Improving an SSVEP-Based Brain Computer Interface Speller

By

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Abstract

MAC KENZIE FRANK, Improving an SSVEP-Based Brain Computer Interface Speller

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A brain-computer interface (BCI) is a novel technology that creates direct assistive communication between the brain and a computer. While numerous electroencephalogram (EEG) based BCI-speller applications have been used for communication by adults with physical disabilities; few BCI studies have included children, and none using BCI spellers. A pilot study of a developmentally-appropriate EEG-based speller-storybook interface that relied on steady-state visual evoked potentials (SSVEPs) by two pediatric users with quadriplegic cerebral palsy showed limited speller reliability (E. Floreani, personal communication, September 30, 2021). In the pilot study, the alphabet was parsed between three boxes, each flashing at a different rate (6Hz, 7.5Hz, 10Hz). The users attended to the box containing the required letter, and the BCI interpreted the resulting fluctuations in the EEG to make the selection. The present study sought to improve BCI speller-storybook reliability by improving stimulus timing and by adding auditory feedback. Speller performance was directly correlated with stimuli reliability but there was no significant difference in the average selection time or accuracy for the auditory-visual versus visual conditions. Nevertheless , auditory feedback may still yield an important addition for impaired participants. The results also suggest the speller is more reliable since participants could complete all the trials. Future work will involve testing the auditory-visual feedback condition for impaired participants. An updated speller-storybook interface with improved reliability still may provide a new educational tool to acquire literacy skills for pediatric users with complex communication disorders.

Improving an SSVEP-Based Brain Computer Interface Speller

Communication serves to increase the quality of life and is important for everyone to have the ability to express their wants and needs (Felce, 1995). The American Psychiatric Association estimates that 10% of all Americans experience some sort of communication disorder across the lifespan (American Psychiatric Association, 2013). This includes children (CDC, 2015). These communication disorders can result from damage to the brain or other parts of the nervous system (American Psychiatric Association, 2013). A brain-computer interface (BCI) creates a direct link between activity recorded from the brain and an external device-typically a computer (Wolpaw et al., 2000), and can be achieved without the need for any muscular control (Rezeika et al. 2018). In these systems, neural signals can be acquired from non-invasive techniques such as electroencephalographic (EEG), magnetoencephalography (MEG), and functional magnetic resonance imaging (fMRI); or invasive techniques like electrocorticography (ECoG), (McFarland and Wolpaw, 2017), but EEG BCI systems are most commonly used because of the lower cost and hardware portability (Chuang et al., 2019).

The electroencephalogram (EEG) shows changes in brain activity useful for diagnosing brain conditions. Electroencephalogram is a test that measures electrical activity in the brain using small metal discs (electrodes) attached to the scalp (Barlow, 1993). Different EEG paradigms can be used to control a BCI such as: the P300, motor imagery, and Steady State Visual Evoked Potential (SSVEP; Amiri et al., 2013). Steady state visual evoked potentials consist of flashing visual stimuli at a set frequency that, when attended, produces oscillations in the EEG over the occipital cortex at the same frequency as the flashing stimulus (Zhang et al., 2021). These signals (SSVEPs) are then processed and translated into commands by the BCI system to, for example, control a robotic arm, an exoskeleton, a wheelchair, a robot, or can be used to translate signals to spell words in speller applications(Zhang et al., 2018). Importantly, SSVEP BCI systems can reach high levels of action accuracy after a short training period (Guger et al., 2012),. Most germane for the present study, high pattern classification accuracy of BCI spellers (Zhang et al., 2018) allow users to make a selection of letters, numbers, or symbols (Rezeika et al., 2018), providing people with severe-motor disabilities to communicate via brain signals (Julia et al., 2020).

Despite the effectiveness of current SSVEP speller systems, there are still problems that need to be addressed. One drawback of an SSVEP-based BCI-speller system may be visual fatigue (Zheng X. et al., 2020). This fatigue may be endemic to the method, or due to BCI Speller reliability. For example, repetitive flashing may promote fatigue in users and be difficult for some. As such increased speller reliability may help improve selection accuracy, and reduce the amount of time to complete the trials to prevent frustration and fatigue. In other words, improving speller reliability would ensure user fatigue was only due to time spent on the user's responses and not on erratic speller operation. Choosing the appropriate feedback is another issue. For example, one speller application (the Bremen Speller) showed an average information transfer rate (ITR) of 25.67 bits/min with a 93.27% accuracy for people with neural deficits when implementing audio feedback (Rezeika et al., 2018); but other research has suggested when two senses are used together (hearing and sight) task interference may interrupt the user's ability to complete tasks (Watanabe & Funahashi, 2014). Thus, how effective audio feedback may be when incorporated into the speller is still an open question.

