Hands-free Computer Access for the Severely Disabled

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Abstract

The feasibility of using the Cyberlink hands-free computer controller as an access solution for individuals with disabilities was investigated. Specific questions evaluated were: (1) Can the Cyberlink be used as a computer access solution for individuals with no other documented means of computer access? (2) Can Cyberlink control be made more accurate and reliable through the use of machine learning and adaptive control techniques? Clinical trials were started with thirty-two participants of varying ages and disabilities. Each participant had been unable to access technology due to physical limitations. Twenty-five of the 32 participants were able to exhibit some form of conscious computer control with the Cyberlink and participated in the complete clinical trial design. Trials consisted of two tasks designed to measure response times and the ability to move a cursor to a target using the Cyberlink. Each task was completed by the participant a minimum of three times. History and performance data were collected and analyzed using Cyberlink software developed specifically for these tasks. Data was also obtained using questionnaires, videotapes and observation. Single trial test results indicate it is possible to recognize and discriminate participant actions using a window of time history to better recognize changes in response patterns. These findings indicate time series analysis of the data can be effective in distinguishing intended user response from background signal activity. In many cases, this permitted the recognition of the participant's intention at an earlier time than a simple threshold crossing rule. This suggests implementing an adaptive control based upon time series analysis will be advantageous.

Introduction

The field of Alternative and Augmentative Communication (AAC), though relatively young, has provided a means for many individuals to express themselves that was not available in the past. Beukelman and Ansel [1] summarized demographic data and suggested that 8-12 individuals per 1,000 (2 million) in the general population of the United States experience impairments severe enough to require AAC. Alternative computer input devices are now available in a variety of options to support special needs communication and access to AAC (i.e., frontalis muscle switch, head and eye-tracking devices, chin switch, "sip and puff," voice activation, etc.). The use of this technology, however, is dependent on the user's ability to control the device.

There are individuals who, because of the severity of their physical limitations, have been unable to access AAC technology. These individuals often have disabilities related to cerebral palsy (CP), amyotrophic lateral sclerosis (ALS), multiple sclerosis (MS), muscular dystrophy (MD), or traumatic brain injury (TBI). Other practical barriers involve physical fatigue associated with use, length and intensity of required system calibration and adjustment, length and intensity of required user training, and expense. Because of access difficulties, communication for these individuals is often limited, left to interpretations by communication partners, or non-existent. The Cyberlink has the potential to bridge the gap between these individuals and the communication technology available to empower and transform their lives. The access gained can easily be extended to include environmental control to further enrich the quality of their daily lives.

The Cyberlink Explained

The Cyberlink uses brain and body forehead bio-potentials in a novel way to generate multiple signals for computer control inputs. Three silver silver-chloride plated carbon-filled plastic sensors in the Cyberlink headband in conjunction with the Cyberlink amplifier circuit can detect bio-potentials as low as 0.3 micro-volts. Signals are easily and non-invasively obtained and impedance levels are usually below 50 K ohms with little or no skin preparation. The forehead is often the last site to suffer degradation in cases of severe disability and degenerative disease. For example, in ALS and MD the ocular motor neurons and ocular muscles are usually spared permitting at least gross eye movements, but not precise eye pointing control.

A Cyberlink bio-amplifier separates the forehead signal into three frequency channels. The lowest channel is responsive to bio-potentials resulting from eye motion. It is band pass derived in the frequency range 0.2 to 3.0 Hz. This signal has been used effectively for left/right computer cursor positioning and discrete switch control. Individuals with severe physical limitations such as a near-total loss of facial muscle functionality may retain some degree of control over eye motion, which the Cyberlink can exploit.

The second channel is band pass derived between 0.5 and 45 Hz, falling within the accepted ElectroEncephaloGraphic (EEG) range. A patented lock-in decoding algorithm [2] subdivides this region into ten component frequency bands with the following frequency centers: three low frequency bands (centered at 0.95, 2.75 and 4.40 Hz), three mid frequency bands (centered at 7.75, 9.50 and 11.45 Hz) and four high frequency bands (centered at 13.25, 16.50, 21.20 and 25.00 Hz). Band-pass magnitude values are derived. For convenience the 10 frequency bands are referred to as F1 through F10. The low frequency bands (F1-F3) are sensitive to eye movements, and the high frequency bands (F7-F10) are sensitive to forehead muscle activity. The bandwidths of each frequency band can be user adjusted, resulting in control of the responsiveness of the frequency magnitude value. The default bandwidth has a 3dB point of 0.6 Hz about the center frequency.

Able-bodied participants have shown that continuous control of these frequency bands is often learned first through subtle tensing and relaxing of various muscles including forehead, eye and jaw muscles. After a few sessions, however, participants began to experiment with more efficient, internal and perhaps EEG-based control methods [3] [4]. It was felt this result would be of particular value for the population whose physical limitations often preclude the use of facial and precise eye muscle-based access pointing devices.

Envelope-detected between 70 and 1000 Hz, the third channel is defined as an ElectroMyoGraphic (EMG) signal. It responds to contractions of the masseter and frontalis muscles and is well suited to discrete on/off switch closures, keyboard commands, and functions of the mouse buttons for users with any significant residual of facial muscle functionality. In a study of Cyberlink EMG discrete control with able-bodied participants [5], response accuracy was found to be extremely high, approximately 98%, and reaction times fell between 0.18- 0.2 seconds, a range considered to be the limit of simple reaction time. Several participants achieved 15-20% faster reaction times with the Cyberlink EMG discrete command than with a manual button.

