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Using Fitts's Law for Evaluating Tongue Drive System as a Pointing Device for Computer Access

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Abstract

In this paper, the results of a 2-D center-out task in a Fitts's law experiment have been presented for measuring the performance of the Tongue Drive System (TDS). Although the end-user population for TDS is individuals with tetraplegia, in this study, we recruited 6 able-bodied subjects in 3 sessions, conducted in 3 consecutive days. They performed the same task with their right hand using a standard mouse for achieving a baseline as well as a standard keypad with their right index finger. The resulting average throughput for TDS, keypad, and mouse were 1.67, 2.17, and 3.99 bit/s, respectively.

I. Introduction

Tongue Drive System (TDS) is an assistive technology designed to enable individuals with severe movement disabilities to access computers or drive powered wheelchairs with their tongue motion [1]–[3]. It consists of four key components, shown in Fig. 1: a small permanent magnetic tracer fixed on the tongue by tissue adhesive, a headset with a pair of three-axial magnetic sensors to detect the magnetic field generated by magnetic tracer, a wireless link established between a control unit on the headset and a USB receiver to send the magnetic sensor data to a computer or smartphone, and finally a sensor signal processing (SSP) algorithm, which recognizes the position of the magnet, hence, the position of the tongue within the oral space. Once the TDS users define specific tongue positions/gestures that they want to associate with particular functions, they can access the computer or drive powered wheelchair (PWC) using their tongue motion.

The current TDS prototype has six individual commands, simultaneously available to the user; four directional (LEFT, RIGHT, UP, and DOWN) and two selection commands. When using TDS for computer access, the directional commands can be used to move the cursor on the screen in four directions and the selection commands can be used to emulate the mouse left-click and double-click functions.

We have previously evaluated the TDS performance as a computer input device using a measure widely accepted in Brain-Computer Interfacing (BCI), known as the Information Transfer Rate (ITR), suggested by Wolpaw [4]. To find this parameter for TDS, subjects were given a certain amount of time to issue a random command out of the six available, while measuring the percentage of the correctly completed commands [3]. *ITR* indicates the rate of information that an input device (BCI) can deliver from the user to a computer.

Fitts's law [5], on the other hand, describes the relationship between movement time, distance, and accuracy in human rapid aimed movements. It has been widely used for human-controlled cursor movements in pointing and dragging tasks with input devices such as mouse, trackball, and touch screen [6]. It has also been adopted by Human-Computer Interaction (HCI) research community to evaluate novel devices. Fitts's law combines movement times over rapid repeated movements between targets of definite widths and distances to calculate a parameter, called throughput, which relates to both speed and accuracy of the human movements. Moreover, throughput calculations have been codified in an international standard, ISO-9241-9, describing the evaluation of non-keyboard computer input devices [7].

In an attempt to measure the TDS performance in a way that it would be compatible with the ISO standards and also comparable with the collective body of prior research [5], in this paper we have implemented a task, known as center-out [8], which applies the Fitts's law in 2 dimensions to calculate the TDS throughput (*TP*). We have also recorded the reaction time (*RT*) of the subjects. To find a baseline, the same task was also performed using a standard mouse, for which a valid range of performance metrics (specifically throughput) already exists in the literature with the purpose of validating our experimental methods, measurement results, and data analysis. In addition, to compare the performances of the hand and tongue in a similar context of switch-based devices (unlike mouse), we tested the subjects while performing the same task on a standard keypad, instructing them to press a subset of adjacent keys using their right index finger.

