University of Alberta

Evaluation of a Tooth-Click Activated Enablement Device for Computer Access

by

Tyler Simpson

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of

Master of Science

Department of Biomedical Engineering

Edmonton, Alberta
Spring 2008

Your file Votre référence
ISBN: 978-0-494-45887-7
Our file Notre référence
ISBN: 978-0-494-45887-7

ABSTRACT

One goal of assistive technology research is to provide alternate methods of accessing devices. In severe cases of spinal cord injury or other neuromuscular diseases, a person's ability to use their hands and arms may be entirely impaired. Computer access options for these people are limited and often very cumbersome. Any improvements to computer access may promote independence and lead to improvements in quality of life. The main goal of this thesis was to evaluate the effectiveness of using tooth-clicks to emulate computer mouse button functionality. Intentional tooth-clicks can be detected with an accelerometer by recording jaw vibrations near the ear. A tooth-click detector was paired with a head-tracking camera for cursor control, and compared with existing alternative mouse devices. Results showed that the tooth-click system was 18 - 24% slower than a sip-and-puff controller (the fastest alternative tested), but it was more reliable, comfortable, and hygienic.

Table of Contents

List of Tables

List of Figures

List of Abbreviations

Abbreviation	Definition
ALS	Amyotrophic Lateral Sclerosis
ANOVA	Analysis of Variance
AT	Assistive Technology
BCI	Brain Computer Interface
CP	Cerebral Palsy
EEG	Electroencephalogram
FFT	Fast Fourier Transform
HMM	Hidden Markov Model
ISO	International Standards Organization
MS	Multiple Sclerosis
PCA	Principal Components Analysis
PDA	Personal Digital Assistant
RAM	Random Access Memory
SCI	Spinal Cord Injury
USB	Universal Serial Bus

CHAPTER 1: ASSISTIVE TECHNOLOGY AND TOOTH-CLICK DETECTION

1.1 Introduction

Spinal cord injuries (SCIs) and other neuromuscular disorders can pose significant barriers to activities of daily living. Mobility is an obvious concern for people with disabilities, and has an active field of research. Even more problematic are conditions resulting in upper limb paralysis, where a person's ability to interact with their environment may be severely limited. Current technology is unable to restore full hand function for people with severe upper limb paralysis, and for such people, alternative ways of interacting with the environment are necessary for independence. We believe a new hands-free remote switch activated by tooth-clicks (Prochazka 2005) can provide an effective interface for controlling devices, with an immediate application in computer access.

The first chapter of this thesis will cover the motivations for developing a tooth-click interface for computer access. The relevant background of the assistive technology field will be discussed, followed by a description of the tooth-click system. Finally, a strategy for evaluating the tooth-click device will be covered. Chapter 2 reports on the results of the testing and evaluation of the tooth-click system. Chapter 3 will begin with a discussion on some topics relevant to the implementation of the tooth-click technology and end with conclusions based on the evaluation study results. A description of the work performed by the student is included in Appendix A.

1.2 Assistive Technology and Spinal Cord Injury

The return to the workforce is an important goal for people following a spinal cord injury. Statistically, people with quadriplegia are less likely to return to work than people with paraplegia. Tables 1.1 and 1.2 show the employment rates of people with SCI at the time of injury, and eight years post-injury. There is an obvious need for facilitating the return to work for individuals with disabilities in order to improve the post injury employment rate. Computers can provide access to employable skills for people with disabilities, which may in turn improve the likelihood of returning to the workforce. Beyond employment, computers are also an important avenue for education, socialization, entertainment, and access to information and services for people with disabilities. A recent study (Drainoni, Houlihan et al. 2004) showed that internet use had a positive influence on several health-related quality of life indicators. As such, a device that

Table 1.1: Employment status (for persons aged 16 – 59) at time of injury (NSCISC 2006).

Employed	58.8%
Unemployed	41.2% (includes students, retired, homemakers)

Table 1.2: Employment status among persons 8 years post injury (NSCISC 2006).

Paraplegic	34.4%
Quadriplegic	24.3%

improved computer access could have immediate benefits within the spinal cord injured population.

Many innovative technologies have been developed to address the unique challenges posed by disabilities. Early research in the assistive technology (AT) field had focused on devices designed to augment the communication capabilities of people with limited speech due to a disability. Solutions ranged from portable typewriters to communication boards with voice output to new symbol-based languages (Vanderheiden 2002). The early successes in the communication field encouraged future assistive technology development that would address other aspects of daily living. For instance, things like sip-and-puff control or head-tilt control allow wheelchair users to navigate without the use of their hands.

