survey indicated that Todd and his wife feel large amounts of frustration, 8 on a scale of 10, when using traditional picture boards. The pre-test interview indicated that this frustration stems from the low customizability and the tedious nature of his wife needing to be standing beside him to receive the expressed desire.

In the first observational period, Todd used a traditional picture board as his chosen AAC device. With Todd's wife out of the room, the investigator discreetly asked Todd to communicate the following three needs to his wife: *cold, sleep*, and *thirsty*. From the perspective of the investigator, communication using the traditional picture board was very difficult. It took Todd a couple of minutes to convey each communication need to his wife. This was primarily due to his high motor impairment, e.g. his inability to fully straighten his finger, and the small text and images on the traditional picture board.

Todd and his wife expressed a significant amount of frustration with the communication process in the mid-study interview. The picture board did not contain very many pictures relevant to Todd which seemed like a waste of space. Todd's wife felt that the lack of personalization made communication difficult. Expanding on this, she noted that adding cards to represent particular individuals in their lives would be very beneficial as determining who Todd was trying to talk to was difficult in past communication.

Next, the investigator showed Todd and his wife how CommBo works and the corresponding features. Similar to before, Todd's wife left to room for the investigator to give Todd three communication needs: *ball, cookie*, and *bathroom*. The investigator observed that the communication process appeared simpler yet still not fluent. Communication sped up to about a minute per communication need. However, Todd's high motor impairment still impacted his ability to use the device. Because of his inability to straighten his finger, other parts of his hand often would simultaneously touch the screen, preventing the system from recognizing the tap on the targeted card. CommBo's adjustable card size feature better accommodated Todd's poor eyesight, helping him identify the card he was searching for.

During the post-test survey and interview, Todd and his wife expressed decently positive results. The frustration in using CommBo scored at a 5 on a scale of 10, improving over the one for the traditional picture board at a 5. As mentioned, communication took about half of the original time to convey a need. The couple praised the customizability of the application and expressed a need for disabling the zoom capabilities of the application to prevent unintentional interactions with the board. He did not make use of any machine-learned suggestions. The results of Todd's TLX surveys can be seen in Fig. 11.

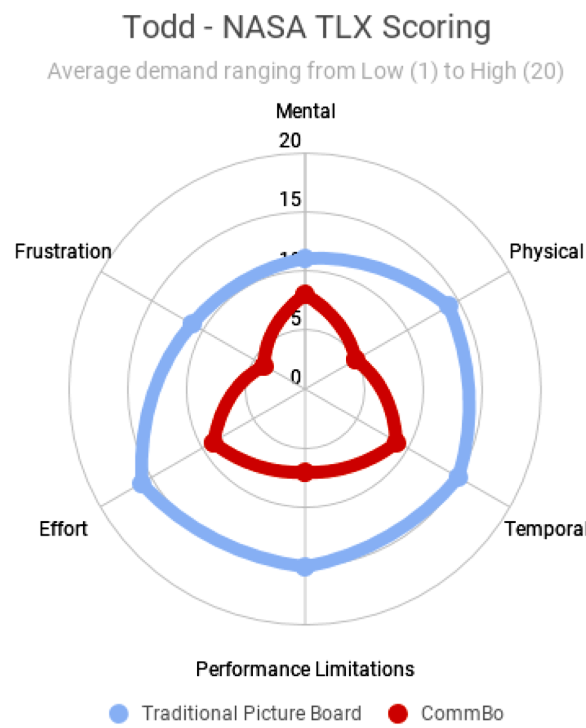

Fig. 11. Todd's NASA TLX comparisons. Lower is better.

7. Analysis

The user study participants who are amongst the major groups who use AAC devices found CommBo to be an improvement over traditional methods. For Briana, existing solutions such as the PECS system and the traditional picture board have problems that prevent her from successfully adopting them. Her caregiver, Briana's mother, notes that these systems either fail to engage Briana or are difficult for her to manipulate. CommBo, on the other hand, intrigued Briana because of how the text-to-speech API enabled Briana to "speak" by interacting with the screen. Charles, who has no speech impairment, found that CommBo's features were accessible to those with autism and that using CommBo was equally or less demanding than a traditional picture board in all aspects. Todd has used traditional picture boards since he began rehabilitation due to a stroke. Using CommBo required less physical demand thanks to its adjustable card size and fixed the lack of customization present in his current methods. While we received some positive qualitative feedback about the machine-learned suggestions, they were not as heavily utilized as other features like zooming and the ability to organize the cards into categories that made using CommBo faster and easier than a traditional board.