II. Methodology

A. Task

Subjects were asked to perform a center-out task similar to previous studies, such as [8], using TDS, keypad, and mouse. In this task blue circular targets with a black crosshair in the center and 3 different diameters (40, 80, and 160 pixels) appeared on a white 800×800 pixel area of the screen at 3 different distances from the center of the screen (80, 160, and 320 pixels) along 8 different directions of evenly spaced 45° radial lines. The Graphical User Interface (GUI) was developed in the LabVIEW environment and presented to the subjects sitting 1 m away from a 22" LCD monitor with 1680×1050 pixel resolution. The GUI was responsible for randomly presenting all 48 targets (Fig. 2), one at a time, moving the cursor on the screen based on the input commands received from TDS or keypad, and capturing the time and location of the cursor on the screen during each trial. There were 4 blocks, each containing all 48 possible targets, one for practice, followed by three for the assessment (a total of 192 trials). For each trial, the cursor jumped to the center of the screen, a new target showed up, and subjects were instructed to move the cursor towards the target as fast and accurately as possible and try to stop as close as possible to the crosshair at the center of each target.

B. Apparatus

1) TDS—The external TDS (eTDS) prototype used in this experiment is shown in Fig. 1. The magnetic tracer was a small disk-shaped ($\varnothing 4.8 \text{ mm} \times 1.5 \text{ mm}$) rare earth permanent magnet (K&J Magnetics, Jamison, PA). The headset was equipped with a pair of goosenecks to bilaterally hold a pair of 3-axial magneto-resistive sensors near the subjects' cheeks, symmetrical to the sagittal plane. A small control unit on top of the headset housed a low-power microcontroller with build-in 2.4 GHz RF transceiver, sampling each sensor output at 50 Hz. All sensor outputs were packed in one data frame, and wirelessly transmitted to a PC equipped with a wireless USB receiver dongle.

The SSP algorithm, running on the PC, uses the K Nearest Neighbors (KNN) classifier to identify the incoming samples based on their features, which are extracted via Principal Components Analysis (PCA) from the data that is collected during a training stage prior to each session [1]. The tongue positions for the aforementioned six control commands plus an additional Neutral position (the tongue resting position) are shown in Fig. 3a. In this experiment we only used the four directional commands and dwelling time (DT) for selection to facilitate the trial. When subjects reach the target, they should simply dwell in the desired position for at least $DT = 0.5$ s by returning their tongue to the resting position to select it.

We should also note that cursor movements in each direction was done in an unlatched mode, meaning that subjects should be holding their tongues in the corresponding location to maintain the cursor movement in that direction. As the cursor moves in a certain direction, its speed increases linearly with the rate of 500 pixels/s^2 until it reaches a maximum level of 350 pixels/s . The rate of acceleration and maximum speed were chosen experimentally based on our pilot experiments in the developmental phase.

2) Keypad—Fig. 3b shows the keys on the keypad designated to the four directional commands, which were selected in a way that they resemble the TDS tongue positions for the same commands. Mouse cursor movements are omnidirectional and proportional to the position and speed of the hand movements, which is quite different in nature from the TDS cursor movements in only four directions with a predefined velocity profile. Therefore, a direct comparison between the mouse and the current TDS prototype is not meaningful. On the other hand, with the keypad we can compare the performance of the index finger with tongue in terms of throughput and reaction time using similar switch-based devices. During keypad task, the GUI sampled the keypad output at 50 Hz and applied the same velocity profile as the TDS for the cursor movements.

Selection using keypad was through dwelling with $DT = 0.5$ s, similar to TDS. When using mouse, however, subjects had to left-click on the targets. We should also note that reaching the targets that were along diagonal directions (45° , 135° , 225° , and 315°) using only 4 directional commands, required issuing at least two commands. Also it would have been faster to minimize the number of horizontal or vertical segments towards a diagonal target because the speed of the cursor movement needed to ramp up from zero following each change of direction. To prevent subjects from adjusting the cursor position with a series of small movements, we limited the total movement time beyond which a new target would have appeared. Subjects were also instructed to focus on issuing correct commands at the right times to reach targets with a minimum number of consecutive commands.

