Evaluation of an adaptive hybrid tongue-brain control framework by individuals with amyotrophic lateral sclerosis

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Abstract
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Objective. Individuals with Amyotrophic lateral sclerosis (ALS) progressively lose muscle functionality and therefore experience both an increased need for assistive robot technologies and a reduced ability to control such robots. While these individuals may use high-performing control systems, such as tongue control, at the beginning of their disease progression, they will eventually be restricted to a lower-performing control system, such as brain control. However, an adaptive multimodal control interface framework consisting of combinations of tongue control and noninvasive brain control can utilize the residual tongue functionality to optimize the control performance throughout the disease progression.

Approach. To investigate this concept, a new adaptive tongue-brain multimodal control framework for manual and continuous control of a 7-degree-of-freedom robot arm is developed, based on a prior validation study. The new framework focuses on improved visual feedback, as individuals with ALS specifically requested this in a previous validation study, and consists of four subsystems: the first uses full tongue control; the second and third use hybrid tongue and noninvasive brain control, with a decreasing need for tongue functionality; and the fourth uses noninvasive brain control only. The framework was evaluated with three participants with ALS.

Main results. All participants were successful with all subsystems. One user could no longer efficiently use the full tongue control interface but achieved good results with the third and fourth subsystems. The second participant achieved significantly better results with the subsystems that included some tongue control, thereby showing the advantage of including some tongue control. The third participant performed well with all subsystems showing the ideal performance progression between each subsystem. Moreover, all participants, including the two with good tongue control, chose a multimodal control interface as their favorite.

Significance. The results indicate that individuals with ALS prefer interfaces that combine multiple control modalities.
Evaluation of an adaptive hybrid tongue-brain control framework by individuals with amyotrophic lateral sclerosis

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Abstract. Objective. Individuals with Amyotrophic lateral sclerosis (ALS) progressively lose muscle functionality and therefore experience both an increased need for assistive robot technologies and a reduced ability to control such robots. While these individuals may use high-performing control systems, such as tongue control, at the beginning of their disease progression, they will eventually be restricted to a lower-performing control system, such as brain control. However, an adaptive multimodal control interface framework consisting of combinations of tongue control and noninvasive brain control can utilize the residual tongue functionality to optimize the control performance throughout the disease progression. Approach. To investigate this concept, a new adaptive tongue-brain multimodal control framework for manual and continuous control of a 7-degree-of-freedom robot arm is developed, based on a prior validation study. The new framework focuses on improved visual feedback, as individuals with ALS specifically requested this in a previous validation study, and consists of four subsystems: the first uses full tongue control; the second and third use hybrid tongue and noninvasive brain control, with a decreasing need for tongue functionality; and the fourth uses noninvasive brain control only. The framework was evaluated with three participants with ALS. Main results. All participants were successful with all subsystems. One user could no longer efficiently use the full tongue control interface but achieved good results with the third and fourth subsystems. The second participant achieved significantly better results with the subsystems that included some tongue control, thereby showing the advantage of including some tongue control. The third participant performed well with all subsystems showing the ideal performance progression between each subsystem. Moreover, all participants, including the two with good tongue control, chose a multimodal control interface as their favorite. Significance. The results indicate that individuals with ALS prefer interfaces that combine multiple control modalities.
1. Introduction

Amyotrophic lateral sclerosis (ALS) is a motor neuron disease that affects both upper and lower motor neurons and causes progressive paralysis and functional loss of bulbar, respiratory, and spinal muscles [1, 2, 3]. Therefore, individuals with ALS experience an increasing need for assistance in simple daily activities, such as eating or scratching an itchy nose [4, 5], which will also cause a negative effect on the mental well-being of the patient and their relatives, who often act as caregivers [6, 7, 8, 9].

An assistive robotic manipulator (ARM) has the potential to provide the patient with the necessary tools to regain some degree of independence and improve their quality of life (QoL) [10, 11]. However, as ALS progresses (and thereby the need for an ARM), the available methods of interfacing with the ARM become increasingly limited due to the progressive paralysis of the user. A commercially available ARM will typically require control through a hand-controlled joystick and requires some muscle functionality in the user’s upper limbs. Approximately 70% of individuals with ALS have spinal-onset ALS [2], where early symptoms appear as weakened muscles of the upper and lower extremities and may experience difficulties using a joystick-controlled ARM even early in their disease progression. Consequently, alternative control modalities, such as movements of the tongue [12, 13, 14, 15], eye [16, 17, 18], or other facial muscles [19, 20, 21], have been investigated.