The EMG can be used as an analog control. One-axis continuous tracking studies have shown that Cyberlink able-bodied users can achieve 90%+ accuracy after a few hours of training [4][6]. Five able-bodied participants participated in a target acquisition study to evaluate the Cyberlink mouse as a hands-free mouse replacement [7]. After four 30-minute training sessions, all five participants were able to use the Cyberlink mouse to position and click the cursor on randomly appearing (Windows icon-sized) targets. Their target acquisition times were often under four seconds and compared favorably with their manual mouse performance on the same task, despite far greater experience with the manual mouse. Several participants reported control with the Cyberlink mouse eventually began to feel more natural and automatic, although it required more conscious effort than the manual mouse initially.

The results of the target acquisition study and other studies with able-bodied participants have positive implications for disabled users. The action of translating and presenting a wide range of forehead bio-signals in an engaging real-time display or through a stimulating training game appears to foster the user to achieve a functional level of conscious control in a very intuitive and efficient manner.

Experimental Approach

The first step was developing the necessary software to generate the needed software for evaluating the possibility of participants using the Cyberlink for computer control. A Cyberlink software platform was developed that could be used by people with disabilities to access computer technology. As part of this platform two specific tests were created; Click Test and Acquire Test. A population of participants was gathered and tested with the test software. Data was collected and results were analyzed.

Click Test Software

The Click Test was developed to test the response time of participants using the Cyberlink (Fig. 1). The participant's task was to respond as quickly as possible to the appearance of targets by generating Cyberlink click events. When the participant generated a click event in response to a target, the displayed target disappeared. Each trial consisted of 16 sequentially presented targets: four possible locations, four times per location, presented in random order. At the beginning of each trial, a three second countdown timer was displayed to allow participants to prepare for the test. Once the countdown reached zero, a pre-target timer was started. If a click event was triggered by the participant during the pre-target timer period, the timer was reset to zero seconds and a false click was registered. When the pre-target timer reached the pre-target max time the first target in the trial sequence became visible. When and if the participant created a Cyberlink click the target disappeared, and the pre-target timer was restarted. This sequence was repeated until a total of 16 targets were presented to the participant and the participant responded with a Cyberlink click. A trial could be stopped before completing the 16 targets by the test administrator (TA) if the participant indicated they wanted to stop or the participant failed to respond in a reasonable time. A reasonable time was decided by the TA based upon experience with the participant.

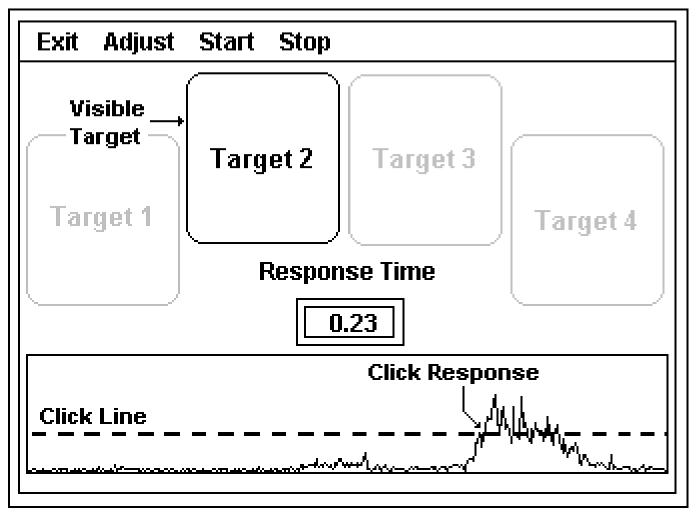

Figure 1: Click Test representation

Bright colors were chosen for the four targets. The participant's Cyberlink click signal was displayed in a sub-window along with a reference Click Line. When the participant's signal went above the Click Line feedback was provided that a click was detected through a click sound and by displaying the message "Single Click" in the sub-window. Participant's Response Time was displayed as well. The participant used the EMG or Muscle (M) signal for creating clicks. If the participant was unable to demonstrate some control with M, the TA was instructed to re-set the Cyberlink control to the F7 (13.25 Hz) signal. If

F7 could not be controlled the TA switched to the F4 (7.75 Hz) signal. If M was used as the control the pre-target max time was 2 sec, if F7 or F4 was used the max time was 10 sec. The pre-target timer was employed to insure the participant could lower their control signal and keep it below the click line during the pre-target time to indicate they could consciously control the Cyberlink.

Acquire Test Software

The Acquire Test was developed to evaluate the participants' ability to move a cursor to a randomly selected target (Fig. 2). Testing could be performed in three modes; up/down axis, left/right axis and two axes simultaneously. The test consisted of 40 possible target sites distributed in a circle about the center of the Acquire Test field. Each target was 48x48 pixels, roughly 16.25x16.25 mm on an 800x600 monitor display. For up/down trials, 10 targets were used extending from the center of the field along the north/south axis. For left/right trials, 10 targets were used extending from the center of the field along the east/west axis. For combination trials, targets randomly appeared at 45 degree intervals around the center of the field. Example target positions are shown in light gray in Fig 2. Note the one target in black; this is representative of the visible target the participant might be moving towards with the cursor. At the start of each trial, the participant's cursor was held in the center of the field while a timer counted down from three to zero seconds. A random target then appeared and the participant's cursor was released. When the participant moved the cursor and touched the target a sound was generated and the participant's cursor was automatically returned to center. Again, the cursor was held in the center. After 2 seconds, a new random target would appear and the cursor was released. As with the Click Test, if the TA observed the participant could not control using M, then F7 was attempted as the up/down control, and if not F7 then F4. For left/right control Cyberlink signal F2 (2.75) was used. For single axis control cursor movement was restricted to that axis only.