Currently, the AT field combines expertise from a wide variety of disciplines, including neuroscience, physiology, occupational therapy, electrical and mechanical engineering, and computer science. Efforts to build assistive technologies for computer access date back to the days when personal computers first became commercially available (Vanderheiden 2002). More recently, a sample of 516 survey respondents with SCI found that 67% owned a computer and 65% had internet access in their home (Drainoni, Houlihan et al. 2004). To access these computers, people with disabilities have been using a wide variety of AT products. Often it is impossible to achieve sufficient control capabilities using one single solution. Instead, users often must combine a few different products to create custom interfaces to their computers. A review of AT devices (Turpin, Armstrong et al. 2005) describes several such alternatives to traditional mouse and keyboard input. Popular

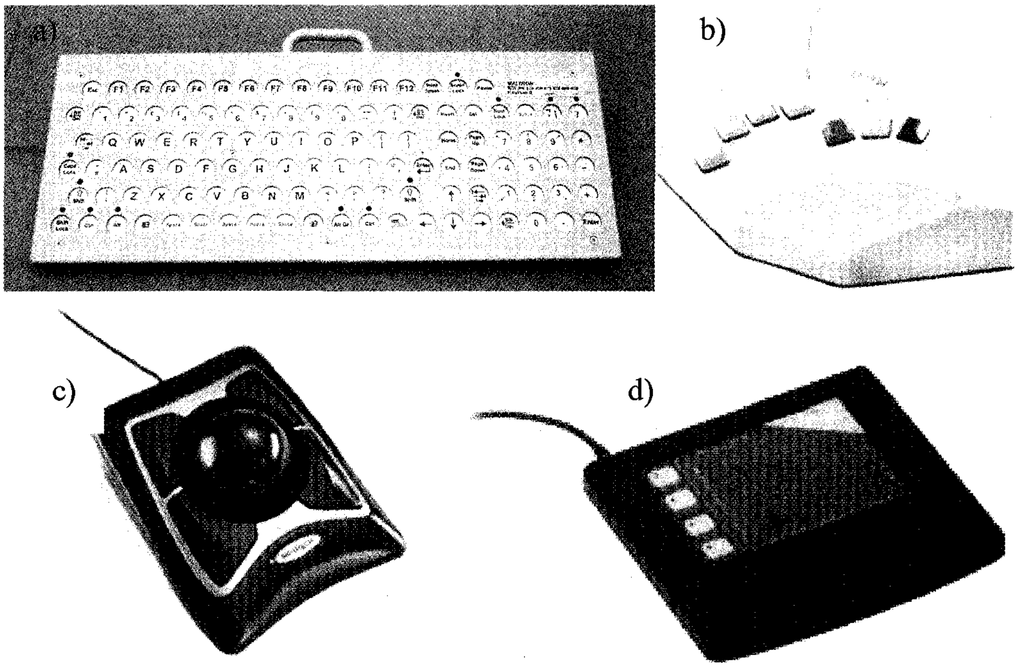


Figure 1.1. Examples of commercially available assistive technology products for computer access. Shown are a) the Maltron Expanded Keyboard (PCD Maltron Ltd., UK), and enlarged keyboard with recessed keys, b) the BAT Keyboard (Infogrip, Inc., USA), a one-hand keyboard with input determined by forming key combinations, c) the Expert Mouse (Kensington Computer Products Group, USA), a trackball with extra buttons for different click actions or other custom macros, and d) the Cirque Smart Cat (Alps Electric Co., Ltd., Japan), a touchpad mouse with scroll and right click capabilities.

products recommended to people with disabilities include expanded or compact keyboards (Fig. 1.1a), keyboards with alternative key layouts (Fig. 1.1b), trackballs (Fig. 1.1c), joysticks, touch pad mouse systems (Fig. 1.1d), and head-tracking camera mouse devices. Of these options, only the head-tracking systems were usable by people with no hand function. The development of a new pointing device may meet the needs of people who are unsatisfied with existing AT approaches.

Head-tracking camera mouse devices are typically mounted on top of the computer monitor and track user head movements. The term "head-mouse" is often used to describe these systems, as the Origin Instruments Headmouse is a popular brand whose name has become synonymous with the product. Other competing head-tracking devices include the Madentec TrackerPRO and the NaturalPoint TrackIR. These devices track a reflective marker worn on the user's head and translate the user's head movements into cursor movements on the computer screen. Other similar strategies for tracking head movements have been developed (Angelo, Deterding et al. 1991; Kanny and Anson 1991; Bradski 1998; Chen, Tang et al. 1999; Betke, Gips et al. 2002; Chen, Chen et al. 2003), but infrared camera systems have been popular as a low-cost solution. An external switch for generating left and right button clicks may be combined with the head-mouse

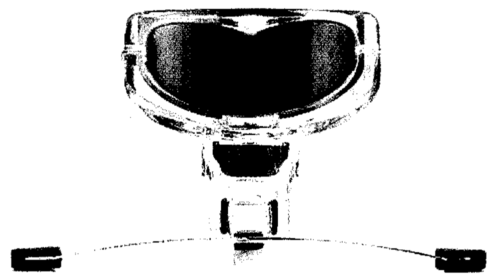


Figure 1.2: The TrackIR (NaturalPoint, Inc., USA) is an affordable head tracking camera device. Shown here is the device used in the study. This model has since been made obsolete by the release of a new product version.