If movement of the tongue is possible, there is potential to utilize one of the best-performing interfaces for people who cannot use a joystick. Tongue control has indeed been used for individuals with tetraplegia to gain high-performing control of electric wheelchairs [22, 23], upper-limb exoskeletons [24], and ARMs with seven degrees of freedom (DoF) [12, 13, 14]. Importantly, it is possible to gain manual control of up to 9-DoF (a 7-DoF robot arm combined with a 2-DoF wheelchair [12]). Using a grid of inductive sensors, a continuous joystick-like signal can be obtained through interpolation and classification of the sensors, creating a touchpad-like interface [25].

Sunny et al. achieved a similar level of control using commercial eye tracking equipment [17]. Several other studies have similarly gained some control over the robot arm using eye tracking [26, 27, 28]. However, eye-tracking technology can have problems with certain eye types, pupil color, glasses, contact lenses, and ambient lighting [29, 30]. Alternatively, electrooculography has been used to provide some control of an ARM [16, 31, 32], but requires facial electrodes, which may be uncomfortable [30]. Lastly, ALS will eventually also affect the ocular muscles and thus heavily affect the performance of an eye-tracking device.

The use of brain signals for control has provided excellent results when invasive electrodes are used [33, 34]; however, this approach requires risky and costly surgery and several training sessions for controlling high DoFs (Benabid et al. achieved 8DoF control 16 months and 106 experiments after the surgery [34]). Noninvasive recording methods, such as electroencephalogram (EEG), provide a cheap and risk-free alternative, but the performance is much poorer [35] and it has only rarely been used for full time-
continuous manual control of an ARM. Studies using spontaneous brain waves (such as motor imagery) have achieved up to 3DoF control of an arm [36, 37, 38, 39], but these interfaces have low success rates and require long calibrations (E.g. Jeong et al. reported an average online success-rate of 43% and needed 3-4 hours to collect EEG data for calibration [36]). A brain control interface (BCI) that uses evoked potentials (such as visually evoked potentials) can achieve much higher performance with less calibration [35]. Studies using evoked brain potentials have achieved up to 7-DoF control of an ARM [40, 41, 42, 43]; however, this type of control is typically discrete in time and sequential which causes poor usability [41].

1.1. The adaptive multimodal control interface

Following the progression of the disease and thus the decreasing number of possible modalities, individuals with ALS are forced to adjust and learn several new control interfaces that each time produce a decrease in performance and independence. For example, a loss of hand function leads to the inability to use a hand-controlled joystick and thus causes a need to switch to other control modalities such as residual EMG, eye-tracking, or tongue control. To ease the transition between modalities, we previously developed and evaluated an adaptive multimodal control framework of a 7-DoF ARM, that focused on the transition from using tongue movements to using brain signals [44].

The inductive intraoral tongue control interface (TCI) is one of the best-performing control systems for people with no muscle functionality below the neck and is therefore ideal for people with ALS who have significant spinal symptoms but with little bulbar symptoms. The ‘iTongue’ is a commercially available TCI (from TKS A/S, https://tks-technology.dk/en/). An adapted version of the ‘iTongue’ was used for this study.

It consists of a mouthpiece unit (MPU) that is placed in the user’s mouth as a palate brace and houses 18 inductive coils that can record if and where any ferromagnetic metal is touching the surface of the MPU. Thus, by placing a small metal unit on the user’s tongue the user can interact with the MPU as a tongue touchpad [15]. The ferromagnetic metal unit (called the activation unit) is typically attached to the tongue as a piercing or by using dental glue (typically used for scientific experiments [44, 12, 13, 24]).

However, within 1-2 years the individual with spinal-onset ALS will often also experience bulbar symptoms, such as speech disturbances, sialorrhea, and (usually in later stages) dysphagia [2]. This will also affect the possibility of using the TCI to its fullest. In our previous study with three individuals with ALS, we noticed that two participants had problems reaching the posterior areas of the MPU surface, while the last participant could not use the TCI at all [44].

To accommodate reduced control, our proposed tongue-brain hybrid control interface (TBhCI) used a combination of tongue movements and brain signals. The interface was implemented to allow 16 time-continuous control commands, regardless of the level of paralysis of the tongue. With a reduced tongue range of motion, there is a reduced number of control commands that can be provided by the TCI. Therefore, the
TBhCI utilized control modes in which brain signals were used to determine how the available TCI commands should be mapped to control commands. As an example: if only two control commands could be achieved by the TCI, then the brain signals would allow the user to select between eight control modes such as 'up-down' or 'left-right'. If the user selected 'up-down', they could then move the robot end-effector up or down using the two available TCI control commands. If only one TCI command was available (i.e., 'on' or 'off') there would be 16 control modes selectable using brain signals.

