Assessment of the Tongue-Drive System using a Computer, a Smartphone, and a Powered-Wheelchair by People with Tetraplegia

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Abstract—Tongue-Drive System (TDS) is a wireless and wearable assistive technology that enables people with severe disabilities to control their computers, wheelchairs, and smartphones using voluntary tongue motion. To evaluate the efficacy of the TDS, several experiments were conducted, in which the performance of 9 able-bodied (AB) participants using a mouse, a keypad, and the TDS, as well as a cohort of 11 participants with tetraplegia (TP) using the TDS, were observed and compared. Experiments included the Fitts’ law tapping, wheelchair driving, phone-dialing, and weight-shifting tasks over five to six consecutive sessions. All participants received a tongue piercing, wore a magnetic tongue stud, and completed the trials as evaluable participants. Although AB participants were already familiar with the keypad, throughputs of their tapping tasks using the keypad were only 1.4 times better than those using the TDS. The completion times of wheelchair driving task using the TDS for AB and TP participants were between 157 s and 180 s with three different control strategies. Participants with TP completed phone-dialing and weight-shifting tasks in 81.9 s and 71.5 s, respectively, using tongue motions. Results showed statistically significant improvement or trending to improvement in performance status over the sessions. Most of the learning occurred between the first and second sessions, but trends did suggest that more practice would lead to increased improvement in performance using the TDS.

Index Terms—Assistive technologies, powered wheelchair, Fitts’ Law, smartphone, and spinal cord injuries

I. INTRODUCTION

In the United States, 5.5 million people have some form of paralysis, caused by stroke (29%), spinal cord injuries (23%), and multiple sclerosis (17%) [1]. As people with severe disabilities strive to improve their quality of life, they are eager to adapt to and to incorporate innovative assistive technologies (AT) in their daily lives [2], particularly important to these persons are input devices to access computers, wheelchairs, smartphones, and home/office appliances [3]. Several ATs such as EEG-based brain-computer interfaces (BCIs), electromyography (EMG), speech recognition, head arrays, eye trackers, and sip-and-puff (SnP) switches have been introduced in the market [4]. However, each device has limitations that prevent its use in daily life. For instance, BCIs are useful to those with high levels of paralysis [5], [6], but they are prone to motion artifacts and interference, and cannot be easily adapted to daily activities [7]. The EMG-controlled switches help people with disabilities access computers [8], [9] or navigate electric-powered wheelchairs (PWC) [10], [11], but the number of commands is limited and long term use can cause muscle fatigue [12]. Speech recognition systems have become widely available on computers and smartphones. Although these technologies allow people to type efficiently [13], they are not efficient for cursor or wheelchair navigation [14]-[16]. In addition, because speech recognition is sensitive to acoustics, they are unreliable in noisy environments [17]. The eye-tracker is efficient for controlling a mouse cursor on a computer screen. However, because it requires a camera in front of the user’s face [18], [19], it can block the line of sight, rendering it not useful for mobile conditions. Head arrays and SnP switches are the most popular ATs individuals with tetraplegia use for driving PWCs [20]. They are affordable and simple, but they offer only a limited number of commands.
and require users to have the ability to control their often weak neck and diaphragm muscles, which are prone to fatigue and not possible for some. Therefore, although individuals with disabilities have access to the above technologies, they have not been able to adapt them to their routine lives for various reasons, leading to an AT abandonment rate of 35% to 75% due to issues such as poor performance, low reliability, environmental barriers, and changes in the users’ functional abilities [21], [22].

The Tongue Drive System (TDS) was developed to overcome some of the aforementioned problems by enhancing the functionality and usability of a wireless and wearable AT that recognizes the voluntary movements of a user’s tongue by processing changes in the magnetic field, generated by a small magnetic tracer on the tongue, and translating them into user-defined commands, shown in Fig. 1. The magnetic tracer should either be glued to the tongue for short-term temporary use (a few hours) or embedded in a titanium tongue stud for attachment to the tongue via a piercing for medium- to long-term use. The performance and learning of able-bodied (AB) participants using the TDS were evaluated with a computer and a PWC in previous studies [23]-[25]. More recently, we published quantitative and qualitative results from both AB participants and those with tetraplegia (TP) using the TDS, and compared to their performance using SnP or their current ATs [26], [27]. Here, we report the results of additional experiments conducted with the same study group that quantify performance using the TDS to control a computer, a PWC, and a smartphone. This study compares the performance of AB and TP participants in five and six sessions, using the TDS and conventional computer input devices, respectively.

II. TDS PROTOTYPE

A. Tongue-Drive Hardware and Software

The external TDS (eTDS) headset in Fig. 2a consists of headgear with four 3-axial magneto-resistive sensors (HMC 1043, Honeywell, Plymouth, MN) placed on a pair of goosenecks near the users’ cheeks, as shown in Fig. 3a. The magneto-resistive sensors (Fig. 2c) are connected to a control unit enclosed in a box on top of the headset (Fig. 2f) and a system-on-a-chip microcontroller with built-in 2.4-GHz RF transceiver (CC2510, Texas Instruments, Dallas, TX) that collects the sensor signals and wirelessly transmits them to a computer or a smartphone. A detailed description of the hardware can be found in [28].