Figure 1.3: The Sip/Puff Switch with Headset (Origin Instruments, Corp., USA) that was used in the study.

to provide full mouse functionality. The TrackIR device (seen in Fig. 1.2) was used in this study as it was the more affordable option.

Sip-and-puff switches and dwell selection software are two popular options for generating button clicks. With a sip-and-puff switch, the user sips or puffs into a mouth tube to produce a left or right mouse click. The mouth tube may be mounted to a headset for ready access as seen in Fig. 1.3. This method may be uncomfortable as the user must hold the tube in his or her mouth for long periods of time. It also requires extra maintenance for hygienic reasons. The dwell selection method consists of holding the cursor steady for a brief amount of time (approximately one second) to generate a mouse click. Different click types (right-click, double-click, etc.) are pre-selected by dwelling on a menu, and then moving to position and dwelling a second time to generate the click. The lag introduced by these dwell intervals causes the dwell selection method to be at least one second slower per click than a direct selection method. Other technologies such as the SCATIR switch (Tash, Inc., USA) allow users to operate a switch using small finger or toe movements, eye-blinks, or eyebrow movements. Such a switch may be used for mouse button control, though it is not as commonly used as sip-and-puff or dwell selection, and was therefore not tested in this study due to time constraints. We hypothesized that using a tooth-click detector in this application as the external switch would provide speed and reliability advantages over popular alternatives, and therefore decided to compare the performance of the tooth-click, sip-and-puff, and dwell methods of mouse clicking.

Another popular assistive technology tool is voice recognition. Voice recognition software enables users to control the computer using verbal commands and converts speech input to text for word processing applications. Cursor control can be achieved through various verbal commands, though this method is much slower than direct point-and-click alternatives. The main concerns with voice recognition software are the reliability of word detection and the cognitive demand of memorizing the various verbal commands. The reliability can be improved by voice training the software over time. This unfortunately makes voice recognition difficult to evaluate as it requires a long-term experiment design. Voice recognition can also be paired with a head mouse system. With this configuration, a user would simply dictate one of a small number of verbal commands to generate mouse button clicks. This type of configuration would likely address the speed and reliability concerns mentioned above, and would have provided a valuable alternative for comparison with the tooth-click system. However, due to time constraints, voice recognition software was not tested in this comparative study.

1.3 Brain Computer Interface Technology

Advances in neuroscience have led to the development of brain-computer interfaces (BCIs), an emerging field of research with potential applications in the assistive technology sector. BCIs for computer access consist of cursor control strategies based on interpreting biological signals recorded on or near the user's brain. These interfaces can be invasive, and currently do not perform as well as existing alternative technologies for most users. In various implementations, the BCI systems read a user's thoughts by analyzing electrode recordings of brain wave patterns or neuronal activity, and produce cursor movements in directions that correspond to different thought patterns (Wolpaw, McFarland et al. 2003; Leuthardt, Schalk et al. 2004; Hochberg, Serruya et al. 2006). These systems are limited by the number of different thought patterns that can be reliably distinguished. Another strategy is to display a selection grid which is automatically scanned through by highlighting different selections (Sellers, Krusienski et al. 2006). When the user's desired selection is highlighted, P300 potentials corresponding to deflections found in electroencephalogram recordings are evoked and recorded with an electrode cap. Wolpaw et al. have shown a P300 system to be effective for people with severe disabilities, such as amyotrophic lateral sclerosis (ALS), and have undertaken a study in which a patient has been using a P300 system at home on a daily basis (Vaughan, McFarland et al. 2006). BCIs are still very experimental systems and are only used if all other options have been unsuccessful. This technology is therefore beyond the scope of the comparison study. Nonetheless, BCI research may have interesting implications for the future of the assistive technology field.

Brain computer interface research may lead to new and creative opportunities for control systems for individuals with severe disabilities. As noted above, cursor control applications have been developed using various electrode recording configurations. However, there would likely be demand for more invasive systems provided they offered significant improvements to quality of life. For instance, one current goal is the development of brain control systems for prosthetic limbs. Taylor et al. (Taylor, Helms Tillery et al. 2003) have shown that the three dimensional control of a robotic arm using neural recordings is possible in real time in an animal model. Human work is not quite as advanced, though Hochberg et al. (Hochberg, Serruya et al. 2006) have shown 2D cursor control by a patient implanted with an electrode array. A limiting factor of this BCI technology is that because of its invasive nature it is really only justifiable in people who have near-complete paralysis and are unable to use the alternative technology.

The tooth-click / head-mouse system is built using proven and relatively inexpensive technology. This confers an immediate commercial advantage to the tooth-click system (and other existing technologies) over BCI alternatives. It is important to pursue research and refine the technology for future applications, though these systems will likely not see much widespread use until the state of the technology improves. A review on BCI research (Schwartz, Cui et al. 2006) cites performance, safety, cost, and overall benefit to quality of life as factors that need to be improved before the technology will move beyond the experimental phases.