To allow up to 16 control commands from brain signals, steady state visually evoked potentials (SSVEP) were used [35, 44]. Here, each control command is presented on a computer monitor as an area that blinks with a unique frequency. When the user focuses attention on the area representing the desired control command, the brain activity at the occipital lobe increases in power at the blinking frequency, which allows for the fast and accurate classification of the user’s intended control command. The brain signal classification algorithm used in the TBhCI was the recursive spatial-temporal beamformer, which allows high-performance classification with low computational costs and therefore can provide a continuous-time control signal [45, 44].

With the full BCI, the user could select the desired control mode and then activate the control command by keeping a focus on the blinking area. However, the performance was inferior to that of the full TCI (approximately 200% slower). This highlighted the need to use the remaining tongue control, as the proposed TBhCI instead allowed for piecewise performance drops of only 4-37% [44].

1.2. The need for improvements

While the TBhCI developed in [44] was successfully validated some issues were also observed. For example, the BCI component did not allow good visual feedback from the robot because of the need for visual attention to the SSVEP stimuli. This study therefore incorporates an end-effector camera to provide improved visual feedback, similar to what has been done in other studies using either tongue or SSVEP-based control of a robot arm [12, 41].

Furthermore, while the previous multimodal framework was developed around a TCI utilizing a discrete button user interface [44], Mohammadi et al. showed the advantages of utilizing the TCI as a 2-dimensional joystick [13]. Therefore, a TCI joystick should also be available within this multimodal framework when sufficient tongue functionality is present.

These two design changes (implementation of camera-feedback and TCI joystick) will require a complete redesign of the previous framework design. While the increased visual feedback will improve the performance of all sub-systems, it will also reduce the monitor’s available space for SSVEP stimuli and thus reduce the number of possible BCI classes. Similarly, the implementation of a TCI joystick will also reduce the number of available TCI commands as a joystick requires a larger area on the TCI compared to buttons.
This study therefore attempts to improve the previously proposed adaptive tongue-brain framework by reevaluating the core design with the goal of providing a better transition between subsystems and increasing the performance of the two control modalities. Since the purpose is to develop a framework that better suits the needs of individuals with ALS it will be evaluated by people diagnosed with ALS.

Figure 1: The integrated technologies used for this framework. It includes a 6DoF robot arm for completing translation and orientational movement tasks with an underactuated 1 DoF end-effector for object-specific grasping tasks. A camera is mounted near the end effector to provide additional visual feedback for the user shown on a portable monitor. EEG is recorded using an EEG cap, while tongue movements are recorded using a hidden intraoral mouthpiece unit. The mouthpiece unit is shown on a dental model as it is not visible while being worn.

2. Methods
2.1. The developed framework

Figure 1 shows the integration of the technologies used in the updated multimodal framework. A camera (RealSense D435i) was implemented on the robot end effector (see figure 1) to provide additional close-up visual feedback, presented at the center of the user interface. The interface was presented on a portable monitor (17.3” ROG STRIX XG17AHPE at a refresh rate of 240 Hz), which was chosen for its portability (that would allow easy mounting on a wheelchair) and its high refresh rate which will allow high-performing visual stimuli that could improve the BCI [46].

2.1.1. Robot arm control As the framework consists of several subsystems with different combinations of tongue and brain control, the user interface differed slightly between
each subsystem. However, all subsystems were designed to have four control modes with each mode having four control commands (for a total of sixteen control commands). Twelve control commands were used for translational and rotational velocity control of the end-effector, two control commands were used for end-effector closing and opening velocity control, and two control commands were used to send the robot toward one of two positions: (1) a fixed home position and (2) the position the robot left when it was sent toward the fixed home position. Thus, the last two control commands allowed easy retrieval and return of grasped objects. All control commands were programmed as velocity commands that required a time-continuous activation, thus the robot stopped whenever no activation was detected.

2.1.2. The transition strategy

The framework developed for this study allows time-continuous control of 16 control commands or 8 DoFs. The control can be divided into three tasks: (1) selecting a different control mode, (2) selecting one of the four control actions within the mode, and (3) providing time-continuous activation of the control action. To transition from full tongue-based control to full brain-based control, the tasks are iteratively changed to be handled by the BCI over the TCI. This transition strategy resulted in four subsystems shown illustrated in figure 2: a subsystem using only tongue movements (the full TCI, figure 2a), two subsystems using a combination of tongue movements and brain signals (the TBhClI and the TBhClI2, figure 2b and figure 2c), and one subsystem using only brain signals (the full BCI, figure 2d).

2.1.3. The full TCI

The full TCI was implemented with a 2D-joy-stick on the anterior TCI MPU-surface, with three buttons that change the control mode which was selectable using the posterior TCI MPU-surface (see figure 2a). The visual feedback of the activation unit on the MPU was presented to the left of the camera feedback. The feedback of the anterior MPU surface also showed the currently selected control mode with both symbols and text, while the feedback of the posterior MPU surface showed the three alternative modes and what areas should be activated to select them.