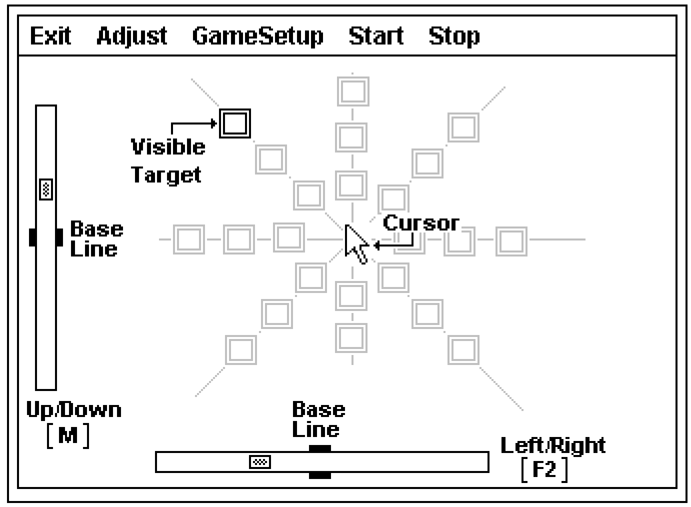

Figure 2: Acquire Test representation

Participants for the Study

To provide a large range of data, it was decided that twenty-five participants that had no prior means of computer access would be studied. Participants were initially recruited from the Schiefelbusch Clinic, University of Kansas, in Lawrence KS. The study was expanded to include participants from three other centers: Providence Center in Portland, OR, Success for Kids in Loma Linda, CA, and the MDA/ALS Center of Hope in Philadelphia, PA. To obtain the twenty-five participants, the TAs used Cyberlinks to evaluate potential participants for the clinical trial. A total of 32 individuals were evaluated from which 25 participants were selected. Seven of the 32 potential participants were unable to exhibit control of the Cyberlink and were thus not included in this study.

Participants included female and male children and adults with CP, ALS, and brain injuries (BI). Participants were grouped into three populations: those diagnosed ALS, those diagnosed CP and the remaining participants with disabilities which included brain injuries (Tables 1 and 2). Participant grouping was done as a result of reviewing disabilities.

Table 1: Subjects by group with ALS and CP designations

Subject	Age	Onset	Disability	Vent	Trach	G-Tube
ALS1	39	26	ALS	✓		
ALS2	56	45	ALS	✓		
ALS3	42	32	ALS	✓		
ALS4	62	49	ALS	✓		
ALS5	20	NA	Paralyzed from neck down	✓		
Subject	Age	Onset	Disability	Vent	Trach	G-Tube
CP1	15	Birth	CP, High Spasticity			
CP2	11	Birth	CP, Right Field Hemiopsia			
CP3	44	Birth	Athetoid CP, Deafness			
CP4	14	Birth	CP secondary to Meningitis			
CP5	13	Birth	CP			
CP6	15	Birth	CP, High Spasticity			

The only diagnosis for participant ALS5 was paralyzed from the neck down and on a ventilator. Since he exhibited cognition and was paralyzed with ALS like symptoms, he was included in the ALS group.

Table 2: Subjects by group with BI designation

Subject	Age	Onset	Disability	Vent	Trach	G-Tube
BI1	55	49	TBI, Memory problems, Diabetes			
BI2	23	15	TBI, Some Diplopia			
BI3	20	19	Encephalitis Quadriplegic			
BI4	7	5	Near Drowning, CP, Spastic Quadriplegia, Mental Retardation			✓
BI5	7	3	PVS, Near Drowning, Spastic Quadriplegia, Seizure Disorder	✓	✓	✓
BI6	12	5	TBI, Subdural Hematoma, Central Apnea, Autonomic Bradycardia	✓	✓	✓
BI7	18	12	TBI, Profound Mental Retardation, CP, Severe Spasticity	✓	✓	✓
BI8	15	Birth	Profound Mental Retardation, Seizure Disorder, Obstructive Apnea		✓	✓
BI9	12	Birth	Profound Mental Retardation, CP, Seizure Disorder		✓	✓
BI10	3	Birth	28 Week Gestation, Legally Blind, Deaf	✓	✓	✓
B11	3	Birth	24 Week Gestation, CP, history of Cardiac Arrest	✓	✓	✓
BI12	7	Birth	Fryn's Syndrome, Seizure Disorder, Developmental Delay	✓	✓	✓
BI13	3	Birth	31 Week Gestation, Dystrophy, Hypoxic Ischemic Encephalopathy	✓	✓	✓
BI14	22	11	CP secondary to Encephalitis			

Data Collection and Analysis Software

Data was automatically collected for each trial. A file was created which contained task, participant name, date, time, and all Cyberlink adjustment and system settings. Raw time history data was collected for later playback and analysis. Qualitative data was recorded by the TA in the form of journal entries and video tapes. All data was sent back to Brain Actuated Technologies for subsequent analysis. Playback and viewing software was created for viewing and analysis of the collected data.

Data Analysis

Each trial was viewed to determine if the participant was exhibiting conscious control. Subsequent analysis was only performed on data in which participants exhibited conscious control. Response times (RT) to each target were computed and tabulated for all participants for both Click and Acquire tests. False clicks (FC) were computed and tabulated for all participants for their Click tests. From these values, average reaction times (RT avg), standard deviations of average reaction times (RT sd) and false click averages (FC avg) were computed for each participant across all targets for the Click and for the Acquire tests. These values are presented in Table 3 along with number of targets per participant (Targets), control signal (Ctrl), and group averages. Entries are blank for those cases in which there was no data for a participant. The data presented represents average response times across all targets. In this way a single measure could be computed for each participant for the Click and the Acquire tests.