C. Performance Metrics

Throughput— TP like ITR shows the amount of information that users can deliver to a computer through an input device in a certain task (cursor control in this case) [8]. According to ISO-9241-9, TP is defined as the ratio between the effective Index of Difficulty, ID , of a certain target to the time it takes to reach that target:

$$TP = ID_e / MT, \quad (1)$$

where ID of the target, measured in bits, is defined by the Shannon formula as

$$ID_e = \log_2(D_e / W_e + 1), \quad (2)$$

where $W_e = 4.133 \times SD_x$ is the effective target width, and SD_x is the standard deviation of x , the distance between the subject's pointed spots in reaching the target to the center of the target, when projected onto the task axis. The task axis is a straight line from the origin of the movement to the center of the target. D_e is the effective distance, defined as the mean of the distances of pointed spots projected along the task axis. x can be positive or negative, when the subject overshoots or undershoots during target selection, respectively. MT in (1) is the mean movement time to point at the target among all trials for a specific target. It only includes the time when the cursor is moving. It neither includes the initial time for moving the cursor nor the dwelling time needed for target selection. ID_e reflects how subjects actually performed, rather than what was presented to them and includes both the speed and accuracy of their pointing tasks [9], [10].

Table I shows the ID s for different width (W) and distance-from-center (D) of targets in this study. Although subjects should be presented to a wide range of ID s, similar to [10], we limited this range to 1.58–3.17 to match the expected use of the TDS for clicking icons and buttons [7]. For each device and for each subject, throughput was computed using (1) and (2) for each target over all the trials and averaged over angles, W s, and D s. The overall TP for each device was computed as the grand mean of TP s of all subjects [6], [8].

Reaction time— RT is the time interval between when a new target is shown on the screen and the initiation of the cursor movement. RT includes the subjects' decision time to which direction to move, which tongue position or key to select, physical movement of the tongue or finger, and the system (including GUI) latency in detecting and translating subjects' commands to cursor movements. The TDS and keypad latencies were measured 160 ms and 80 ms, respectively.

D. Protocol

The necessary approval was obtained from the Georgia Tech's institutional review board. All subjects, 2 females and 4 males, were GT-Bionics lab members, aged 22–29 years old. They were all able-bodied and right handed. 4 of the subjects had 3 hours of previous experience with TDS in a pilot study. Two of the subjects had used TDS multiple times but not on a regular basis. The experiment was conducted in 3 consecutive days, in 45 min sessions. At the beginning of each session the TDS headset was placed on the subjects' head and sensor positions were adjusted (see Fig. 1). After calibration, a new magnetic tracer was washed with tap water, sanitized in 70% isopropyl alcohol, dried, and attached to the subject's tongue, about 1 cm from the tip, using a cyano-acrylic adhesive (GluStitch, Point Roberts, WA). After a 5 min training, in which tongue positions were defined, according to Fig. 3a [3], subjects began the center-out task with randomly ordered devices. Subjects were allowed to take 1 min rests between consecutive blocks.

III. Results and Discussion

Fig. 4 shows the average throughput and reaction time for TDS, keypad, and mouse with their 95% confidence intervals. The mouse throughput, which is our reference point, was found to be 3.99 ± 0.32 b/s, well within the acceptable range of 3.5–4.5 b/s [10]. For TDS and keypad, average throughputs were 1.67 ± 0.37 b/s and 2.17 ± 0.19 b/s, respectively.

Repeated measures ANOVA followed by pairwise comparison with *Bonferroni* adjustment showed statistical difference between keypad and TDS throughputs ($p = 0.026$). Mouse throughput was significantly different from the other devices ($p < 0.0001$), because of its proportional and omnidirectional control capability ($F_{2,5}$ equaled 114 for the RM-ANOVA). However, there was no significant difference between the reaction times of TDS and keypad ($p = 1$) which were 0.652 ± 0.08 s and 0.627 ± 0.08 s, respectively. Out of these, 160 ms and

80 ms of TDS and keypad reaction times are due to system latency, shown by the hatched part of the bars in Fig. 4b. The mouse latency was below our time measurement accuracy of 20 ms. The mouse reaction time, 0.16 ± 0.06 s, was significantly different from both TDS and keypad ($p < 0.0001$). Even after excluding the system latency, there was no significant difference between the keypad and TDS reaction times ($p = 0.452$). Hence, considering the fact that these are both switch-based devices, the speed of the tongue as a mean to control a computer input device (TDS) seems to be similar to that of the index finger (keypad).