2.1.4. The TBhCI1

The first hybrid subsystem, the TBhCI1, was implemented with a 2D-joy-stick on the anterior TCI MPU-surface, with three buttons that change the control mode which are selectable using the BCI (see figure 2b). Thus only the anterior plate was shown as the posterior plate was disabled (see figure 1). Instead, the corners of the screen presented the three selectable modes as visual stimuli. These areas of the screen blinked, but only when the user no longer activated the TCI (to avoid fatigue and disturbances while controlling the robot).

2.1.5. The TBhCI2

When the user can no longer properly control a joystick with the tongue, the TCI instead becomes an on/off push-button in the TBhClI2 (figure 2c). The control selection is therefore presented as four additional visual stimuli placed above, below, to the left, and to the right of the camera feedback. These stimuli blink whenever
the TCI is not activated and allow the user to select one of the directions within the selected control command. When the user selects any of the visual stimuli, it will stop blinking and turn dark green. To finally select the command, the user must activate the TCI (turning the stimulus light-green). If the chosen command is a control command the robot will move while the TCI remains active. If the command is a mode-switch command, the control mode will be switched to the selected one after activating the TCI for 1 second. The user can also re-activate the TCI to rotate to the third or fourth control command.

2.1.6. The full BCI When only BCI was used (figure 2d) all stimuli blinked constantly. Here, the robot moved while the user selected a control command, and it shifted control mode if the user selected a mode-shift for more than 1 second. Additionally, as proposed by one of the previous participants with ALS, ”BCI activation” feedback was added to each stimulus. Here, the focus points located at the center of each stimulus (the red dots on figure 2b, 2c and 2c) changed color from red to green based on the associated stimulus activation level of the BCI (red for no activation and green for full activation).

2.2. EEG recording and classification

2.2.1. EEG Recording More EEG electrodes were included to improve the BCI performance compared to the previous adaptive multimodal study [44]. EEG was
recorded at 1000 Hz from 16 wet electrodes (T7, C3, Cz, C4, T8, P7, P3, Pz, P4, P8, PO3, POz, PO4, O1, Oz, and O2) using the OpenBCI Cyton+Daisy board with a WiFi board connection to the main laptop. At the beginning of each experiment, the experimenter set the EEG cap and checked that all electrodes had an impedance below 5kΩ.

2.2.2. Calibration The sub-systems used in this experiment used up to seven stimuli, these were programmed to have the frequencies from 9.5Hz to 15.5Hz with 1Hz increments. The participant then performed a calibration of the BCI classifier through a cued program, where each stimulus was cued in random order 8 times. Each cue followed the sequence: (1) all stimuli were idle. (2) One stimulus was highlighted to the participant. (3) When the participant was ready, the experimenter started the stimuli. (4) All stimuli blinked for five seconds. (5) The program selected the next cue and returned to Step 1 unless all cues had been presented.

2.2.3. Classification All EEG recordings were filtered using a fourth-order Butterworth bandpass filter from 7-35H and a second-order notch filter at 50Hz. In the corner of the visual monitor, a photoresistor was placed and connected to the EEG acquisition board, which allowed a simple synchronization of the EEG to the stimuli phases. The calibration data were used to train the BCI classifier, a recursive spatio-temporal beamformer (STBF) [45, 44], which was evaluated after each calibration using an 8-fold cross-validation.

The STBF provides an activation level for each stimulus that is updated at the same rate as the investigated stimulus frequency. Using a zero-order hold, the main program could evaluate the most recent activation values for all stimuli and determine any activation following a decision function that detected an activation if only one of the activation values was above a threshold of 0.5. To reduce false positives a dwell time was also implemented, such that the target should be activated undisturbed for at least 0.2 seconds before sending the activated target control command.

2.3. Tongue motion detection and classification

For this study, the MPU was fastened to the participant’s mouth using a user-designed thin plastic dental brace to improve comfortability, compared to the adaptive multimodal study [44]. Based on the inductance, the MPU records a level of activation for each of the 18 inductive coils. Before being transmitted from the MPU to the central unit (using radio waves) and further down to the main laptop (using a USB connection), the activation levels are translated to 18 8-bit numbers (0-255). As the temperature of the MPU can affect the measurements, the activation is truncated to be approximately 220 for no activation and 70 for full activation, but these values can drift independently over time. Therefore, an adaptive adjustment of the minimum and maximum activation values was implemented.
Since the activation unit provides a small and precise contact area that can only activate a small area of the MPU, if a coil is activated it is ensured that all coils not neighboring the active coil must be inactive. Thus, it is possible to adjust the maximum value by utilizing a median of recent coil data where no activation is ensured. Similarly, if a coil is active and achieves a signal below the recorded minimum value the minimum value can be adjusted. With the adjusted minimum and maximum values, the coil signals can be normalized to activation values between 0 (no activation) and 1 (full activation).