Table 3: Click Test and Acquire Test results for all subjects

Subject	Click Game					Acquire Game										
						Up/Down				Left/Right				Two Axes		
	RT avg	RT sd	FC avg	Targets	Ctrl	RT avg	RT sd	Targets	Ctrl	RT avg	RT sd	Targets	Ctrl	RT avg	RT sd	Targets
ALS1	0.22	0.06	0.07	96	M	0.7	0.31	160	M	1.16	1.06	120	F2	3.57	4.41	180
ALS2	0.39	0.19	0.14	320	M	2.18	1.79	220	M							
ALS3	0.42	0.09	0.0	320	M	1.88	1.02	220	M	5.06	7.91	220	F2	9.13	10.5	220
ALS4	1.68	2.70	0.1	123	M	5.71	7.09	60	M	4.01	3.18	40	F2	29.1	34.8	17
ALS5	0.73	0.42	0.5	8	M											
ALS avg	0.94	1.07	0.2	173		3.79	4.06	165		3.41	4.05	127		13.9	16.6	139
CP1	2.67	3.28	9.1	84	M	13.2	16.0	56	M							
CP2	4.03	4.76	0.4	128	M	4.82	5.54	84	M	17.1	26.8	40	F2			
CP3	1.44	1.34	8.1	102	M	7.36	9.80	180	M							
CP4	9.36	10.8	1.7	113	M	11.9	14.1	120	M							
CP5	4.34	3.71	3.5	16	F7	13.0	16.2	43	F7	24.4	33.9	20	F2	142.9	169.6	3
CP6	0.36	0.28	0.1	320	M											
CP avg	3.70	4.04	3.8	132		10.1	12.3	97		20.8	30.4	30		142.9	169.6	3
BI1	1.59	1.52	0.9	153	M	9.01	19.5	134	M	13.2	30.1	66	F2			
BI2	7.18	7.76	0.5	142	F4	15.0	28.7	100	F4	14.1	21.7	93	F2			
BI3						12.6	12.1	19	M							
BI4	5.82	2.95	3.7	16	M	17.1	29.0	94	M							
BI5						9.53	10.6	40	M							
BI6	16.5	8.59	5.3	6	M	54.1	85.9	4	M							
BI7	2.23	3.75	5.6	26	M	16.5	24.9	58	M							
BI8	1.42	2.37	0.3	32	M	12.1	24.4	39	M							
BI9	15.0	23.4	7.2	49	M	16.4	24.0	80	M							
BI10						13.3	16.8	25	M							
BI11	5.01	5.03	2.9	43	M	20.6	32.4	40	M							
BI12						13.6	20.6	60	M							
BI13	5.15	6.53	1.9	20	M	12.4	18.0	63	M							
BI14	6.02	9.04	4.0	135	M	25.1	43.5	72	M							
BI avg	6.59	7.10	3.2	62		17.7	27.9	59		13.6	25.9	80				

Missing data indicates that participants were unsuccessful in completing the Click Game or Acquire Game. From the table please note that 21 out of the 25 participants could complete the Click Game, 23 participants could complete the Up/Down Acquire Game, 7 participants could complete the Left/Right Acquire Game and 4 participants could complete the Two Axis Acquire Game. All 25 participants completed at least one of the games.

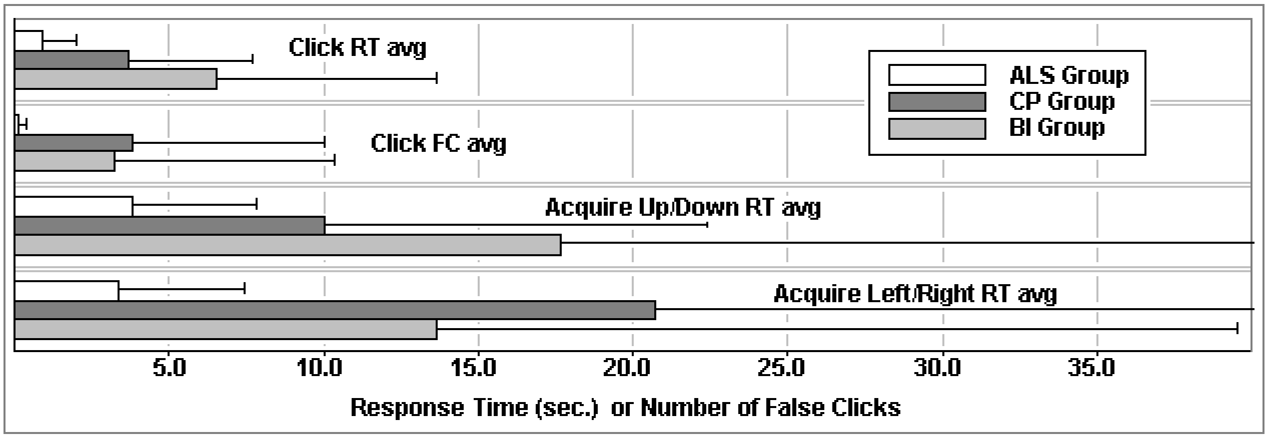

Figure 3: Group averages for Click and Acquire response times (RT) and Click false clicks (FC)

Group averages are plotted in Figure 3 to provide visual comparisons across the three groups. The ALS group exhibited the fastest response times, smaller deviations in performance, less false clicks, and on average there were more trials per participant obtained. The BI group, on average, exhibited the longest reaction times with the greatest variability.

Single Trial Click Test Results

A simple state machine, referred to as "Rule 1", was used to determine Click Test clicking in the clinical trials. When the participant's Cyberlink signal went above the adjustable value, referred to as the Click Line in Figure 1, a click was detected. An alternative criterion was developed to permit the software to ignore involuntary spikes. This approach is referred to as Rule 1f, where the f indicates a filter is used to limit the impact of spurious signals caused by muscle spasms. If the Rule 1f filter was selected by the TA for the participant, a click was recorded only if the participant's signal went above the click line and stayed above the line for a minimum time called "Min-Click". Each participant started with Rule 1 for click determination. If the TA observed that the participant was exhibiting spurious muscle spasms Rule 1f was employed.