The TDS-PC transceiver dongle, shown in Fig. 2e, receives magnetic sensor signals from the eTDS headset and conveys the raw data to the PC through a USB connection. The TDS-PWC smartphone interface, shown in Fig. 2b, does a similar function for the smartphone (iPhone). Using a magnetic sensor signal processing (SSP) algorithm, both PC and smartphone can translate the raw data into TDS commands in real-time [29], [30]. There are used to access the PC, smartphone applications, or the PWC. A digital-to-analog converter in the TDS-PWC smartphone interface converts the commands into necessary voltages to control the PWC in linear and angular directions. A specific TDS command is designated to control the power switch in the PWC mode, changing it from drive mode to weight-shift mode through a 3.5 mm audio jack. To avoid repeating of the training procedures on the smartphone, the TDS-PWC smartphone interface wirelessly receives TDS calibration and training data from the PC. Details of the eTDS headset, TDS-PC transceiver, and TDS-PWC smartphone interface can be found in [25].

A dedicated graphical user interface (GUI) was developed in LabVIEW environment (LabVIEW v9.0, National Instruments, Austin, TX) and displayed on a 22” monitor with 1280 × 800 pixel resolution, as shown in Fig. 3a. The screenshows of the GUIs for the computer access tasks are shown in Figs. 5a-d. The GUIs for the PWC navigation tasks (plus phone dialing and weight shifting for the TP participants) were developed in the iPhone SDK (Xcode v3.2.5 for iOS 4.2) environment. Dedicated applications are shown in Figs. 6a-f.

B. Sensor Signal-Processing Algorithm

The SSP algorithm consists of two parts: electromagnetic interference (EMI) attenuation and command classification. To reduce the effects of EMI, the algorithm subtracts the output signals of the 3-axis magnetic sensor on one side from the other side after mathematically rotating the signals to bring them parallel; then the algorithm minimizes common mode signals such as the earth’s magnetic fields and EMI and maximizes the differential mode signals generated by the tongue magnetic tracer, called the “calibration procedure” [28], [29]. These magnetic sensor outputs, followed by EMI
attenuation, are translated into one of six user-defined commands (plus neutral) using the command classification algorithm. To apply the command classification, participants performed a “training procedure” during which they repeatedly and consistently placed their tongues then times in seven suggested command positions shown in Fig. 4a to collect the sensor signals. A feature extraction based on the principle component analysis (PCA) used the training data to form a set of command clusters in virtual 3-D space, each representing one of six TDS commands. During the TDS operation mode, incoming sensor data were reflected in the PCA space and then applied to eight classifiers that include K nearest neighbors (KNN) combined with Mahalanobis and Euclidian distance, linear, and quadratic classifiers. The final commands were determined by a majority voting algorithm, which selected the most frequent outputs from the classifiers [29]-[31].

Each session began with calibration and training. For the system calibration that applied the EMI attenuation algorithm, the researcher adjusted the sensor poles symmetrically near the participants’ cheeks and captured signals from the magnetic sensors for 30 s while the participants rotated their heads and held their tongues stationary in a neutral resting position. Next, the system-training GUI captured the magnetic sensor data in order to classify each command. For this procedure, the users placed and held their tongues (and consequently the tongue magnets) in seven recommended command positions as shown in Fig. 4a. The participants started with two-command training “LEFT or RIGHT” or “UP or DOWN” followed by four-command and then six-command training. Each command, repeated ten times, was randomly selected by visual and auditory cues. At the end of the training session, the GUI generated a 3-D view of the command clusters in the PCA space, so the researcher could eliminate outliers.

III. PERFORMANCE EVALUATION

A. Human Subjects

To evaluate the performance of TDS users, experiments were conducted with nine AB participants in five sessions and 11 TP participants in six sessions at three sites: the Georgia Institute of Technology (GT; Atlanta, GA), Northwestern University (NU; Chicago, IL, in conjunction with the Rehabilitation Institute of Chicago, RIC, Chicago, IL), and Shepherd Center (SC; Atlanta, GA). Required approvals from the institutional review boards (IRBs) of the sites were obtained as well as written informed consent from each participating subject. The results of the first phase of this project are explained in previous publications [23], [24] that report on AB participants, who already had tongue piercing in place and, performed computer access and PWC driving tasks using the TDS.

In the second phase, we recruited 24 AB participants (14 from Atlanta and 10 from Chicago) who agreed to receive a tongue piercing and to participate in the five-session trials. The ages of the nine AB participants who completed the trials ranged from 19 to 29 (median: 22 years old). Five (four males and one female) participants were from GT and the remaining (four females) from NU/RIC. In the third phase, we consented 21 participants with tetraplegia (11 from Atlanta and 10 from Chicago), eight withdrew and two were withdrawn from the study. The ages of the 11 participants who completed all trials ranged from 27 to 56 (median: 37 years old). Seven (six males and one female) participated at SC and four (three males and one female) participated at NU/RIC. In this paper, we report the results from the second and third phases of the project.