This study sought to improve the system reliability and integration of previously used BCI components by ensuring the code used to collect the EEG (Schalk et al., 2004), the SSVEP-based BCI speller (Akce et al., 2017), and the storybook application (E. Floreani, personal communication, September 30, 2021) communicated efficiently, and to test if the addition of auditory feedback would support more or less effective BCI use.

Method

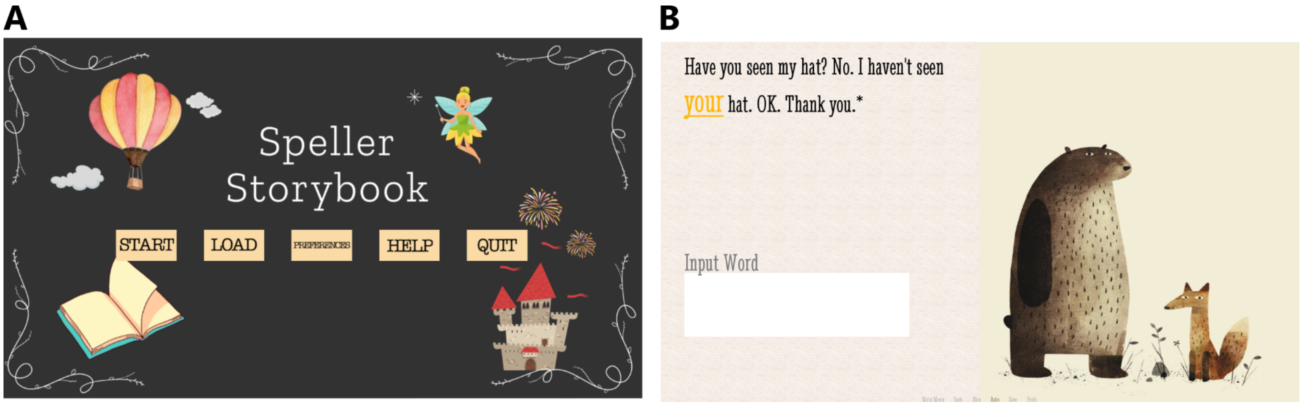
Participants

Three adult participants (1 female and 2 males) with no history of neurological disorders completed this study. All three of the participants had previous experience with SSVEP-based BCIs. Before completing the experiment all participants provided written informed consent. All studies were approved by the Stratton VA Medical Center institutional review board.

Materials and apparatus

Storybook

The previously used storybook component aimed to provide a more developmentally appropriate and child friendly application especially for children with severe motor disabilities to practice communicating. The goal of the application is to engage children with the storybook while spelling alongside the speller application. The storybook displays an interesting story for the kids to read along to when they spell the words. The storybook, as seen in Figure 1, was designed using Ren'py, a python game (Consalvo, 2020). In this game, users choose from a selection of loaded stories or create their own by importing a text file and folder of story images. Upon selection of a story, the text and images are presented on the screen a single page at a time. A target word is highlighted within a displayed text. Each target word is chosen by an imported custom target list within the application settings. Letters identified through the use of the BCI speller are placed into the input box positioned below the text. Users are given three tries at spelling the word correctly before the application proceeds to the next page (E. Floreani, personal communication, September 30, 2021).



Have you seen my hat? No. I haven't seen your hat. OK. Thank you.*

Figure 1: Screenshots of the virtual storybook application. A) Shows the start screen, where users can select which story to load, upload target words and adjust difficulty settings. B) Shows a page of the storybook, with a target word highlighted for spelling and an input box that will display text received from the speller application.