1.4 The Tooth-Click Head-Mouse System

By reviewing the advantages and disadvantages of commonly used products, the desirable attributes of a pointing device were identified. These attributes helped guide the development of the tooth-click head-mouse system. An obvious requirement of a new assistive technology product was that it must offer some benefit over existing devices. It was assumed that the ideal device should be easy to use, comfortable, fast, reliable, easy to learn, useable independently, non-invasive, of low maintenance, and compatible with different computers.

Existing AT products for computer mouse button control were researched, and their weaknesses identified. For instance, the sip-and-puff was quick, but tethered the user to the computer, required maintenance to keep mouth tubes sanitary, and was uncomfortable as the user had to hold the sip-and-puff tube in their mouth for the duration of their computing task. Some of these problems could be circumvented by using the software-based dwell selection approach to generating mouse clicks. However, the dwell method was found to be very slow, and it required precise head control. Voice recognition systems were well-suited for text entry, but could also be used for cursor control. The challenge in using voice recognition was that the software required good vocalization, often had reliability problems, and was cognitively demanding due to the amount of commands required. We hypothesized that using the tooth-click detector for mouse button control would offer improvements on all of the above weaknesses.

The development of the tooth-click system occurred along two independent streams, and as such the device and the interface portions of the development will be discussed separately. Device hardware was designed and implemented by Michel Gauthier and Colin Broughton. The device is controlled by a Texas Instruments MSP 430 F1611 microprocessor, powered by a rechargeable 3.7 V lithium polymer battery.

The battery was selected for its low weight (3.1 g) and was capable of delivering 90 mA-h of power output. The microprocessor came equipped with 48 KB of programmable memory and 10 KB of RAM, which was sufficient to process three channels of sensor input at a 9.102 kHz sampling rate.

Figure 1.4: Current tooth-click detector prototype showing case (grey) and sensor arm (black) geometry.

Wireless communication was achieved with a RFM3000 transceiver chip transmitting on the 433.92 MHz band with a Rainsun chip antenna. The sensor is an ADXL330 accelerometer from Analog Devices. The ADXL330 is a 3-axis accelerometer capable of measuring signals in the range of +/- 3 G. The signal bandwidth was defined by capacitors on the output stage, with an upper bound of 1600 Hz on the X and Y axis and 550 Hz on the Z axis. The accelerometer was powered with 3.1 V. The sensor arm extending from the device casing was designed and built by the student. Fig. 1.4 is a rendering of the device showing external geometry.

Positioning of the sensor was determined by examining signal recordings from various locations on the head and face of multiple subjects. It was found that the tragus, part of the ear anterior to the meatus, was the area that produced the strongest signal during tooth-clicks. Initial device prototypes and detection algorithms were designed with sensor placement on the tragus. Later, the area above the tragus and anterior to the helix was also tested. It was known that this area provided an attenuated signal when compared to those recorded at the tragus, but it was still consistently above detection threshold during tooth-clicks, and the sensor was less prone to being shifted out of position than when it was held near the tragus. To improve reliability, the latter position was chosen and a new sensor arm bracket was designed to hold the accelerometer at that point.

1.5 Recognition Algorithms

The algorithm used in the tooth-click device was custom built to achieve reliable detection using accelerometer sensor data. Pattern recognition is a common task in computing applications, and several pattern recognition strategies and algorithms exist. For instance, speech recognition applications often employ hidden Markov model (HMM)-based recognition algorithms (Rabiner 1989). HMM algorithms use statistical models of transitions between hidden states to classify signals of interest. In a voice recognition application, the hidden states may be phonemes, the units of sound which combine to form words. The algorithm would calculate the probability that a measured voice signal was evoked by an underlying word model previously trained and stored in the algorithm's vocabulary. Hevizi et al. have used HMMs to find usage patterns from different subjects using a head mouse device, which could be used to adaptively tune device parameters for better personalized performance (Hevizi, Biczo et al. 2004). A HMM approach to tooth-click recognition may have been effective as a general algorithm that could adapt to different inputs, though it was not feasible to implement on the hardware used by the device due to the computational complexity of such an algorithm.

Other signal analysis techniques that were considered, but again deemed too computationally complex for the hardware, were voice activity detection (Kuo and Lee 2001) and information-theoretic feature extraction (Hild II, Erdogmus et al. 2006). Elements of these algorithms influenced the final identification and classification routines in the tooth-click detection algorithm, which was optimized for code efficiency. Voice activity detection is used in telecommunication applications to separate speech signals from background noise or silence. There are two basic assumptions of voice activity detection: that voice signals have highly variable frequency spectra, and that voice signals are of higher amplitude than background noise. These assumptions were applied to tooth-click detection and influenced the algorithm used to identify candidate tooth-clicks from noise, which is described in Chapter 2.3-A. Information-theoretic feature extraction is a method of optimizing the classification of a signal by determining which features of the signal are most important for classification. In that sense, it is comparable in operation to neural networks or principle components analysis (PCA) for training the classification portion of a recognition algorithm. The principle of identifying important features for classification obviously influenced the development of the tooth-click recognition algorithm. However, again due to hardware constraints, the algorithm had to be optimized for code efficiency instead of performance. More intuitive features were used in the classification algorithm, based on a statistical model of tooth-click energy distribution patterns, as described in Chapter 2.3-A. These features were fast to compute with parameters that were easy and intuitive to retune if future changes to the sensor were necessary.