The participants who did not finish the trials in both phases dropped out of the experiments during the initial stage because of time constraint, study disqualification, dissatisfaction with the piercing location, loss of interest, and/or removal of the barbell resulting in closure of the piercing tract. More detailed reasons are provided in [25], [26]. The majority of reasons for early termination from the study were neither related to the tongue-piercing nor TDS dissatisfaction. The AB participants were not familiar with either the TDS or the PWC. The TP participants were new to the TDS, but familiar with the PWC; six of them were using the SnP to drive their PWCs on a daily basis, and the rest were using a joystick with limited hand movements. All of the AB participants used a computer mouse and a keyboard in their daily lives, but four of the TP participants had not used a computer on a daily basis.

B. Experimental Design

The study began with a tongue piercing by a physician, performed in a medical facility at each site for all participants. Before and after the piercing, photographs of the participants’ tongues were taken and their tongue sizes (AB participants – width: 38.4 ± 5.57 mm, thickness: 10.5 ± 3.20 mm, TP participants – width: 41.1 ± 8.77 mm, thickness: 14.6 ± 4.50 mm) and oral cavity volumes (before the piercing: AB participants – 86.4 ± 14.2 mL and TP participants – 72.3 ± 23.8 mL) were measured on a daily basis by the researchers using a Boley gauge and oral plethysmography. A detailed description of the procedure and the measurement of the tongue were reported in [25], [26], and [32]. After a four-week recovery period, the initial barbells were exchanged for shorter, titanium, magnet-containing barbells as shown in Fig. 2d. The length of the barbell (12-21 mm) was determined by using a Boley gauge to measure tongue thickness.

The experiments were scheduled in five or six consecutive sessions at intervals ranging from 2 to 10 days. The average time for each session, which included computer and PWC sections for the AB participants, was three hours; two hours for computer and an hour for PWC sections. For the TP participants, the computer and PWC testing sections (with the smartphone task) were split into two days because of the additional experiments and the extra time for the experimental
Fig. 5. TDS graphical user interface (GUI) for the experiment on a PC: (a) horizontal tapping (HT), (b) vertical tapping (VT), (c) total possible targets for the multi-directional tapping (MT) and (d) the example MT tasks cursor movement.

setup (e.g., exchanging wheelchairs, weight shifting, and resting). Both testing sessions, typically scheduled over the course of a week with a one- to three-day interval, were considered one session. Each section of the session was completed within ~2.5 h on average.

The AB participants were asked to perform the unidirectional and multi-directional tapping tasks using a computer mouse during the first session only, and a keypad, and the TDS over all five sessions. The TP participants performed the same tasks using only the TDS for six sessions. The speed of the mouse cursor for the tapping tasks on the computer was increased from zero until it reached 350 pixels/s at a rate of 500 pixels/s². Both AB and TP participants were asked to perform the wheelchair driving tasks using the TDS for five and six sessions, respectively. The TP participants were expected to perform the phone-dialing and weight-shifting tasks using the TDS for six sessions. The number of sessions for each task with both AB and TP participants using each device is summarized in Table I. The participants completed a practice round and three testing rounds for all tasks in each session. The average results of the three testing rounds are reported. At the end of each session, all participants were asked a “yes or no” question about feeling tongue fatigue.

1) Unidirectional Tapping Tasks

The unidirectional tapping task, a type of Fitts’ Law tapping task [33], [34], included horizontal tapping (HT) and vertical tapping (VT). A group of rectangular targets with three widths (W = 30, 61, and 122 pixels) and three distances (D = 122, 244, and 488 pixels) created nine paired conditions calculated to be between 1.00 and 4.11 (mean: 2.32) on the index of difficulty (ID, units: bits). One of the nine pairs was shown at a time on a 610 × 610-pixel screen (see Figs. 5a-b). The nine conditions randomly appeared during three rounds, and each condition was repeated 18 times for a total of 54 (3 × 18) trials per round. Participants were instructed to move the cursor as quickly and as close to the center of the bars as possible in back-, and forth movements, using the left/right and up/down commands in the HT and VT tasks, respectively, to reach the target bars and change the direction of movement. AB participants using the mouse were also instructed to click on the target bar. The order of the unidirectional tapping tasks was randomly selected, so some participants started with the HT, followed by the VT, and others started with VT followed by HT. To evaluate these tasks, the throughput and the error rate are reported. The throughput is defined as the ratio of the effective index of difficulty (IDₑ) of the targets and the movement time (Eq. (1)), which is from the beginning to the end of cursor movement [23]. The unit of the throughput is bits/s. The IDₑ is defined on the Eq. (2) with respect to the effective distance (Dₑ) and the effective width (Wₑ). Dₑ defines the mean of actual distance along the task axis, and Wₑ is 4.133 × standard deviation of the distance between the center of the target and the actually selected position [23], [26]. The definition of the throughput comes from Soukoreff and MacKenzie’s paper [34]. The error rate is the percentage of attempts that do not hit the target.