To determine the feasibility of using time series analysis to improve the performance of the Cyberlink, an expanded set of rules based on the analysis of the participant's previous actions was explored. This time series algorithm was called "Rule 2". The algorithm for Rule 2 computed the largest value of a running average of the participant's click signal prior to the presentation of a target. The average was taken over an adjustable sliding window of prior signals. A new response time was noted when a post-target-appearing running average equaled a multiple of the largest pre-target running average, indicating that the participant had detected the stimulus and was reacting to it. Experimentation with participant data indicated that a sliding window of 5 samples (.05 sec) and a multiple of 2 provided promising results for the three participants shown below. For other participants, a bigger sliding window and a smaller multiple provided better results.

Representative click responses are plotted in Figures 4, 5 and 6. Each figure includes the control signal time history and the Rule 1 adjustable click line (horizontal long dots). The time the target appeared is marked Target On. The time the click was detected during the actual trials is marked either R1 or R1f depending upon which Rule 1 was operating. The Rule 2 times, determined during data analysis, are marked R2. The three figures are representative of the single click responses obtained for all the participants. These figures were chosen as each figure illustrates noteworthy aspects of participant performance.

Figure 4 illustrates the desirable effect of incorporating the filter in Rule 1f. Note the three crossings of the click line prior to the appearance of the target. Min-Click had been set to 0.06 sec to ignore these three clicks, which were probably involuntary muscle spasms for this participant. The presence of small involuntary spasms is typical for persons with ALS. The filter allows the system to ignore the three `false clicks' that would have occurred prior to the presentation of the target.

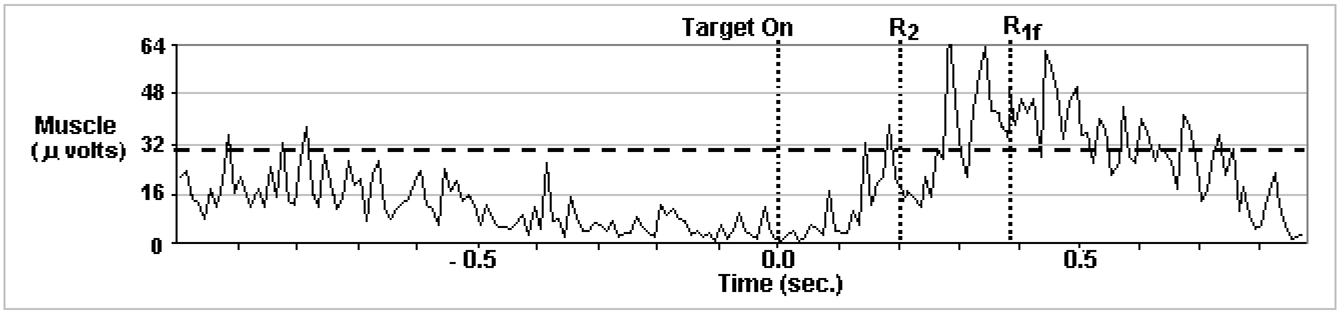

Figure 4: Subject ALS2 click response to single target. Target appears at Target On. Rule 1f detected click at 0.38 sec. Rule 2 would have detected target at 0.20 sec.

A second attribute worth noting is the way the muscle signal, on average, slowly builds over time until it stays above the click line. This is also typical for persons with ALS. By contrast an able-bodied person would normally exhibit a dramatic transition from almost no signal to a large signal, and then back down just as quickly. The Rule 2 click is detected in almost half the time of detection taken by Rule 1f.

Figure 5 illustrates a response behavior similar to that noted above in ALS users. Generation of a facial muscle signal for clicking follows the path of a gradual build-up and then a gradual decay. Note the two gradual build-ups in signal at 1.0 sec and again at 3.0 sec. These small peaks suggest the participant was trying to generate a click signal, was unsuccessful but had to wait at least 1.0 sec before they could try again. The Rule 1f algorithm detected a click at 4.0 sec with a Min-Click time of 0.03 sec. The Rule 2 click relies on the area under the click signal which exhibited a significant change at 0.95 sec, thus it predicted a click more than four times faster than detected by the Rule 1 algorithm.

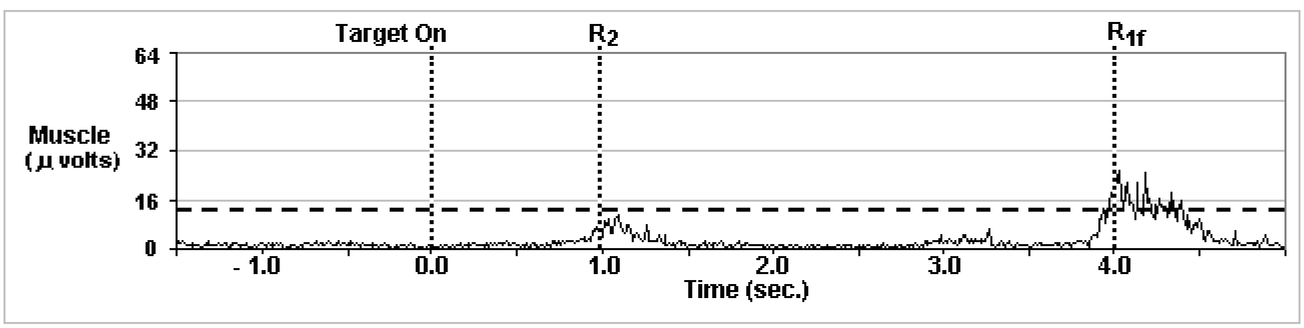

Figure 5: Subject CP2 click response to single target. Target appears at Target On. Rule 1f detected click at 4.0 sec. Rule 2 would have detected click at 0.95 sec.