1.6 Mouse Click Interface

Two major strategies were evaluated for generating different types of mouse clicks. First was temporal tooth-click patterns, and the second was a menu selection method.

The temporal click method required the user to produce tooth-click patterns corresponding to the different mouse button functions. For instance, a single tooth-click generated a left mouse click. Two tooth-clicks in succession produced a double click on the computer, and three clicks generated either a right mouse click or a click-and-drag, depending on the timing of the tooth-clicks. The timing patterns of "click, pause, click, click" for click-and-drag, and "click, click, pause, click" for right-click were used. The temporal pattern strategy necessarily introduced some lag into the clicking process. Since a given tooth-click could either be a single click or the first of a series of clicks in a temporal pattern, the algorithm had to allow for a window in which the user could perform second or third clicks. Hence, single clicks were not transmitted to the computer until a substantial (300-500 ms) time window had elapsed. Other than mis-clicks due to lag, there were also errors caused when any one of the tooth-clicks in a temporal pattern was not properly recognized. The device's detection reliability had been found experimentally to be up to 97% for single clicks.

This was sufficient for producing left mouse clicks as they required just one tooth-click, but other click types requiring double and triple clicks were unreliable.

To alleviate this lag problem, a menu selection interface was implemented. Single tooth-clicks in this method were immediately transmitted to the computer. A circular menu interface popped up at the cursor's location, and the type of mouse click was selected from the menu by moving the cursor (using the head mouse) towards the appropriate selection, or by performing a second tooth-click in the case of a double mouse click. It was initially assumed that the temporal click method would be preferred over menu selection as it was a more direct form of click generation. However, due to the lag introduced in the temporal click system, the menu system turned out to be the faster of the two systems.

The menu interface was used for the evaluation of the tooth-click system. It was circular in design with four quadrants for selecting different mouse functions. The mouse functions mapped to this menu included left-click, right-click, click-and-drag, double-click, and the option to close the menu without generating any click. These functions were mapped to positions on the circular interface that would be intuitive and easy to learn. For instance, a left mouse click would be generated by flicking the cursor (with a small head motion) towards the left section of the menu, while a right-click would be generated by flicking to the right. Click-and-drag was activated by moving to the lower quadrant, and double-clicks was generated by performing a second tooth-click without moving the cursor out of the menu's centre region. Flicking the cursor upwards closed the menu without generating any mouse clicks.

1.7 Evaluation of Alternative Input Devices

Many attributes of an input device are difficult to measure quantitatively (for instance comfort, aesthetics, fatigue, and physical and mental exertion), and as such experiments designed to evaluate different technologies are necessarily limited in scope. For this study, speed and reliability were examined. An independent study that gathered user impressions with a standardized instrument could provide useful information on the qualitative aspects of the devices. Such a study should focus on long-term users as their experience using the devices to complete common computing tasks would be more useful than a first impression evaluation. An example instrument based on ISO standards can be found in (Douglas, Kirkpatrick et al. 1999). It was specifically tailored for hand-operated pointing devices, though some of the measures would be relevant for a head-operated device. Such a questionnaire was not used during this study because the experimenter's association with the tooth-click device was a potential source of bias.

For a quantitative evaluation, the speed and reliability of the devices was examined. These were measured by two software programs in which users were prompted to generate mouse clicks. Previous studies have used "center-out" tasks to measure input speeds of pointing devices (Douglas, Kirkpatrick et al. 1999; Betke, Gips et al. 2002; Hochberg, Serruya et al. 2006). Such tasks consist of moving the cursor to the center of the screen to activate a trial, then reacting by moving to (and possibly clicking on) a target that appears at a randomized position away from the center. The time required to complete each trial is recorded. Some possible modifications to the task include varying the size of the target and, in the case of this study, varying the type of click required at target.

Other pointing device studies have required subjects to complete a task that required multiple cursor movements and clicks. One example of such a study had subjects typing lines of text using an on-screen keyboard (Angelo, Deterding et al. 1991), while a different study had users copying a picture using basic shapes in a drawing program (Kanny and Anson 1991). In both cases, the task was more cognitively demanding than a center-out task, and as a result, the reliability of producing correct clicks could be measured.

Another aspect of device performance that can be quantified is the amount of trials required before successive attempts stop showing systematic improvement. This can be measured by determining the point at which a certain number of successive trials fall within a specified range of each other. In a comparative study on head pointing devices (Kanny and Anson 1991), a subject was determined to have learned the task after completing four to five successive trials with times within 5% of one another. The shape moving task described in this study used a small number of trials repeated with different devices, so it was not possible to precisely determine the point at which no further learning occurred. In a preliminary experiment, it was found that a large amount of improvement in time to completion for the shape moving task occurred within the first two trials. Thus the first two trials per device were regarded as practice and would not appear in the reported results.