Throughput = \frac{IDₑ}{Movement\ Time} \quad (1)

\quad IDₑ = \log_2 \left( \frac{Dₑ}{Wₑ} + 1 \right) \quad (2)

2) Multidirectional Tapping Tasks

Eleven circular targets with two different diameters (W = 57 and 76 pixels), which appeared within the circumferences of two different diameters (D = 305 and 534 pixels) of the multidirectional tapping (MT) task, were composed of three paired conditions (condition 1: W = 57 pixels, D = 305 pixels, condition 2: W = 57 pixels, D = 534 pixels, and condition 3: W = 76 pixels, D = 534 pixels) [23], [34] as shown in Fig. 5c, the IDs of which were calculated to be between 2.67 and 3.37 (mean: 3.01). The targets were highlighted one at a time in clockwise direction across the diameter of the outer circle as shown in Fig. 5d. Participants were instructed to move the cursor as quickly and as accurately as possible to reach the target using the left, right, up, and down commands, and to click the target using either left-select or right-select commands for the keypad and the TDS. The AB participants were instructed to reach the target using the mouse and click on reaching the target. Each round consisted of 33 trials with all three paired conditions for the AB participants, and 11 trials with one of three randomly selected paired conditions for the TP participants. One of the selection commands (either left-select or right-select) was required to register the end point for the TDS and the keypad. The measurements were the same as those of the unidirectional tapping tasks.
3) Wheelchair Driving

Fig. 3b shows the experimental setup for the PWC driving tasks with a participant wearing the TDS headset and a researcher walking next to the PWC holding an emergency stop switch. The floor plan of the obstacle course, which was ~50 m with 13 turns and 24 obstacles, is shown in Fig. 4c. Three driving strategies (unlatched, latched, and semi-proportional) were used to evaluate the system using the TDS for both groups. The unlatched mode was selected because it was the simplest control strategy that activated the linear and rotational speed of PWC when commands were issued. The latched mode was selected because it was one of the popular strategies using alternative controls, especially SnP [35], and the linear speed was constant until new commands were issued (like cruise control). The semi-proportional mode was selected to evaluate a modified version of the latched mode that was a constant linear speed with proportional rotational speed. The four-directional TDS commands (up, down, left, and right; GUI: Fig. 6b) corresponded to the commands for driving the PWC: forward, backward, left, and right for the unlatched and latched strategies. The unlatched mode consisted of constant speeds for forward (0.95 km/h) and backward (-0.95 km/h) directions, which were applied when the forward or backward commands were issued. The latched mode consisted of three forward speeds, forward-1 (0.95 km/h), forward-2 (1.25 km/h), and forward-3 (1.6 km/h), and one backward speed (-0.95 km/h), and the forward or backward commands could increase or decrease the speed of the PWC. Once an issued command changed the speed of the PWC, the linear speed remained constant until a new command was issued (GUI: Fig. 6c).

The semi-proportional strategy entailed different driving mechanisms, which were “latched for linear speeds with proportional rotation” to navigate the PWC (GUI: Fig. 6c). The forward and backward commands were defined by quick touches to the inner left and right cheeks. Changes in the linear speed, three forward speeds and one backward, were controlled by the same speed steps and mechanism as that of the latched strategy, while the rotational angle with constant speed was altered according to the tongue’s location along the lips. Participants were instructed to slide their tongues from one corner of the lips to the other corner to change the rotation. Strategies were randomly selected for all sessions except for the first session. For each strategy, participants were asked to complete one practice and three testing rounds. To evaluate the performance of TDS-PWC driving, two measurements were used: time of completion and the number of navigation errors, which was a sum of the number of times the PWC collided with obstacles and the number of times the PWC wheels moved out of the track. In the middle of an obstacle course, an alarm for the emergency stop was randomly activated to resemble actual road conditions, and participants were instructed to stop immediately, using the TDS commands or a head switch placed on the head rest of the PWC. The time of completion also included the time spent for the emergency stop. More detailed explanations of these tasks can be found in [25].

4) Phone Dialing

The TP participants were asked to dial a phone number using TDS commands: four directional commands along with select and delete commands. A visual prompt of a randomly selected ten-digit target phone number appeared at the top of the GUI screen, shown in Fig. 6e, and the participants entered the same number in the following line as quickly and as accurately as possible. A yellow-highlighted cursor appeared in the middle of the smartphone keypad in the location of “5” which indicated the current location of the cursor. The cursor was moved from one to another number on the keypad with 0.5 s dwelling time for the four directional commands. After navigating the cursor to the correct number, a selection command (i.e., the left-select used in the computer trial) was issued to register the number on the screen by holding 1 s. If a wrong number was registered, the participants were able to delete it using either the delete command (Right-select was designated for the delete command) or by selecting the delete key, which appeared in the bottom-right of the keypad on the GUI of the smartphone (iPhone) as shown in Fig. 6e. After entering the number, the participant was instructed to move the cursor to the green-colored “CALL” button in the middle of the bottom line to complete the trial. The completion time was part of the evaluation of the user’s performance and it included the dwelling and command holding times.