To gain touchpad-like performance with the TCI (required for the full TCI and the TBhCI1), it is necessary to interpolate the position of the activation unit using the activation values. Here, an algorithm was used, which first determines whether there exists an activation by evaluating the most activated coil (the coil with the highest activation value). If the maximum activation level of the coils exceeds a threshold (12% of a full activation) an activation of the MPU is classified, otherwise no activation is classified and the algorithm waits for new data. Upon classifying an activation, the algorithm evaluates the activation levels of the most active coil and its neighboring coils. Then, a linear interpolation across the coil-neighborhood is utilized to approximate the position of the activation unit on the MPU surface.

To reduce false positives a dwell time was also implemented, such that the MPU should be activated undisturbed for at least 0.6 seconds before sending the MPU control command.

2.4. Experiment

Three people diagnosed with ALS tested the developed framework. Table 1 provides demographic data of the participants, including their ALS Functional Rating Scale-Revised (ALSFRS-R) scores, which is a widely applied functional rating system for ALS patients [3]. The score consists of 12 questions, each scored from 0-4, that can be separated into four symptom groups of three questions: Bulbar symptoms, Fine motor symptoms, Gross motor symptoms, and respiratory symptoms. Each group can thus get a subscore between 0 and 12, with 12 indicating no observable symptoms and 0 indicating no remaining functionality.

As training is impactful to the performance [44], the experiment was conducted over three days with each session lasting a maximum of three hours. In the first session, the participant only tried the full TCI and the full BCI systems to gain training with the two control modalities separately. In the second session, the participant tried all subsystems in order from full TCI to full BCI, and in the last session, the participant used the four subsystems in a randomized order. Each session started with the preparation of the EEG and the collection of calibration data for the BCI classifier. For calibration, each BCI target was cued in a random order eight times. After each cue, the participant focused on the target while all stimuli blinked for five seconds.
2.4.1. Experimental task  To complete the task, participants were required to move the robot end-effector from the home position to the bottle (on average this movement from the home position was 18cm, -12cm, and -26cm in the X, Y, and Z directions), close the gripper sufficiently to hold the bottle, and send the robot back to the home-position using the allocated control command. The task completion times were measured as the time spent between the first send control command and the start of the go-home command. The reach time, i.e. the time to reach the proximity of the bottle was also recorded to provide a performance measure for the gross movement performance. The participant was asked to complete the trial three times with each subsystem on both day 2 and day 3. On day 3, the participant was asked to rate each subsystem using the NASA-TLX questionnaire [47], after completing the last trial with the given subsystem. The NASA-TLX scores were verbally given as a number between 1 and 10, with a lower number indicating a better system. After completing all trials the participant was asked to choose a favorite subsystem.

3. Results

The task completion time for the three participants over the last two days is presented in table 2. It can be seen here that most of the trials were successful; however, P1 had some difficulties, especially with the complete TCI and the TBhCl2 on day 2. For this reason and to not exhaust the participant, only two trials were completed with each subsystem. With the full TCI, he had issues reaching the posterior MPU surface and could thus not properly change control mode. With TBhCl2 he had problems activating the MPU. However, on the third day, he was able to use all subsystems, including the full TCI, leading to the successful, albeit slow, completion of the trials for this subsystem. On day three, P1 had one failed trial with TBhCl2 and BCI caused by moving the end effector far and tipping the bottle. Similarly, P3 also had one failed trial with the TCI on day two that was caused by a slight misplacement of the end-effector which tipped the bottle when she attempted to close the gripper.

<table>
<thead>
<tr>
<th>Participant</th>
<th>ALSFRS-R</th>
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<tr>
<td>P1</td>
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<td>P2</td>
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<td>P3</td>
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Table 1: Participant information including participant identification (ID), age, sex, months since diagnosis (MSD) and ALS Functional Rating Scale-Revised (ALSFRS-R). The ALSFRS-R scores are reported as the four subcategories. Each subcategory can score a maximum of 12 points which indicate no observable symptoms.
3.1. Task Completion Time

The results of the second and third days are also presented in figure 3a. It can be observed that the participants on average performed better on the third day compared to the second, showing that some training was still occurring. P2 improved from an average completion time of 114s to 57s using the full TCI, from 168s to 64s using the TBhCI1, and from 113s to 76s using the TBhCI2. However, her BCI performance slightly worsened from an average completion time of 162s to 172s. Similarly, the BCI performance by P3 also performed worse over the two days (from 68s to 73s), while the improved with the other subsystems (62s to 55s with the TCI, 83s to 56s with the TBhCI1, and 112s to 68s with the TBhCI2). As P1 had only a few successful trials on day two, it is clear that his performance was improved on day three. With the TBhCI1 his average completion time was reduced from 346s to 321s, and with the BCI it was reduced from 158s to 129s. While he was unsuccessful in completing any trials using the TBhCI2 on day two, he reached the bottle after 230s in one of the trials. However, on the third day, he achieved this much faster in all three trials with an average reach time of 95s.