Speller Paradigm and Language Model

The BCI speller in this study used the steady-state visual evoked potential (SSVEP) paradigm as described in (Akce et al., 2015). As seen in Figure 2, the system displays multiple simultaneous flickering targets at different frequencies which are associated with different presented commands. The user then attends to the stimulus associated with their intended command, and when a certain threshold is reached in the a related SSVEP the BCI interprets the target selected. The threshold is a set power (1.6) of the frequency of the SSVEP stimuli flashing which the user attends to. To increase the power and pass the threshold to make a selection the speller-inference model predicts the best queries to show based on the information the user has given it and the probability of the next characters based on the English language. The number of targets that can be selected directly relates to the number of different frequencies that the user may be responsive to. In all BCI speller applications the number of targets is typically less than what is required for spelling (i.e, less than 26 characters in the alphabet). Therefore, a sequence of increasingly focused queries is needed to select each intended character during spelling. The queries are associated with either a range of characters (range query) or a specific character (character query). Each selection updates the speller inference model about the user's desired character (Acke et al., 2015). Once the inference model selects that desired character it is displayed within the text box, and sent to the storybook. The speller-inference model is trained using the latency and accuracy of the user's selections. It is important to note that SSVEPs are non stationary, meaning they flash at a constant frequency. Therefore, BCIs that depend on these signals for control must be calibrated for use at the beginning of each session. In the calibration phase, three boxes flash at different rates. An arrow beneath the display indicates where the user should attend. The cues are arrayed in a random order and repeat until the system isolates a discrete response for each frequency. When a selection is being made during actual spelling, the signal is compared to the target class collected in this calibration phase. Every trial that doesn't include a classification is counted as a misclassification. The duration of each trial (latency) also trains the inference model. Additional information regarding the speller and language model can be found in (Acke et al., 2015).

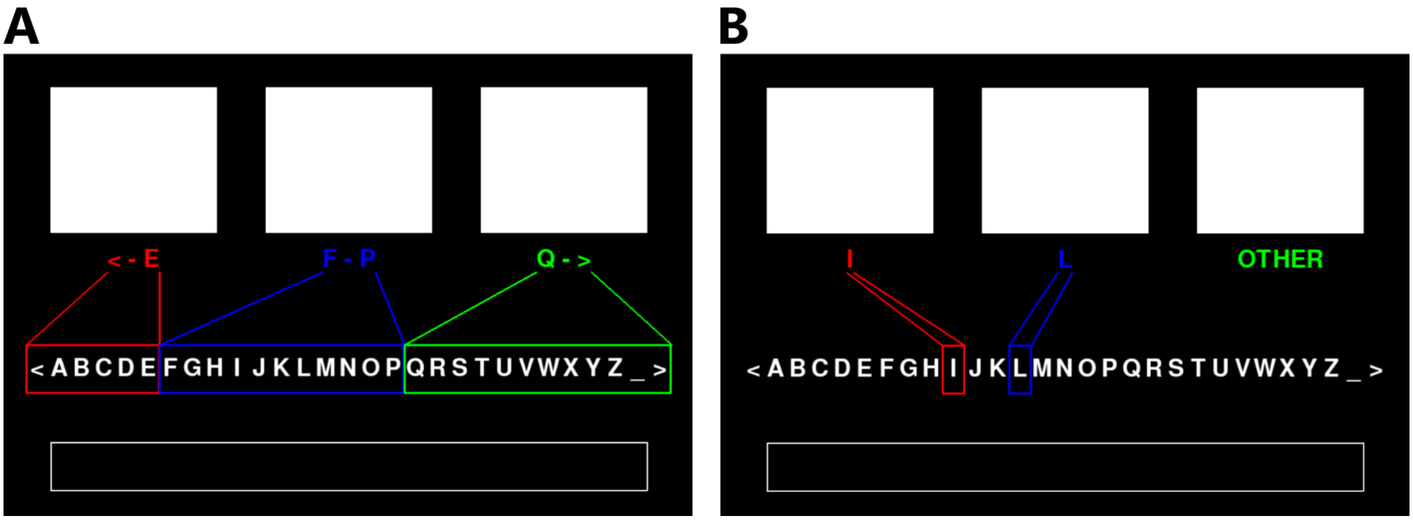


Figure 2: Screenshots of the speller application. A) Shows the "range" query, where groups of characters are presented and the user must select (attend to) the target that corresponds with the group that contains their desired character. B) Shows the "character" query, where the user must select (attend to) the target that corresponds with their desired character, or the last target if their desired character is not shown. The white boxes along the top are the SSVEP stimuli that flash at different distinct frequencies (e.g., 7.5Hz, 10Hz and 12Hz).