5) Weight Shifting

To avoid decubitus ulcers, people with paralysis who remain in wheelchairs over the long term must engage in periodic wheelchair tilting to reduce ischemic pressures produced by prolonged sitting. Therefore, the design of the TDS included commands that change the PWC from driving mode to tilting mode to control the wheelchair angle. By holding the right-select command for 2 s, the wheelchair mode could be switched between a sequence of modes which was a default setting option for the wheelchair controller (Q-Logic.
Drive Control System, Pride mobility, PA): driving mode 1 (PWC speeds: 0.95-1.95 km/h), driving mode 2 (PWC speeds: 1.95-2.95 km/h), driving mode 3 (PWC speeds: 2.95-3.95 km/h), the control enhancement display mode, and the tilting (weight shifting) mode. Participants were instructed to change the mode from “driving mode 1” to “tilting mode” and then change the angle of the wheelchair from “up-straight” to “most-tilted” using the “up” command. When they reached the most-tilted state, they issued the “down” command to return to the “up-straight” state. The up or down commands changed the tilt angle from 10° - 78° with constant speed, and it took about 12 s from “up-straight” to “most-tilted” or vice versa (GUI: Fig. 6f). Performance was evaluated based on completion time that included the command holding time. At the end of the sixth session, participants were asked about the effectiveness of weight shifting using the TDS in comparison with their current ATs in a five-point Likert scale question (1: completely ineffective, and 5: very effective).

C. Statistical Analysis

To analyze the learning effects of the TDS to control a computer, a PWC, and smartphone applications, a repeated measure analysis of variance (rmANOVA) [36], on the Statistical Package for the Social Sciences (SPSS) v. 21, was used. An initial examination of the data set was conducted for elimination of outliers using the interquartile range method [37]. Even though most of the data were in the interquartile range, outlier data sets were recorded when participants did not properly follow instructions. For the session-by-session learning effect, pairwise comparisons with the least significant difference (LSD) were used.

IV. RESULTS

A. Results of the Unidirectional Tapping Tasks

A-1) Throughputs for AB participants

As all of the AB participants had had extensive experience using a computer mouse, it was assumed that they achieved a high level of performance at baseline. The results are presented with mean and 95% confidential interval (CI) throughout the results section. In the first test session, the throughputs of the AB participants using a mouse for HT and VT were 4.24 ± 0.29 b/s and 4.38 ± 0.28 b/s, respectively; the throughputs using the keypad were 82.2 % and 78.8 % of that using the mouse for HT and VT, respectively. The throughputs using a keypad for both unidirectional tapping tasks increased significantly from the first to second sessions (HT: P\textsubscript{1,2} = 0.020) and the third and fourth sessions (P\textsubscript{3,4} < 0.001) and then reached saturated levels as shown in Figs. 7a-b. The definition of a saturated level was unchanged performance between consecutive sessions within five or six sessions.

Even though the participants were familiar with a keypad, the layout of the keypad (as shown in Fig. 4b) was not the conventional layout used on a regular keyboards [23], [26]. Therefore, we were also able to observe the learning effect from the first to second sessions. In the first session, the throughputs of AB participants using the TDS for HT and VT were 2.03 ± 0.17 b/s and 2.27 ± 0.23 b/s, respectively. They were 47.9 % and 51.9 % of that using a mouse for the HT and VT, respectively. In the fifth session, finally, the throughputs reached 2.59 ± 0.21 b/s and 2.69 ± 0.19 b/s for HT and VT, respectively (Figs. 7a-b).

A-2) Throughputs for TP participants

In the first session, the throughputs of TP participants using the TDS for both unidirectional tapping tasks were 1.52 ± 0.18 b/s and 1.44 ± 0.16 b/s, which were 74.8 % and 63.4 %, respectively, of the throughputs of the AB participants using the TDS for the HT and VT tasks. However, significant improvements in the HT were observed between the first and second sessions (P\textsubscript{1,2} = 0.020) and the third and fourth sessions (P\textsubscript{3,4} < 0.001) and in the VT between the first and second sessions (P\textsubscript{1,2} < 0.001).

The throughputs of the TP participants using the TDS for the HT and VT tasks were lower than those of the AB participants. However, among the TP participants, there were two groups of people, experienced computer users (ECU) with their own assistive devices and inexperienced computer users (ICU) as shown in Figs. 7a-d. Seven of the 11 TP participants were in the ECU group (median: 37 years old) and the rest were in the ICU group (median: 41 years old). On average, during all six trial sessions, the ECU group performance was approximately 31.4% (about 0.50 b/s) better than that of the ICU group.