P1 achieved his fastest time with the TBhCI1, his best average time (129s) was performed with the full BCI, which was close to the average time for the TBhCI2 (137.5s). His average times for the TCI and TBhCI1 were 208s and 254s. P2 and P3 both

Table 2: Experimental data: Reach time (RT) and completion time (CT) in seconds for the control task using each of the sub-systems. The best times are highlighted in bold. *The robot did not grasp the bottle properly when sent home. - indicate no time was measured as the trial failed before reaching and/or completing the task.

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The successful reach times (top plots) and the task completion times (bottom plots) for the participants’ successful trials (dots) and the averages across the successes (triangles) from days 2 (left plots) and 3 (right plots).

(a) The successful reach times (top plots) and the task completion times (bottom plots) for the participants’ successful trials (dots) and the averages across the successes (triangles) from days 2 (left plots) and 3 (right plots).

(b) NASA-TLX scores from the three participants (P1-P3). Scores were given between 1 and 10, with a lower score indicating a better interface.

Figure 3: Visual representation of the performance measured (a) and NASA-TLX scores (b) by the three participants (P1-P3) using the different subsystems within the framework.

had the fastest average completion time using the full TCI (57s and 55s, respectfully); however, the hybrids showed very similar performance (64s and 56s for TBhCI1, 76s and 68s for TBhCI2). With the full BCI, also P3 performed with only a slight increase in average time (73s), while P2 showed a much slower average time (172s). Thus, P1 had an average performance change between subsystems when moving from the TCI to BCI interface of 22%, -46%, and -6%. P2 had a performance decrease between subsystems when moving to a less TCI-based control with 12%, 19%, and 126% increasing the completion time. Similarly, P3 had an increased average completion time dependent on remaining TCI control of 2%, 21%, and 9%.

3.2. NASA-TLX

The participants also rated the systems using the NASA-TLX scores, as shown in figure 3b. P1 indicated that none of the subsystems caused temporal demand or frustration. He rated TBhCI2 and BCI to have the best performance (3 versus 4 or 5). The TBhCI2 caused the least mental demand (3 vs. 4 or 5), but the highest physical demand (2.5 vs. 2 or 1). Overall, TBhCI2 achieved the best NASA-TLX total score of 12.5, whereas
the other subsystems achieved a total score of 14, 15, and 14 for TCI, TBhClI, and BCI, respectively. When asked after the experiment, he rated TBhClI as his favorite subsystem. P2 also rated the TBhClI as having the lowest mental demand (2 vs. 3 or 4), but the BCI as having the lowest physical demand (1 vs. 2). However, the BCI was rated as having a much higher temporal demand (4 vs. 1 or 2) and slightly worse performance (3 vs. 2.5 or 2). She also rated the TCI as requiring more effort compared to the other subsystems (3 vs. 2) but with a similar performance to the TBhClI. For her, the TBhClI achieved the lowest total score (10 vs. 13, 13.5, and 15 for the TCI, TBhClI, and BCI, respectively), similar to P1 and she also rated the TBhClI as her favorite sub-system. P3 rated TBhClI as the subsystem with the lowest mental and physical demand (1 vs. 3 or 4 and 2 vs. 3 or 6), and in fact, noted this subsystem as “the easiest today” on the third day. However, she also rated it (and the BCI) as the subsystems that need most effort and cause the most frustration, which she explained was caused by it not moving despite her looking. The TCI was rated as the most mentally and physically demanding sub-system. While TBhClI achieved medium scores in mental and physical demand, she rated it as having the best performance (2 vs 3 or 5), demanding the least effort (2.5 vs 3, 5, or 6), and causing the least frustration (4 vs 5, 6, or 7). Indeed, TBhClI also achieved the lowest total score (15.5 vs. 22, 19, or 23 for TCI, TBhClI, and BCI, respectively). She also ranked the TBhClI as her favorite subsystem.