CommBo's average NASA TLX scores for the two individuals who use AAC devices were lower than those for the traditional picture board as shown in Table 1. To determine the significance of this difference, a two-tailed t-test was performed for each type of demand with 2 degrees of freedom as given in Table 2. Physical Demand, Performance Limitations, Effort, and Frustration were all statistically significantly lower with $p < 0.05$. Mental Demand and Temporal Demand were not significant; this is understandable as CommBo uses the same communication style and still possesses the physicality of being a board. The organization and suggestion features and adjustable card sizes reduced the effort and physical demand, but it still takes attention and time to select cards. That said, the mental and temporal demands are still lower with CommBo. With these things in mind, it can be concluded with high confidence that CommBo is less demanding to use than a traditional picture board.

8. Future work

CommBo's base functionality is largely complete, but there are many aspects to be improved. Firstly, we should perform a more detailed evaluation directly on the system's machine learning capabilities. As in Briana's case, the intelligent suggestions may not be useful for everyone as they could be either distracting or confusing. We included an ability to toggle such extended features on or off depending on the user's preference, but we would like to further explore how users interact with and make use of machine-learned suggestions. Beyond an extended evaluation, the machine learning algorithms could be expanded to make suggestions more precise. This includes adding geolocation, specifically geofences, to make the suggested cards more suitable to the present environment. For example, the system could suggest cards based on current location in an optional tab. Secondly, speech generation could be expanded to include multiple voice and dialect options, potentially even offering a way to implement voice recordings for further personalization. Thirdly, providing robust image searching and storing functions would be a helpful tool. Finally, with data from more users, the account creation process could include options for the starting board configuration.

Table 1
NASA TLX score comparison for AAC users.

Briana		Mental	Physical	Temporal	Performance	Effort	Frustration
	Picture board	13	12	6	16	15	12
	CommBo	11	6	5	10	11	6
	Percent change	**15. 4%**	**50%**	**16. 7%**	**37. 5%**	**26. 7%**	**50%**
Todd		Mental	Physical	Temporal	Performance	Effort	Frustration
	Picture board	11	14	15	15	16	11
	CommBo	8	5	9	7	9	4
	Percent change	**27. 2%**	**64. 3%**	**40%**	**53. 3%**	**43. 8%**	**63. 6%**

Table 2
Results of two-tailed *t*-test comparing the average NASA TLX ratings for participants who use AAC devices. Statistically significant ($p < 0.05$) metrics are highlighted in bold.

NASA TLX metric	**Average score**		***p*-value**
	Traditional	CommBo	
Mental demand	12	9.5	0.2999
Physical demand	13	5.5	**0.0215**
Temporal demand	10.5	7	0.5510
Performance limits	15.5	8.5	**0.0474**
Effort	15.5	10	**0.0389**
Frustration	11.5	5	**0.0283**

9. Conclusion

The ability to communicate is a human right and is essential for an individual's mental health. AAC systems enable those who cannot communicate verbally to communicate meaningfully. Most AAC systems, however, either lack the flexibility to customize according to the user's needs or are prohibitively expensive while still providing only a limited feature set. Additionally, many AAC users feel that the current solutions are too slow, making communication tedious (Morris et al., 2013).

CommBo is a high-tech, speech generating picture board that mitigates the shortcomings of existing solutions by offering a large suite of features while also being highly customizable. To ensure that the board has the necessary vocabulary for situational contexts, CommBo allows users to create their own cards with customized images, labels, and voice outputs. This design feature also allows the users to view the communication as being from themselves instead of just a generic machine output. Instead of the user having to dig through multiple menus to find what they want to communicate, the cards can be categorized and CommBo uses machine learning to appropriately suggest cards based upon time and frequency of use. This makes communication faster and simpler by placing what the user will need right in front of them.

To evaluate CommBo, two people who use AAC devices in their daily lives participating in an in-depth user study to compare using a traditional picture board to using CommBo. The results showed that CommBo was the preferred choice. CommBo was less demanding mentally and temporally, required less effort, caused less frustration, and had fewer performance limits than the alternative traditional picture board for our test group. The overall response was positive, especially amongst the participants who use AAC devices.

Alongside other advances in high-tech AAC applications, CommBo has the potential to improve the lives of people with speech impairments. It is extremely accessible as it can be used on any device with a web browser and does not require a constant internet connection. It has a flexible interface, accommodating the needs of its users while remaining easy to use even for people with motor impairments or learning disabilities. It improves on existing, similar solutions thanks to its high customizability and its card suggestion system that make communicating significantly faster and less frustrating.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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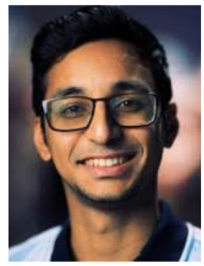

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