The following chapter of this thesis is a modified version of a paper submitted for publication in IEEE Trans. Biomed. Eng. detailing the methodology and results of a study designed to evaluate the tooth-click / head-mouse system. The description of the experiment builds upon the background information contained in these preceding paragraphs. Following that will be a chapter of extended discussion topics and some short concluding remarks on the project.

Bibliography

Angelo, J., C. Deterding and J. Weisman (1991). "Comparing three head-pointing systems using a single subject design." Assist Technol **3**(2): 43-9.

Betke, M., J. Gips and P. Fleming (2002). "The camera mouse: visual tracking of body features to provide computer access for people with severe disabilities." IEEE Trans Neural Syst Rehabil Eng **10**(1): 1-10.

Bradski, G. R. (1998). "Computer Vision Face Tracking for Use in a Perceptual User Interface,." Intel Technology Journal(Quarter 2).

Chen, Y. L., W. L. Chen, T. S. Kuo and J. S. Lai (2003). "A head movement image (HMI)-controlled computer mouse for people with disabilities." Disabil Rehabil **25**(3): 163-7.

Chen, Y. L., F. T. Tang, W. H. Chang, M. K. Wong, Y. Y. Shih and T. S. Kuo (1999). "The new design of an infrared-controlled human-computer interface for the disabled." IEEE Trans Rehabil Eng **7**(4): 474-81.

Douglas, S. A., A. E. Kirkpatrick and I. S. MacKenzie (1999). Testing pointing device performance and user assessment with the ISO9241, Part 9 standard. . Proceedings of the ACM Conference on Human Factors in Computing Systems - CHI '99, New York, ACM.

Drainoni, M. L., B. Houlihan, S. Williams, M. Vedrani, D. Esch, E. Lee-Hood and C. Weiner (2004). "Patterns of Internet use by persons with spinal cord injuries and relationship to health-related quality of life." Arch Phys Med Rehabil **85**(11): 1872-9.

Hevizi, G., M. Biczo, B. Poczos, Z. Szabo, B. Takics and A. Lorincz (2004). "Hidden Markov model finds behavioral patterns of users working with a headmouse driven writing tool." Proceedings of the IEEE International Joint Conference on Neural Networks, 2004. **1**: 669-674.

Hild II, K. E., D. Erdogmus, K. Torkkola and J. C. Principe (2006). "Feature Extraction Using Information-Theoretic Learning." IEEE Trans. Pattern Analysis and Machine Intelligence **28**(9): 1385-1392.

Hochberg, L. R., M. D. Serruya, G. M. Friehs, J. A. Mukand, M. Saleh, A. H. Caplan, A. Branner, D. Chen, R. D. Penn and J. P. Donoghue (2006). "Neuronal ensemble control of prosthetic devices by a human with tetraplegia." Nature **442**(7099): 164-71.

Kanny, E. M. and D. K. Anson (1991). "A pilot study comparing mouse and mouse-emulating interface devices for graphic input." Assist Technol **3**(2): 50-8.

Kuo, S. M. and B. H. Lee (2001). Real-Time Digital Signal Processing: Implementations, Applications, and Experiments with the TMS320C55x. Chichester, England, John Wiley & Sons, Inc.

Leuthardt, E. C., G. Schalk, J. R. Wolpaw, J. G. Ojemann and D. W. Moran (2004). "A brain-computer interface using electrocorticographic signals in humans." J Neural Eng **1**(2): 63-71.

NSCISC (2006). Spinal Cord Injury Facts and Figures at a Glance. U. o. Alabama. Birmingham, The National SCI Statistical Center, University of Alabama.

Prochazka, A. (2005). Method and apparatus for controlling a device or process with vibrations generated by tooth clicks. US Patent 6 961 623.

Rabiner, L. R. (1989). "A Tutorial on Hidden Markov Models and Selected Applications in Speech Recognition." Proceedings of the IEEE **77**(2): 257-286.

Schwartz, A. B., X. T. Cui, D. J. Weber and D. W. Moran (2006). "Brain-Controlled Interfaces: Movement Restoration with Neural Prosthetics." Neuron **52**: 205–220.

Sellers, E. W., D. J. Krusienski, D. J. McFarland, T. M. Vaughan and J. R. Wolpaw (2006). "A P300 event-related potential brain-computer interface (BCI): the effects of matrix size and inter stimulus interval on performance." Biol Psychol **73**(3): 242-52.

Taylor, D. M., S. I. Helms Tillery and A. B. Schwartz (2003). "Information Conveyed Through Brain-Control: Cursor Versus Robot." IEEE Trans Neural Syst Rehabil Eng **11**(2): 195-199.

Turpin, G., J. Armstrong, P. Frost, B. Fine, C. Ward and L. Pinnington (2005). "Evaluation of alternative computer input devices used by people with disabilities." J Med Eng Technol **29**(3): 119-29.