3.3. Qualitative feedback

During the experiment, P1 mentioned difficulty in reaching the posterior MPU surface (indicating reduced tongue flexibility) and that the position of the activation unit on either of the MPU surfaces felt like “guesswork”. Similarly, P2 requested a hover function with the TCI similar to a computer mouse, that could allow the user to see where the activation unit is without risking a wrong activation. She also requested increased feedback for when a subsystem successfully shifts control modes, here she suggested a better visual indicator to highlight mode changes. P2 also requested minor changes to the visual feedback, as she found it difficult to both focus on a visual stimulus and the video feedback from the end-effector. She suggested making everything more compact. P3 noted that she found the “BCI activation”-feedback frustrating, as it sometimes turned green but still didn’t activate. This was a result of the decision function which only activated a command if only one stimulus was detected as active. Thus, if multiple stimuli were above the threshold, they would all indicate an activation but not provide an active command.

4. Discussion

Similar to the previous adaptive framework study [44], the improved proof-of-concept framework developed within this study demonstrates the advantage of a hybrid tongue
brain ARM control interface for people with ALS. While this study evaluated the framework with potential end-users, only three individuals with ALS were included. While this number of participants is similar to other studies investigating robot or computer control with two to four end-users who have ALS [44, 48, 49, 50, 51, 52], it must be noted that the discussions and observations made in this study can not be generalized to all individuals with ALS. Quite importantly, participants for this study had only minor Bulbar symptoms as it was intended they tried all subsystems to let them evaluate the entire framework. Thus, their feedback and performance were anticipated to tend toward more tongue-based control.

4.1. System performance

In this study, the task completion times of the full BCI were closer to those of the full TCI compared to the previous study. If the participant moved directly from the full TCI to the full BCI (i.e. not utilizing the hybrid systems), the task completion time would increase by -38%, 202%, and 33% for participants 1 to 3, respectively, while the previous study saw an average increase of 616% and 108% for two participants with ALS. This could indicate a more similar control performance across control modalities likely caused by the improved BCI, as the participants in this study achieved much faster average completion times with the BCI (129s, 73s, and 172s) compared to the two participants who were able to complete a similar trial in the previous study (with an average time of 315s and 208s). The BCI was improved on several points but the implementation of camera feedback was likely the most important, as it allowed much more focused visual attention around the SSVEP stimuli on the monitor.

The TCI was designed as an improvement to the previous study by allowing joystick control. However, the two participants with decent tongue control (P2 and P3) both achieved slower average task completion times (57s and 55s) compared to the best-performing participant (44s) in the previous study [44]. Still, they achieved a faster performance than the second participant with decent tongue functionality in that study (100s). With only three participants in each study, who have unique reduced tongue functionality, it is not possible to conclude on the best TCI layout. While other studies have investigated joystick versus button layouts for the TCI and indeed concluded in favor of a joystick [13], the reduced tongue functionality appearing with ALS may affect these results. Thus, future studies focusing on optimizing the TCI design for individuals with ALS should be made.

P2 also highlighted well the advantage of including tongue control, even for just providing a single time-continuous activation signal, as she achieved 126% reduced completion time with the TBhCl2 compared to the BCI. Her second biggest performance decrease between subsystems was from the TBhCl1 to the TBhCl2, with 19%. Between these subsystems, P3 experienced her biggest performance decrease (21%). This step-wise decrease in performance could be reduced by implementing a third hybrid subsystem between TBhCl1 and TBhCl2. The performance of P1 showed well, that even
though a control modality can no longer be fully utilized it can be advantageous to still utilize the remaining functionality. While his bulbar symptoms caused problems using the full TCI, he achieved relatively good results when using more BCI-based control. Interestingly, he achieved the worst average performance but the best single trial performance with the TBhCI1. During the experiments, it was observed that he had issues with tongue precision; nevertheless, it is possible that with further training he would achieve the best results with this subsystem. The improvements observed from day two to day three, particularly those for subsystems utilizing some tongue movements, indicate that training was still happening and that it may need even more days of training before the participants perform to their full capability.

4.2. User preference

However, the participants seemingly found other factors than just completion time important. All participants selected a hybrid control interface as their favorite control interface, despite performing better with a single modality control interface. P1 and P2 both selected TBhCl2 despite achieving faster average completion time with other subsystems. Similarly, P3 chose TBhCl1 as her favorite but achieved the fastest completion times with the full TCI. All participants highlighted that TBhCl2 was the easiest subsystem to use, likely because it has the simplest combination of the two control modalities: select what the robot should do with your visual attention and make the robot move by touching the MPU with your tongue. As the full BCI also requires visual attention to move the robot, it requires some multitasking with both attending to the stimulus and the robot (using the camera feedback). Similarly, as the full TCI and TBhCl1 require more complex tongue positioning, it may also encourage visual attention to the TCI feedback, thus also creating a division of attention. Still, previous studies have shown the possibility of eye-free tongue control [24], indicating that training with the TCI may improve the ease of use. Still, there was a good acceptance with all subsystems, and the feedback provided by the participants consisted of only small suggestions that can easily be implemented in future versions of the framework.