A-3) Error rates for AB participants

The error rates for AB participants using a mouse for HT and VT were 5.4 % and 2.1 % in the first session as shown in Figs. 7c-d. The error rates of HT and VT when using the keypad were 1.96 and 4.90 times, respectively, higher than those when using a mouse. The error rates decreased over the sessions, but the decrease was not as significant as that of the throughputs. The error rates using the keypad continuously declined and after the third session reached 6.0 % for HT and 7.2 % for VT. In the first session, the error rates for both tapping tasks using the TDS were 2.5 and 2.1 times higher than those using the keypad. In the first session, the error rate for HT was 17.7 % and that for VT was 14.6 %.
A-4) Error rates for TP participants

The TP participants missed the targets for HT and VT in the first session with error rates of 37.4 % and 39.2 %, respectively, and the error rates of these participants using the TDS were 1.38 and 1.83 times higher than those of the AB participants (HT: 27.1 %, and VT: 21.4 %). The error rates of the ECU and ICU groups on both unidirectional tapping tasks showed a similar tendency, but the ECU group rates were closer to those of the AB participants than those of the ICU group. In the sixth session, the error rates of the TP participants using HT and VT had reduced to 20.2 % and 19.4 %, respectively. Interestingly, the ECU group error rates, of 16.3 % and 15.8 %, respectively, were similar to those of the AB participants. Over the sessions, the error rates of the TP participants continuously declined until the sixth session, when ECU group reached error rates similar to those of the AB participants, as shown in Figs. 7c-d. Even though the performance of the ECU group in terms of speed and accuracy was slightly lower than that of the AB participants during the first four sessions, the ECU participants reached a similar performance level to that of the AB participants during the fifth or sixth session.

B. Results of the Multidirectional Tasks

B-1) Throughputs for AB and TP participants

In the first session, the throughputs of AB participants using a mouse on the MT task was 3.99 ± 0.23 b/s, as shown in Fig. 8a; the throughputs using the keypad and the TDS were 34.8 % and 19.9 % of that using the mouse for MT, respectively. The throughputs using the keypad significantly improved between the first and third sessions (P1,2 < 0.001 and P2,3 = 0.012), when they reached the saturated range (~1.8 b/s). The throughputs using the TDS continuously improved over the five sessions, significantly improving between the third and fourth sessions (P3,4 = 0.011). In the fifth session, they finally reached 1.16 ± 0.12 b/s, which was not yet in the saturated range. Over the sessions, the throughputs of the TP participants using the TDS for the MT task were lower than those of the AB participants (1st: 0.37 ± 0.06 b/s and 6th: 0.72 ± 0.11 b/s). This difference was most significant between the third and fourth sessions (A3,4 = 0.18 b/s, P3,4 = 0.001).

B-2) Error rates for AB and TP participants

The error rate of AB participants using a mouse on the MT task was recorded at 2.6 % in the first session, which was similar to that using the keypad (2.7 %). The error rate using the keypad did not significantly improve, it was probably because it was already low during the first session.

Fig. 8. Results of multi-directional tapping (MT) tasks over the five or six sessions for the AB participants (-A) and TP participants (-T). The TP participants were categorized into ECU and ICU. (a) The throughputs and (b) the error rates of MT tasks. Error bars represent the 95% CI.

Statistically significant improvement was recorded between the third and fourth sessions (P3,4 = 0.048), and the error rate was 6.9 % in the fifth session. The error rate for the TP participants using the TDS as shown in Fig. 8b, estimated at 58.1 % in the first session, was 2.71 times higher than that of the AB participants and decreased significantly over the sessions to 27.8 %. The most significant change occurred between the second and fourth sessions (P2,3 = 0.009 and P3,4 = 0.013). The error rates did not change significantly after the fourth session, and they remained at 27 %.

For the MT task, the throughput of the ECU group was higher than that of the ICU group over all sessions. The performance of both groups improved moderately over the sessions, but neither group reached a saturation point by the end of the sixth session. The ECU group participants selected the targets with about a 15 % error rate after the fourth session, and the performance gap between the ECU group and the AB participants had lessened.

C. Results of the Wheelchair Driving Tasks

C-1) Completion time for AB and TP participants

The results of the TDS-PWC driving with the three control strategies are shown in Figs. 9a-d. In the first session, the average completion times of the AB participants and the TP participants using the unlatched strategy on the obstacle course were 231.4 ± 34.3 s and 253.3 ± 23.9 s, respectively. Even though the completion time of both groups using the unlatched mode decreased most significantly between the first and third sessions (AB participants: P1,2 = 0.023, P2,3 = 0.004, and TP participants: P1,2 = 0.021 and P2,3 = 0.001), it continuously improved over the course of the remaining sessions, as shown in Figs. 9a and 9c. The completion time for both groups using the unlatched strategy was between 157 s and 170 s. The completion time when both groups used the latched strategy was longer than the time using the unlatched strategy. Although the overall completion time of the AB participants using the latched strategy was 23 s longer than the time when they used the unlatched strategy over the five
sessions on average, it declined significantly between the first and second sessions \((P_{1,2} = 0.040)\) and moderately during the following sessions. The completion time for the TP participants continuously decreased over the six sessions \((179.4 \text{ s})\) until it entered a range similar to that of the AB participants during the fifth session \((181.7 \text{ s})\).