Data Acquisition & Signal Processing

EEG data for the SSVEP speller was obtained using a g.tec gUSB amplifier and 16 active tin electrodes placed over occipital region (O1, Oz, O2, PO7, PO3, POz, PO4, PO8), and frontal region (F3, F4, Fz, AFz, AF3, AF4, F1, F2) according to the internationally recognized 10-20 placement system (Herwig, 2003), referenced at Cz and grounded at an ear lobe. The signals were sampled at 256 Hz, with a highpass of .1Hz and lowpass of 60Hz and analyzed using standard canonical correlation analysis (CCA; Afifi et al., 2004). Data acquisition, processing, and classification were done in real-time using BCI2000 (Shalk et al., 2004).

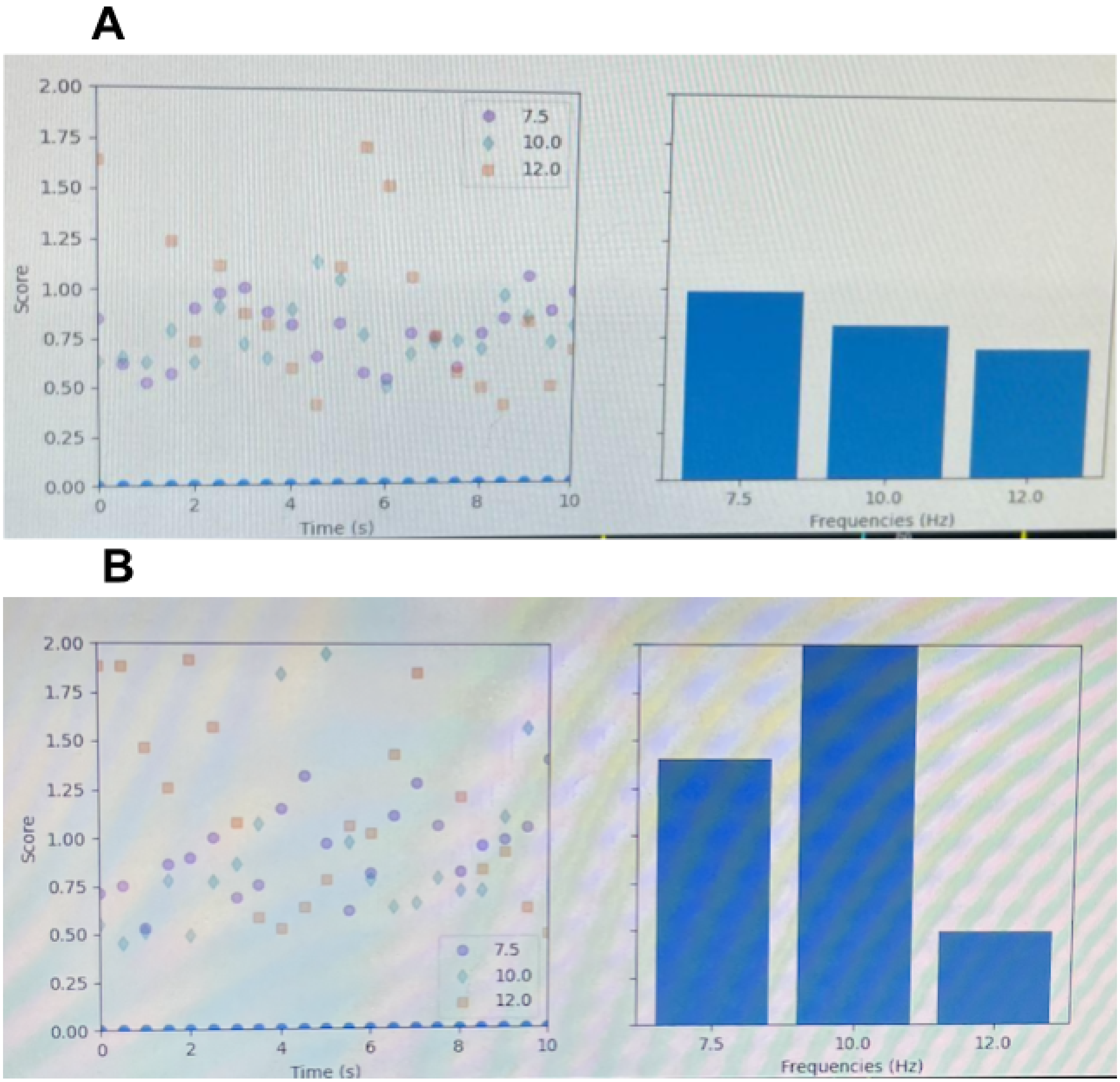


Figure 3: Screenshots of Canonical Correlation Analysis (CCA). X-axis displays time(s) and frequency of SSVEP stimuli boxes. Y-axis shows the threshold score assigned. Threshold number we assigned was 1.6. A) Shows graphical representation when the user does not engage with any of the SSVEP stimuli. Each bar graph is relatively the same value. B) Shows graphical representation when the user attends to the 10Hz SSVEP stimuli box. The 7.5Hz frequency score passes 1.6 and makes a selection.

Trigger Hub

In order to integrate the EEG with the Speller, a trigger hub was built using KiCad (Kanagachidambaresan, 2021), an open-source software platform for Electronic Design Automation. KiCad allows you to acquire information from the speller and transmit and record it in the EEG. In this way, one can align the SSVEP and EEG when a selection is made. Building the printed circuit board (PCB) included using a schematic of the symbol layout that was constructed on KiCad. The symbol libraries (collection of symbols) were then associated with their corresponding footprint libraries, the actual electrical components. The required parts were ordered and soldered to their designated location based on their footprint layout on KiCad. The PCB was tested using a multimeter to ensure current was flowing properly through it. A potentiometer was incorporated into the PCB to change the sensitivity of the trigger and make it more adaptive to different monitors.

System Software Changes

Speller software changes were required to address issues with incorrect triggers, inconsistent use of the enter button, and misalignment of the speller and the storybook user interfaces. After the trigger hub was built and operating properly offline, it was added to the speller screen. Initially each selection was erroneously recorded as multiple triggers. This issue necessitated software changes to ensure a discrete trigger per selection.