4.3. System Acceptance

The need for a tongue piercing as an activation unit for a home-use TCI version has a mixed acceptance rate among potential users. From interviews and discussions with people who have either ALS or a spinal cord injury, we have learned that some individuals would get a tongue piercing while others are more hesitant, as also observed in a previous study [53]. There exist several proposed tongue control systems that do not require the activation unit which could be implemented as a replacement for the TCI used in this study [54, 55, 56]; however, these devices typically have fewer control commands. Recent studies have investigated a new inductive TCI, where the activation unit is placed on the MPU rather than as a piercing [57]. This device is thus not dependent on a piercing, but still has a high number of control commands; therefore,
it may be better suited for some people with ALS. Similarly, from our discussions with potential users, it has often been noted that an EEG cap should be made more aesthetically acceptable. Huggins et al. showed that 84% of people with ALS would accept an EEG cap [5]. Still, it would likely benefit to have an aesthetically pleasing EEG recording device, especially in the early stages of ALS when the participant will only use the device for improved performance and not as a last resort. As SSVEP is recorded from the back of the head (near the occipital lobe), it may be possible to incorporate the electrodes into the headrest of a wheelchair, thus allowing a covert EEG recording.

4.4. Modality selection

Eye-tracking devices could replace the proposed BCI control modality in a tongue-eye multimodal control framework, thus completely removing EEG from the solution. Sunny et al. proposed an eye-tracking robot control system similar to the full BCI system used in this study (but without visual feedback) and achieved good performance [17]. However, studies have shown that not all eye types can be tracked properly, with 10-20% of people unable to use eye-tracking systems [30]. The progression of ALS will further affect the performance of eye-tracking systems. It has been shown that individuals with late-stage ALS have poor performance with eye-tracking systems (up to 50% and 63% accuracy for the two participants with late-stage ALS) but can still achieve good performance with an SSVEP-based BCI (89% and 100% accuracy for the two participants) [51].

Furthermore, incorporating a BCI early in the progression of ALS may benefit the user later when no other control modality can be used. It has been shown that it is possible to extract training data for a tongue movement-based BCI by recording EEG while using the TCI [58]. Therefore, a long-term covert EEG data collection could be considered, in which the user uses the best-suited TBhCI for daily activities, while the TCI and EEG recordings are also used to collect training data for an independent movement-based BCI. If the user then reaches a complete locked-in stage where SSVEP can no longer be successfully utilized, a new movement-based BCI can be implemented with little to no need for BCI calibration. However, this concept still needs investigation and validation.

4.5. The future of the framework

Future studies should include more participants over a longer period, to further evaluate effects such as training, disease progression, and usability. Other robots may also be considered for future versions of the framework. As the framework now includes visual feedback, it will be beneficial to investigate the remote control of a wheelchair and ARM combination, as in other studies [12, 41]. Similarly, since it was developed for a 7DoF ARM, it will also be possible to use the interface for robots with less DoF, such as most exoskeletons [24, 59] or wheelchairs [22, 60].
While this study focused on transitioning from a TCI to a BCI, some users with ALS may benefit from including additional modalities. As the progression of ALS is unique to the individual, it is also beneficial to evaluate the implementation of other modalities such as eye movements, head movements, and/or electromyography.

5. Conclusion

The adaptive multimodal framework was evaluated with three individuals diagnosed with ALS. Two of them had sufficient tongue control to utilize the full TCI and achieved the best performance with this subsystem; however, both preferred to include some BCI control using a hybrid subsystem. The last participant had poor tongue functionality and performed best with the full BCI; however, he also preferred a hybrid subsystem that included some TCI control.

Based on the user feedback from our existing work, we showed that visual feedback could be integrated into the system with good effects. Despite the successful proof-of-concept with the actual end users, further refinement and usability testing with more end users are needed to ensure the robustness and effectiveness of such a control scheme for robotic devices. Nevertheless, all the individuals with ALS who participated in this study preferred a multimodal control interface, which emphasizes a desire for interfaces that include and combine multiple control modalities.

6. Data availability statement

Any data that support the findings of this study are included within the article.

7. Ethical statement

The participants gave written informed consent to participate in this study. All experimental procedures were approved by the local ethical committee of Region North Jutland (N-20210008) and followed the Helsinki Declaration.

8. Acknowledgments

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9. Conflict of interest

The authors declare no competing interests related to this study.
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