In the first session, the completion time of the AB participants driving the PWC using the semi-proportional strategy was \(217.8 \pm 15.1 \text{ s}\), which was less than the time it took for them to complete the obstacle course using the unlatched and latched strategies. The TP participants, using the semi-proportional strategy, took \(319.2 \pm 38.5 \text{ s}\) to complete the obstacle course during the first session, which was \(1.47 \text{ times}\) as long as the time taken by the AB participants; and it was \(65.8 \text{ s}\) longer than the time taken by the TP participants using the unlatched strategy. However, they effectively learned how to use the semi-proportional strategy during the TDS, showing the highest improvement between the first and second sessions \((\Delta_{1,2} = 80.04 \text{ s}, P_{1,2} = 0.001)\) and between the fourth and sixth sessions \((P_{4,5} = 0.002, P_{5,6} = 0.005)\). After the fifth session, the TP participants completed the course within a similar time range to that of the AB participants.

\(C-2\) Number of navigation errors for AB and TP participants

In the first session, the number of navigation errors, between 7.8 and 10.6, was within a similar range for both groups for all driving strategies as shown in Figs. 9b and 9d, except for the semi-proportional strategy used by the AB participants—\(2.6 \pm 0.9\). Even though the AB participants using the semi-proportional strategy showed the least improvement over the sessions, they were able to navigate the PWC with the lowest number of navigational errors. The AB participants exhibited the most significant improvement between the second and third sessions \((P_{1,2} = 0.001)\), and between the fourth and sixth sessions \((P_{4,5} = 0.002, P_{5,6} = 0.005)\). After the fifth session, the TP participants completed the course within a similar time range to that of the AB participants.

The number of navigation errors committed by TP participants using all strategies continuously declined. Analysis revealed significant improvement between the fourth and fifth sessions \((P_{4,5} = 0.012)\) when using the unlatched strategy; between the first and second sessions \((P_{1,2} = 0.043)\), and fourth and fifth sessions \((P_{4,5} = 0.013)\) when using the latched strategy; and between the first and second sessions \((P_{1,2} = 0.007)\) and the third and fourth sessions \((P_{3,4} = 0.019)\) when using the semi-proportional strategy. Finally, in the fifth session, their number of navigation errors using all strategies was about 3.0, which was similar to that of the AB participants using the latched strategy.

\(D\) Results of Phone-Dialing and Weight-Shift Tasks

\(D-1\) Completion time of phone-dialing for TP participants

The average completion time of dialing a phone number for the TP participants, shown in Fig. 10a, was \(187.7 \pm 22.5 \text{ s}\) in the first session. It exhibited the most significant decline between the first and second sessions \((\Delta_{1,2} = 78.6 \text{ s}, P_{1,2} < 0.001)\). It decreased slightly between the second and third sessions, and the decline between the third and sixth sessions \((P_{3,4} = 0.780, P_{4,5} = 0.839, P_{5,6} = 0.257)\) was statistically insignificant. In the sixth session, the completion time was \(81.9 \pm 7.8 \text{ s}\).

\(D-2\) Completion time of weight shifting for TP participants

The completion time for weight shifting by the TP participants, shown in Fig. 10b, was \(116.18 \pm 14.6 \text{ s}\) in the first session, and then significantly decreased between the first and second sessions \((\Delta_{1,2} = 41.4 \text{ s}, P_{1,2} < 0.001)\). The completion time did not vary significantly after the second session \((P_{2,3} = 0.532, P_{3,4} = 0.637, P_{4,5} = 0.844, P_{5,6} = 0.494)\), and in the sixth session, it was \(71.5 \pm 7.9 \text{ s}\). When asked about its efficacy, nine of the 11 participants stated that weight shifting using the TDS was very effective and the average scores for their responses were \(4.9 \pm 0.2 \text{ out of 5}\).

When the participants were asked about tongue fatigue at the end of each trial, one or two of 9 AB participants answered that they had some tongue fatigue during the experiment in each session. Similarly, one or two of 11 TP participants felt some tongue fatigue during the experiment in each session.

\(V\) Discussion

The performance of the AB and TP participants using the TDS for the computer access with several tapping tasks can be compared with that using other existing ATs. One of the eye tracking systems has been evaluated using a similar experimental setup with MT task in [38], and the reported performance of 16 AB participants between 2.30 and 3.78 b/s depended on their strategies. In addition, the head tracking system has been evaluated with 15 AB participants in [39] with similar testing setup, and their throughputs were reported between 0.78 and 0.92 b/s for the joystick mode, and 1.68 and 1.93 b/s for the pointer mode. We have already reported the performance of the TDS compared with the SnP, which is one of the most popular ATs, with a similar setup, yet with other tasks in [26]. The results revealed that the performance of the TDS was up to three times better than that of the SnP. Even though the performance using the eye tracking system was higher than that of the TDS, when considering its proportional control mechanism, the TDS performance with AB participants was comparable. The head tracking system also controls the cursor proportionally, but the throughputs were lower than this study. We plan to implement a new signal processing algorithm to control the cursor proportionally with full tongue tracking in 2D; at which time we expect the performance, especially for the MT task, will be enhanced.