Figure 6 behavior is typical for the BI group. Note the signal strength in this figure compared to the signal strength of Figures 3 and 4. The y axis scale is 4 times smaller. BI participant signals were often of much smaller amplitude than observed for the ALS and CP groups. In this example a Click Response was detected at 1.26 sec using Rule 1. With Rule 2 a click was detected at 1.54 sec. If Rule 1f had been implemented the peak detected as a click at 1.26 sec would most likely have been classified as a sporadic involuntary click. The subsequent peaks would also have been classified as non-peaks. These results point to the value of Rule 2 to detect increased activity as a measure of intention to click on the part of the participant.

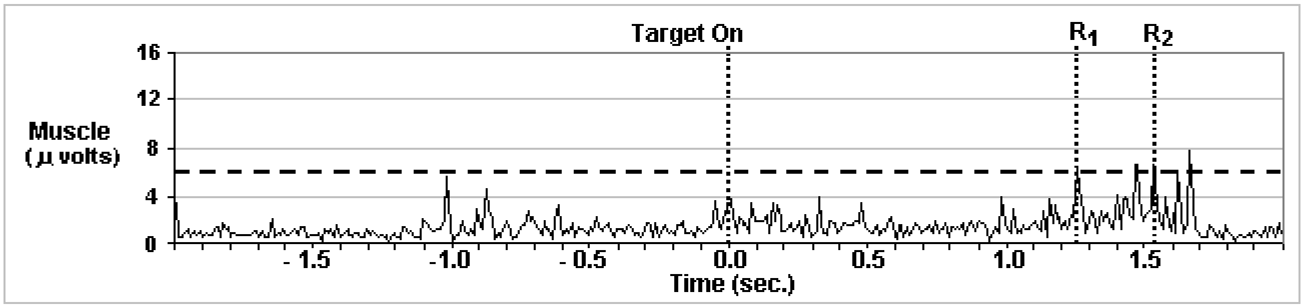

Figure 6: Subject BI7 click response to single target. Target appears at Target On. Rule 1 detected click at 1.26 sec. Rule 2 would have detected click at 1.54 sec.

<u>Control Using F7 and F4</u>

As indicated in Table 4, Participant CP5 used F7 for control and participant BI2 used F4 for control. A close look at their frequency time history data provides an opportunity to better understand what control processes were being used by these participants.

In Figure 7 the participant's control F7 along with their low frequency signal F4 and their muscle signal M are plotted along the same time axis. It is noteworthy that F4 goes down as the click control F7 goes up to create the click. The participant has CP with low muscle tone.

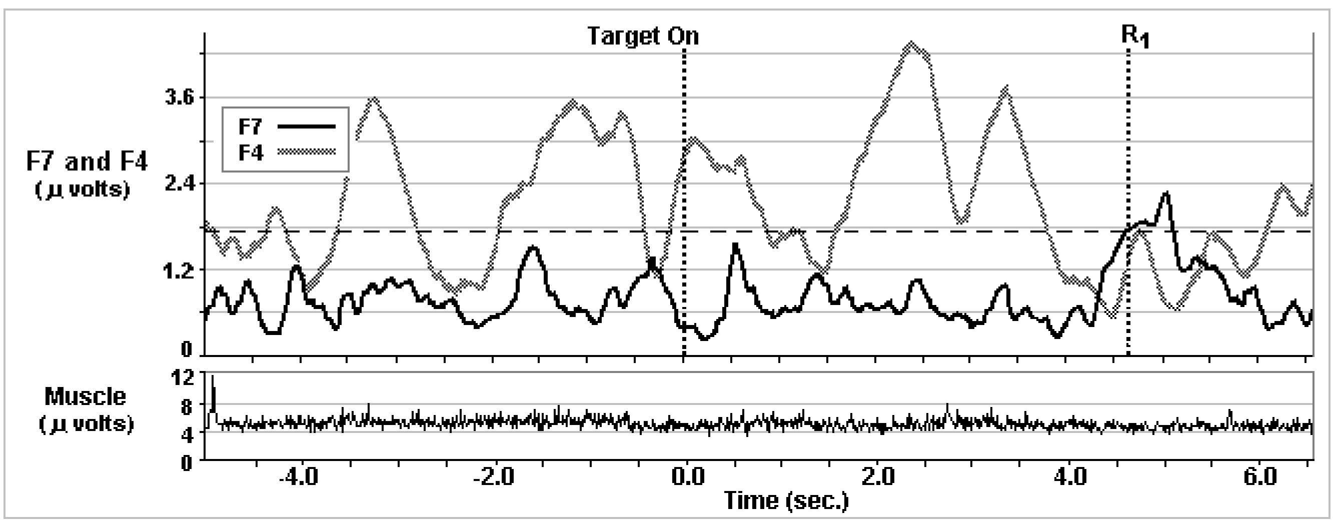

Figure 7: Subject CP5 click response to single target. Subject control signal is F7. Magnitude values of F4 and M also shown.

Figure 8 shows the response for participant BI4 in which he used F4 as the control. The muscle trace indicates that the participant's muscle signal exceeded the maximum input range of the muscle channel input most of the time during the trial. Even though the muscle signal was saturating, the participant was able to make his click control signal F4 go up in response to the presence of the target, while keeping F7 low. The presence of involuntary muscle spasms as show in this Figure 8 was observed in other participants. Of note is that these other participants were setup to use the muscle signal as the control. Thus when their muscle signal saturated their trial was terminated. As seen below, even with the muscle signal saturated, the participant was able to complete the trial using F4 as the control.