Fig. 5 shows the average TP vs. angular orientation of the targets from the center. Unlike mouse's omnidirectional control, TP in TDS or keypad depends on the angle. The average TP over cardinal and diagonal directions are 2.3 and 1.1 b/s for TDS and 2.97 and 1.36 b/s for keypad, respectively. The lower TP over diagonal directions compared to cardinal directions is due to a higher number of commands needed to reach diagonal targets (at least two) and all the delays associated with issuing each new command as well as lower average speed due to extra stops. Table II benchmarks the TDS against a few popular assistive technologies (AT) that are often used for computer access in terms of their normalized TP with respect to mouse.

Measuring certain performance metrics, such as path efficiency, average speed, overshoot percentage or target re-entry could help in better understanding different aspects of a new computer input device [8], [12]. There are also qualitative and subjective performance measures such as ISO-9241-9 questionnaire, which may provide useful information on how to further improve this device.

Setting $DT = 0.5$ s, as suggested in [11], seemed to be just right. Shorter DT leads to system's misinterpreting the stops as selections especially when pointing towards diagonal targets, while longer DT seemed to reduce the TP , probably by reducing subjects' agility. The velocity profile also plays a key role in defining TP for switch-based devices like the present TDS [8]. Several velocity profiles, such as the 2nd or 3rd order polynomials of time, need to be examined.

The results of medium and long term practice with the TDS are still unknown. A longitudinal study to derive the slope and plateau of the learning curve is necessary for this new AT. Attachment of the magnetic tracer to the tongue via adhesives lasts only 2–3 hours at a time. Other methods of attachment, such as tongue piercing or implantation, should be employed. TDS Performance should also be tested in other tasks such as dragging, typing, etc. Uni- and multidirectional tapping tasks of ISO-9241-9 can be quite useful in this case [7].

IV. Conclusion

We have evaluated the Tongue Drive System, a tongue operated AT for the severely paralyzed, as a switch-based pointing device with four directional commands for computer access. We measured its performance in terms of throughput and reaction time, and directly compared it with mouse (as a reference) and four adjacent keys on a standard keypad. Results showed that the tongue performance is comparable to the index finger under similar device conditions. Further research needs to be conducted by applying other quantitative and qualitative performance metrics, deriving optimal velocity profiles, and investigating the effect of users' daily practice in TDS performance improvements.

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Fig. 1.

Tongue Drive System (TDS) is comprised of a permanent magnetic tracer on the tongue, a headset with a pair of 3-D magnetic sensors, a control unit that includes a transmitter, a USB receiver, and a sensor signal processing (SSP) algorithm running on a PC (not shown).

Fig. 2.

All possible targets that can randomly appear on the screen (one at a time). Variables are width, distance, and angle from the center of the screen.

Fig. 3.

(a) Recommended tongue positions for six TDS commands plus the resting position which is considered neutral. (b) Designated keys on the keypad to resemble the position of the TDS directional commands.

Fig. 4. Average throughput (a) and reaction time (b) for TDS, keypad, and mouse with their 95% confidence interval.

Fig. 5.
Throughput vs. angle of the targets for TDS, keypad, and mouse.

Table I

Indices of difficulty for Targets Used in this study

Targets' Width, W (pixels)	Distance from center, D (pixels)		
	80	160	320
40	1.58	2.32	3.17
80		1.58	2.32
160			1.58

Table II

Benchmarking Assistive Technologies in terms of Normalized Throughput

Device	Reference	Normalized <i>TP</i>
Mouse	Natapov [10]	1
Eye tracker	Zhang [11]	0.49–0.65
TDS	(this work)	0.42
Vocal Joystick	Harada [13]	0.3
Head Orientation	Williams [8]	0.2
EMG	Williams [8]	0.16