Vanderheiden, G. C. (2002). "A journey through early augmentative communication and computer access." J Rehabil Res Dev **39**(6 Suppl): 39-54.

Vaughan, T. M., D. J. McFarland, G. Schalk, W. A. Sarnacki, D. J. Krusienski, E. W. Sellers and J. R. Wolpaw (2006). "The Wadsworth BCI Research and Development Program: at home with BCI." IEEE Trans Neural Syst Rehabil Eng **14**(2): 229-33.

Wolpaw, J. R., D. J. McFarland, T. M. Vaughan and G. Schalk (2003). "The Wadsworth Center brain-computer interface (BCI) research and development program." IEEE Trans Neural Syst Rehabil Eng **11**(2): 204-7.

CHAPTER 2: TOOTH-CLICK CONTROL OF A HANDS-FREE COMPUTER INTERFACE[1]

2.1 Introduction

Computers have provided people with disabilities an important avenue for social interaction and self expression. A recent study (Drainoni, Houlihan et al. 2004) indicated that internet use has a positive influence on quality of life for people with spinal cord injuries. However, disabilities brought on by such injuries or from other neurological diseases may impose barriers to computer access. Traditional keyboards and mice have been difficult if not impossible to use by people with upper limb paralysis.

Many AT products have been developed to address motor disabilities, though those developed specifically for people with no hand function have been quite complex (Bradski 1998; Chen, Tang et al. 1999; Chen 2001; Turpin, Armstrong et al. 2005; Hitchcock 2006). These technologies ranged from non-invasive (e.g., voice recognition) to very invasive (Brain Computer Interface implants) (Wolpaw, McFarland et al. 2003; Leuthardt, Schalk et al. 2004; Hochberg, Serruya et al. 2006). The goal of this study was to determine to what extent small tooth-clicks that could be produced by persons with severe upper extremity paralysis could be used as control signals for enabling computer access.

[1] This is a modified version of a manuscript that has been accepted for publication in the IEEE Transactions on Biomedical Engineering. Co-authors: Mr. Colin Broughton, Mr. Michel Gauthier, and Dr. Arthur Prochazka.

Discrete tooth-clicks were found to elicit vibrations in the jawbone and skull that could be recognized and used as a control signal to be transmitted to a host computer or other application (Prochazka Nov. 1, 2005). The system described in this study combines existing head tracking technology for cursor movement with a novel wireless transmitter triggered by tooth-clicks for mouse button activation. This approach is much less invasive than BCI alternatives, though it does of course require the user to be capable of controlled head movements and intentional tooth clicks. Head and jaw movements are typically preserved in all but the most severe cases of spinal cord injury, multiple sclerosis and cerebral palsy (Anson, Glodek et al. 2003). The sensor is wireless and is similar to a hearing aid. It is less obtrusive and more convenient than a sip-and-puff system, which requires frequent cleaning and sterilization of tubes.

Using an accelerometer positioned against the ear, the detector device was able to recognize the jaw vibration patterns evoked by the user clicking his or her teeth together. The device was able to distinguish between the transient vibrations associated with intentional tooth clicks and those associated for example with speech or head movements. Tooth clicks triggered a wireless transmission to a receiver box which was connected via a USB interface to a host computer. The control signal caused a menu to be displayed on the computer screen, from which the user could select desired mouse button functions.

The tooth-click device could be paired with any cursor movement system to provide mouse button functionality. Head tracking systems that track infra-red light from a reflective marker on the head provide an affordable and intuitive mode of hands-free cursor control (Angelo, Deterding et al. 1991). This type of device is often referred to as a head-mouse, the original name coined by Origin Instruments Corp. For our study, subjects learned to use a head-mouse and tooth-click combination to control a computer cursor. Mouse actions performed included left click, right click, double click, and left-click-and-drag. Performance with this combined system was compared to existing alternatives.

2.2 Methods

The goal of the study was to quantitatively compare the tooth-click detection system with established alternative mouse-click devices. Performance measures of speed and accuracy were recorded as users performed structured tasks. The tooth-click system was compared with a sip-and-puff controller and with a dwell time program that generated clicks when the user held the cursor in place for a specified time interval. Minimal practice was required to attain a basic level of proficiency with each device. Voice recognition is another recognized method of hands-free cursor control, but in an initial evaluation we found that it required much more initialization and practice to achieve the same level of proficiency, and it was therefore deemed beyond the scope of our study.

A. Equipment

1) TrackIR head tracking camera: Movement of a cursor on the screen of a computer monitor was controlled using the TrackIR head-mouse camera (NaturalPoint Inc., Oregon). The camera, mounted on top of the computer monitor, tracked a reflective dot worn on the user's head and translated head movements into cursor movements. Various head-tracking cameras were available from several different companies. The TrackIR was selected due to its availability, affordability and ease of use.