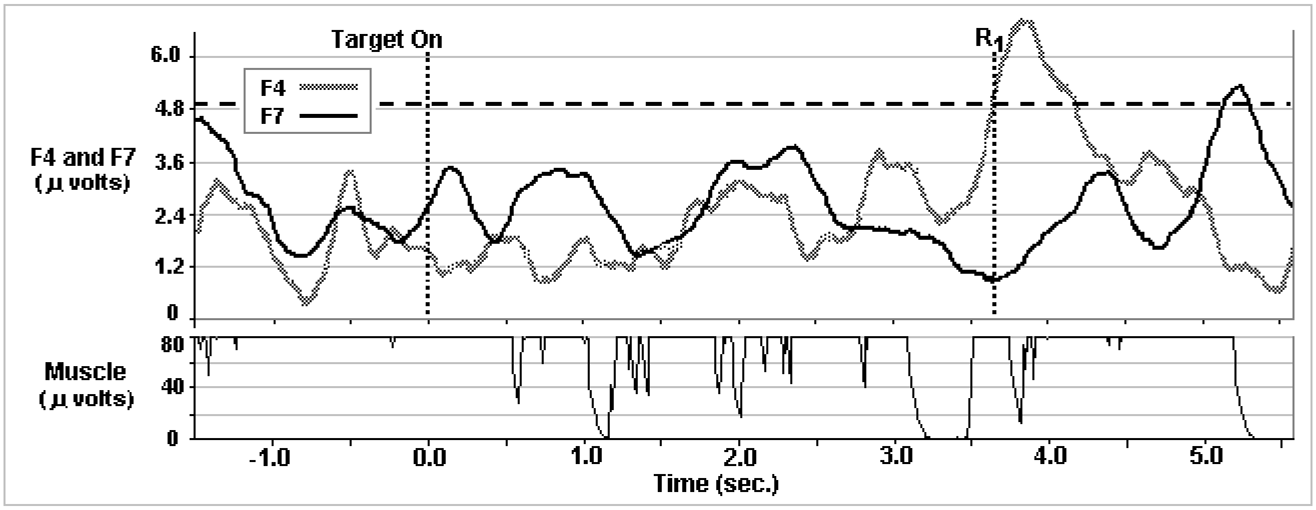

Figure 8: Subject BI2 click response to single target. Subject control signal is F4. Magnitude values for F7 and M also shown

Significance of Study Findings

Answer to Specific Aims Question (1): Can the Cyberlink be used as a computer access solution for individuals with no other documented means of computer access?

A total of 32 individuals with no other documented method of computer access were tested with the Cyberlink treatment to see if they could achieve computer access with the Cyberlink. Of these 32 individuals, 25 were found to be able to exhibit conscious control with the Cyberlink. These 25 individuals were selected as the participant population for this study. All 25 participants were able to complete at least one of the tasks of the Cyberlink treatment. Task completion can be interpreted as a demonstration of computer access, since all participants started with no documented form of computer access.

Approximately 78% of the individuals tested, 25 out of 32, were able to achieve some form of access with the Cyberlink. These results are quite remarkable considering the profoundness of the disabilities of many of the participants. Looking at the successful performance scores can mask the reality of the severity of the participants' disabilities. Tables 1 and 2 provide some indications of the involvement of the participants' disabilities.

ALS1, ALS2 and ALS3 are totally paralyzed except for a small amount of remaining jaw muscle control. Each of these participants started to use the Cyberlink as their means of computer access and communication when nothing else would work for them. They use the Cyberlink in their daily lives as their only means of computer access. In fact the Cyberlink data collection software was modified so they could start and run their own trials for themselves. These three participants exhibited Click reaction times that were comparable to reaction times obtained by able-bodied users.

As a contrast to the above referenced ALS participants the data for participant ALS4 represents the first time working with the Cyberlink. He ran one session with the Cyberlink; his results indicate that he was able to achieve successful control. At the time of running this session he had no other form of computer access. The participant could move his eyes for yes and no, with his simple method of communication he indicated that he was quite impressed with the Cyberlink system.

Prior to working with the Cyberlink participant BI7 had the diagnosis of "Persistive Vegetative State" (PVS). As a result of working with the Cyberlink the participant's PVS diagnosis was removed. The staff at Success for Kids, where participant BI7 resides, reported they now have ways to actually interact and communicate with their brain injured kids. Before the Cyberlink, their options were to simply move the kids, read stories to the kids, or sit and watch TV with them. With the Cyberlink they have a communication link.

Each participant of this study has a unique story that is heart warming and heart wrenching. The subjective feedback from the TA's and the performance data from the Click and Acquire tests indicate the Cyberlink is a feasible means of computer access for people with no other access method. Missing data entries reported in Table 3 are indicative of certain tasks uncompleted. Of note is that some participants could complete the Click Game and not the single Axis Acquire Game while some participants could complete the Acquire Game and not the Click Game.

Answer to Specific Aims Question (2): Can Cyberlink control be made more accurate and reliable through the use of machine learning and adaptive control techniques?

As demonstrated in the single trial test results it is possible to recognize and discriminate participant actions using a window of time history to better recognize changes in the user's response patterns. This was referred to as "Rule 2" in the single trial discussion section. The parameters used in this processing rule were data window size, length of time step and discrimination level. The control was limited to a single user action and used a set of parameters that were preset to distinguish the onset of a user response from his background signals.

These findings indicate time series analysis of the data can be effective in distinguishing intended user response from background signal activity. In many cases, this permitted the recognition of the user intention at an earlier time than the simple threshold crossing rule. These findings suggest that implementing an adaptive control based upon time series analysis will be advantageous. An earlier recognition of the user intention will permit the development of software to facilitate the completion of the intended task and the incorporation of an adaptive control scheme will facilitate self-adjusting of the Cyberlink to the user's abilities. Both of these additions will make the system easier to operate.