Moving the storybook to the next page requires selection of one of two commands (represented by ‘>’ or ‘>->’). In the original code , choosing these icons did not advance the page. Rather, the user entered into a selection loop, increasing incorrect selections, increasing time per page and reducing overall accuracy. Software modifications and user training and testing followed.

The misalignment issue mentioned above desynchronized the storybook from the speller. If the user did not complete spelling a target word and selected the '>' or '>->' the speller recorded the '>' character in the speller box and moved the storybook onto the next page with a different target word. The misalignment issue was fixed allowing the user to make an incorrect enter button selection ('>' or '>->') before spelling the word without disrupting the alignment of the storybook from the speller. These fixes allowed the user to complete the speller/storybook with properly calculated accuracy and fix arrow commands without misaligning the speller and storybook.

Audio Feedback

Audio feedback was implemented using python baseline commands integrated into the master branch of the speller programs enabling functionality such that once a character was selected a corresponding audio output (e.g., naming the selected letter or command) occurred for all selections. Additionally, feedback occured when the program started up by saying welcome to the user. To ensure the audio feedback worked after every selection, the number of audio output selections were tested. During two subsequent audio testing sessions, the system produced audio feedback events 62 out of 62 times, confirming it was 100% accurate.

Procedure

Once the coding issues were resolved two conditions were tested while running through the speller/storybook and recorded on an iphone camera. In the first condition participants used the speller/storybook with audio feedback. In the second condition one participant used the speller/storybook without audio output. Data was collected by carefully transcribing everything in each video into a separate spreadsheet. A total of 22 trials were collected. Each trial included the total selections made, time for each selection (seconds), target word, if audio output occured upon selection, and errors that occurred, what they were and at what selection. The selection accuracy and duration of each trial were analyzed. The percentage of correct selections and execution time across all 22 trials was calculated for analysis.