A study limitation relates to direct comparison of the performance for AB and TP participants undergoing the MT task, since the number of trials for the AB participants in a
session differed from that for the TP participants. We tried to mirror the experimental setup for both AB and TP participants as closely as we could under the circumstances, however, the TP participants, who were older and less experienced computer users, took more time to complete tasks. The average ID was higher for the MT targets than HT or VT tasks. Moreover, the MT task required the use of four directional commands which required much more mental loading. Therefore, we reduced the number of trials in a session, which was 1/3 of the number of trials for AB participants. Even though the total time that both AB and TP participants experienced with the TDS was similar, the actual number of trials was different between groups for the MT task. Thus, it is inappropriate to compare the learning effects for the AB and TP participants for the MT task.

The definition of the saturated levels was not a statistical or mathematical function. The performance was only noted within five or six sessions. Thus, the observed saturated levels may not be the actual saturation points, and would probably be different in longer experimental sessions. In actuality, the saturation times may have been limited by the fixed speeds of the cursors and wheelchairs, and dwelling and command holding times. Therefore, with longer use and different settings, one would expect higher saturation levels of performance.

The average ages of the ECU and ICU groups were about 15 years and 20 years older respectively than that of AB participants (22.6 ± 4.0 years old). It appears that the two main factors affecting performance were age and familiarity with computers. Older people are known to have slower computer learning curves than younger people Error! Reference source not found., so it is not surprising that those in the ECU group, who had a similar level of familiarity with computers to the AB participants, learned more slowly than the AB participants. However, it is likely that with more practice, the performance of the both ECU and ICU groups on unidirectional and multidirectional tapping tasks would continue to improve.

For the phone-dialing task, we have reported a similar experimental setup with four young AB participants in Error! Reference source not found.. The average completion time for dialing a phone number was 42.8 s, which was 1.9 times faster than that of the TP participants. The speed of the cursor and command holding time was set for all participants and for all sessions, thus limiting the dialing speed. If the speed of the cursor and the command holding time were modified based on the users’ skill and proficiency, we would expect to see faster and more efficient phone dialing performance. Similarly, the completion time of the weight shifting did not shorten much over the experimental sessions, but this might change with reduction in the command holding time to switch the PWC mode from one to another related to increased familiarity with the TDS and subsequent skill improvement.

Given the results in the current study, it is our expectation that, with ongoing practice, the participants in both groups for all computer, wheelchair and smartphone tasks, would improve their performances using the TDS. Particularly, upon further training of the ECU and ICU groups on the TDS, continued improvement in both speed and accuracy would be expected for computer access tasks.

VI. CONCLUSION

In this research, we developed the Tongue Drive System (TDS), which allows individuals with severe disabilities to access computers and dial phone numbers, drive power wheelchairs using voluntary tongue motions. We recruited both AB and TP participants to engage in experiments during which they successfully completed computer access tasks, including Fitts’ law tapping and wheelchair navigation tasks, using a smart phone to perform three driving strategies, phone dialing, and weight shifting. The results of usability experiments for all participants showed that they could learn to use the TDS to access a computer and navigate a wheelchair efficiently. The greatest improvement occurred between the first and second sessions, but both groups, using tongue motions to move the magnetic stud to control and issue commands, continued learning throughout the five or six sessions of the experiments. For the tests using computers and wheelchairs, the overall performance of the AB participants was faster and more accurate than that of the TP participants, but we conclude that both age and familiarity with computers may have led to these results. After practice, the performance of the TP participants who had had experience on computers was comparable to that of the AB participants. We conclude that recruitment of a larger number of older AB participants and young adult TP participants for a future study will sufficiently test the assumptions that familiarity with computers influences outcomes for TDS use. In addition, the performance of TP participants using the TDS continuously improved throughout the sessions, never reaching saturation. Therefore, it is reasonable to conclude that, with more experience and continuous usage of the TDS, these individuals would learn to control the computer and wheelchair even more quickly and accurately.

The TP participants were able to dial a phone number with acceptable speed, but it was not as fast as that of the AB participants. Even though the completion time did not vary after the third session, we expect that faster cursor speed would lead to faster dialing. The TDS was also tested on a weight shifting task, revealing an acceptable completion time. To activate and complete weight shifting, the TP participants did not require additional help from the researchers or their caregivers. The ability to weight shift independently is one of the greatest advantages of using this type of assistive technology. In a future study, it is likely that we by increasing the number of sessions and the number of participants, at the same time controlling for age, the extent of disability, familiarity with computers and electric-powered wheelchairs, and other variables, it will be possible to show a broader and stronger utility as well as applicability of the TDS for people with TP.

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