Further Insights to Be Gained from the Phase I Study:

All but two of the participants controlled the Click and Acquire test programs with their muscle signals. Participant CP5 used F7 for control. This is a frequency band which is resident in the low beta brainwave region. A single click response is shown for this participant in Figure 7. The simultaneous activity of the participant's F4 frequency band, resident in the low alpha brainwave region, is also shown in Figure 7. The participant's simultaneous muscle signal is included in Figure 7 as well. The muscle signal is quite low with little activity as would be expected by someone with low tone CP. Of interest is the action of this participant's alpha resonance indicated by F4. It was high but went down when they increased there F7 signal to create a click.

In contrast to CP5, participant BI2 used F4 as their control. Figure 8 shows this participant's single click response F4 along with their simultaneous F7 and muscle (M) time histories. From the participant's muscle trace it can be observed that their signal was saturated most of the time. Even with their muscle signal saturated, they were able to control F4 to create a click. As the participant increased their F4 signal their F7 signal went down. A careful look at the participant's muscle signal indicates they briefly lowered their muscle signal prior to achieving a successful click response. It can be hypothesized that the lowering of their muscle signal caused their F7 signal to go down as a result of a broad band affect of the muscle signal into the F7 region. This would not account for the increase in the participant's F4 control signal.

It is generally agreed that the brain generates more alpha resonance when a person relaxes. Further, when a person shifts into a more mentally focused state, alpha resonance will decrease. There may be an interaction between the alpha, beta and muscle frequency bands that could be exploited to facilitate training and control with the Cyberlink. From the above observed results we would hypothesize that appropriate feedback and training of a user's dynamic alpha/beta relationship would be useful as feedback to enhance their Cyberlink control. The more informative and timely that information is being fed back to the user in a closed-loop control situation the better chance the user will have of responding appropriately.

The muscle channel was saturated most of the time for participant BI2. The observed decrease in the muscle signal just prior to the user creating a click response suggests the presence of useful information in the muscle signal. The Cyberlink in its' present form was designed to obtain only the envelope detected magnitude of the muscle frequency spectrum. The availability of individual muscle frequency bands derived with the Cyberlink decoding algorithm may provide more useful feedback for improved control if available.

All the participants tested had problems with neural-muscular control. The ALS group performed the best and with the most consistency (Fig 3). It is hypothesized that the better performance is due to the higher cognitive level of the ALS participants and that the day to day variations in neural muscular control due to ALS degeneration was not as large as was experienced by the CP and BI participants. There was a great deal of within group participant differences in the BI and CP groups (Table 3). It supports the notion that each participant would benefit from a predictive and adaptive control system that could compensate for these differences.

Variability in the data was affected by the disabilities of the participants and other contributing factors. Three of the participants were below the age of 4 years. Participant BI12's disability affected their vision. For these participants the Click and Acquire tests were probably not appropriate. In fact the TAs reported that the participants' attention on these tests did not last a full hour. Most of the participants used some form of medication because of their disability. The medication probably affected the participants' ability to use the Cyberlink. This was confirmed by the TAs and some of the ALS participants. The cognitive ability of the BI group was unknown or unclear for many of the participants. BI participants exhibited control comparable to a poorly trained able-bodied person one time and then exhibited no control or control with weak signals the next. Due to the expected user variability an adaptive controller will be invaluable.

It was insightful to observe the videos of some of the participants with CP as they controlled the Cyberlink. Spastic activity was exhibited. Their head and arms moved in what appeared to be uncontrolled motion. To facilitate the participants' ability to use the Cyberlink, adjustments had to be made to baseline and sensitivity. This resulted in making the Cyberlink less sensitive to the participant's uncontrolled muscle signals or "background noise". Unfortunately it also made the Cyberlink less sensitive to the participants' consciously generated control inputs. CP participants achieved control but they may have had to expend excessive energy to bring their conscious signals above their self generated noise, which was may have been quite fatiguing. We would hypothesize that if these participants were made aware of their self-generated noise in an informative way they would reduce some of the noise. Feeding back a measure of their alpha/beta-muscle ratios in a meaningful signal format would provide them with an informed ability to reduce their noise. For this to be successful it will probably be necessary for them to be engaged in a Cyberlink control task in which the feedback is intimately coupled to the task being performed. Feedback in this context would be more engaging and would have more relevance. When the Cyberlink is used as a switch the user has to move from a relaxed state to an active state to create a click. For someone with CP the lower the signal and background noise is during the relaxed state the less of a conscious signal they will have to create to transition to an active state. Thus if they can be made aware of the level of their relaxed state they may be able to shift down or reduce some of the "uncontrolled" background noise. Each time they were successful at doing this and experienced the reduced effort needed to transition to an active state would be effective feedback as well. We envision the paradigm where the user is engaged in control of a

Cyberlink with an adaptive controller that tracks the user's changes and makes the user aware of the changes. In this case the resulting control system of user and Cyberlink would have a good chance of improving over time. The proposed predictive and adaptive Cyberlink controller will be able to provide feedback to create learning paradigms of this kind.

All but two of the participants were able to achieve some degree of one-axis control in the Acquire test. They had at least one signal they could use for Cyberlink analog control. Therefore if mouse control can be achieved with one analog signal, participants may be able to take advantage of the benefit of being able to move the mouse and engage in tasks of direct selection, instead of or in addition to scan and click control. The same benefit might be realized in an on-screen keyboard that can be controlled in a direct select mode. We have begun the creation of software that can be controlled by one analog input. We are also in the process of creating a training task that will provide users with the opportunity to experience fine tuning of Cyberlink analog control with a bio-potential controlled "joystick".

Most participants could create a click. As a result of our findings we have begun to create software that will provide mouse and list based on-screen keyboard access, controllable through the combination of analog and click control signals, or through only click control.

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