Experiments with all participants consisted of a calibration phase, training/spelling phase, and spelling phase. During the calibration phase, participants were asked to complete six target selections to calibrate the speller's inference model. The calibration phase occurred before both the training/speller phase and speller phase. After calibration, in the training/speller phase, participants used the speller-storybook interface to spell the first three changed highlighted words (BACK, SEEN, AROUND) of the story, "I Want My Hat Back" (Klassen, 2011). Each participant completed the training/speller phase once for both the audiovisual and visual condition to get the users more comfortable with the interface. After the training/speller phase, the first three words were changed back (WANT, ANY, YOUR) before beginning the spelling phase. In the spelling phase participants completed 22 trials of the speller/storybook in each condition (i.e, audiovisual and visual only). During each phase, the BCI speller included three SSVEP targets. These targets were set to flicker at 7.5, 10 and 12Hz (from left to right respectively; figure 2). Before any phase, a description of the speller/storybook paradigm, and the two conditions (audiovisual, visual) were explained to the participants. The audiovisual condition presented the sound of the letter upon making a selection. The visual condition consisted of spelling the words without any auditory component. The order that the audiovisual and visual conditions were counterbalanced across participants. Finally, participants were instructed to complete as much of the story but given the option to stop if they became fatigued or frustrated.

Results

Validating the system improvements

Trigger hub

The number of triggers (from the watches window of the BCI) made out of the total selections were calculated from a total of three sessions. Out of 347 total selections, 339 triggers were recorded to have occurred, resulting in97% trigger accuracy.

Prior to the modifications to the code noted above, 522 selections were made to test the enter button. Seventy-nine selections were incorrect (approximately 15%). After the modifications, testing of 230 selections showed 220 correct selections with only 10 incorrect (less than 5%).

Spelling Phase - All Participants

All three participants successfully used the SSVEP Speller to complete the training phase (training phase). All three participants successfully completed the storybook selections, such that in the spelling phase they read the book and made letter selections that allowed them to complete cued words and turn the page using the SSVEP-based BCI i. Completing the storybook required all participants to make an average of 102 character selections to have a perfect performance. Yet, the total number of selections greatly varied based on the number of incorrect selections made by each of the users who are identified below with the abbreviations STB1, STB2, and STB3. To move through the spelling phase participants were required to correct incorrect selections. Thus, the variability in errors between participants explains why the number of target selections varied from 182 (STB1), 97 (STB2), 111 (STB3) for the audiovisual and 118 (STB1), 115 (STB2), and 154 (STB3) for visual conditions. Overall, average target selection accuracy across all participants was 92.7% and 97.6% for audiovisual and visual conditions respectively. The time taken for each participant to complete all 22 trials of the speller/storybook was 793 sec (STB1), 325 sec (STB2), and 413 sec (STB3) for the audiovisual condition and 457 sec (STB1), 404 sec (STB2), 581 sec (STB3) for the visual condition. The average total time to complete all of the trials across all participants was 510sec for the audiovisual and 480sec for the visual condition. The average of the average selection time for each trial for all the participants was 23.2 (sec) and 21.8 (sec) for audiovisual and visual conditions respectively. There were no statistically significant differences between the two conditions in selection accuracy or time taken to complete the speller/storybook. It's also important to note that when participants were asked about which condition they preferred, all of them said the auditory component helped guide them about the selections they made.

Discussion

It was hypothesized that the auditory-visual condition would improve speller reliability over the visual condition. The present results, however, did not support this outcome. Across both measures (speller accuracy, time taken to complete all trials) there was no significant difference between the visual and auditory-visual conditions. While this was not the expected, it does suggest that the auditory-visual condition does not significantly impact the users performance as suggested by Watanabe & Funahashi, (2014). Importantly, healthy individuals would not be expected to necessarily perform differently between the two conditions because their vision is not impaired. In other words, the auditory feedback was unnecessary for these participants. But, a user with a complex communication disorder whose vision is impaired may still benefit greatly from the addition of auditory feedback in the speller. Given that the speller application displays a lot of information (SSVEP stimuli, selections) to navigate the speller/storybook paradigm correctly, having auditory feedback seems to help the users know where they are. Clearly the low number of participants tested in this study provided for low statistical power of the present study. Future work will include testing with larger samples Even though there was not much support differences between the two conditions , this work developed a functional trigger hub and streamlined coding providing for a more stable and reliable speller that can work in an auditory and visual mode. As such the next steps in this research program is to assess if this optimized system will allow for improved performance for individuals with complex communication disorders.

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