2) Origin Instruments Sip-and-Puff Switch: Origin Instruments Corporation (Texas), manufacturer of the HeadMouse brand head tracking camera, offered a sip-and-puff switch as an accessory device for hands-free mouse button control. The sip-and-puff tube was mounted on a headset with a flexible mouthpiece, which could be positioned to reach the user's mouth. The user puffed into the mouthpiece to perform a left mouse button click or sipped on the mouthpiece to perform a right mouse button click. The switch had a stereo or mono output to interface with a head tracking camera, though it was not compatible with the TrackIR device. As a compromise, we built an interface device to translate the stereo sip-and-puff signal into USB mouse commands, which could be directly interpreted by the computer.

3) Dragger32 dwell-click software: Dwell clicking was the process of holding the cursor at a target area for a specified interval to generate a mouse button click. The Dragger32 software, from Origin Instruments Corporation, enabled dwell clicking and provided an on-screen menu interface for selecting different types of mouse button clicks. The dwell interval was adjustable, and we chose a value of one second, which avoided annoying false positives.

4) Tooth-Click Detector: The tooth-click detector used in this study was a wireless communication device worn around the ear that sensed when a user clicked his or her teeth. The device that was used for the majority of subjects is shown in Fig. 2.1 (a). A newer prototype, shown in Fig. 2.1 (b), was built and used towards the end of the experiment.

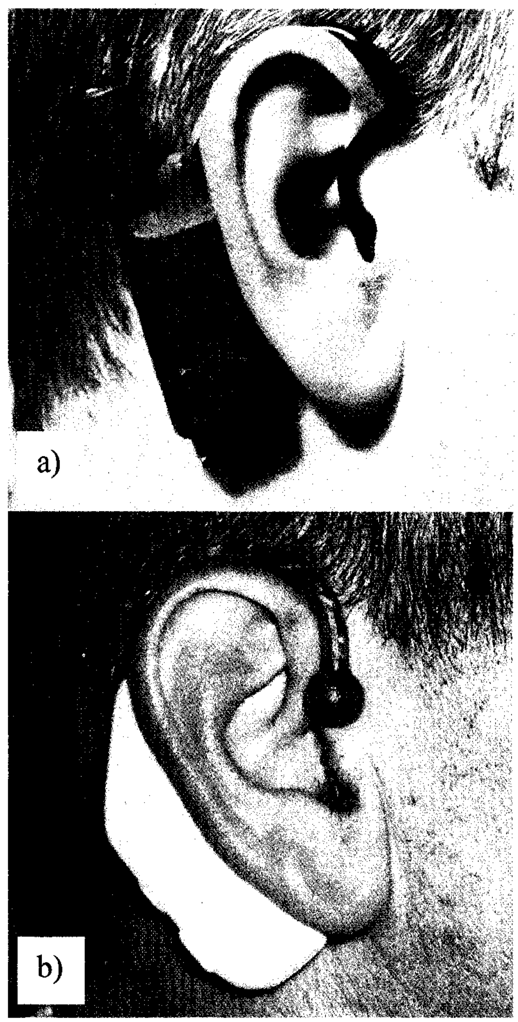


Figure 2.1: Tooth click detector device shown worn behind the ear. The older prototype in (a) was used for the control group and the majority of the patient group. The newer prototype in (b) contained the same hardware and firmware but was repackaged to be smaller and lighter.

The tooth-click detector continually monitored a three-axis stream of accelerometer data. The device's sensor arm was designed to hold the accelerometer in place against the anterior part of the ear, near the tragus, the cartilaginous protrusion anterior to the meatus. It was found that a sensor could pick up strong vibrations from this position during tooth-clicking. The device filtered the incoming data stream and searched for transient vibrations generated by sudden contact between the upper and lower teeth. A tooth-click was distinguished from noise by ensuring the spike energy was contained within a specified time window and was surrounded by relative quiet. All processing required for this recognition task ran internally on the device's microprocessor unit.

5) Tooth-Click USB Receiver Box: The Tooth-Click Detector transmitted a 433.92 MHz transient radio signal whenever a tooth click was detected. A receiver interface was built that interpreted the radio signals and transmitted a USB message to the host computer. The interface was powered via the USB connection with the host computer. We found that reliable communication required the receiver to be positioned within line-of-sight of the user.

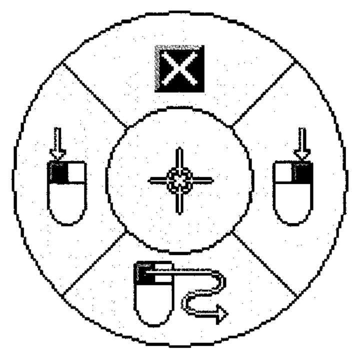


Figure 2.2: Radial menu interface used with the Tooth-Click Device. The menu appeared when the user performed a tooth-click. Different click types were selected by flicking the cursor toward one of the four quadrants. Left quadrant = left click, Right quadrant = right click, Bottom quadrant = left click and drag, Upper quadrant = cancel. A second tooth-click produced with the cursor in the center zone generated a double click.

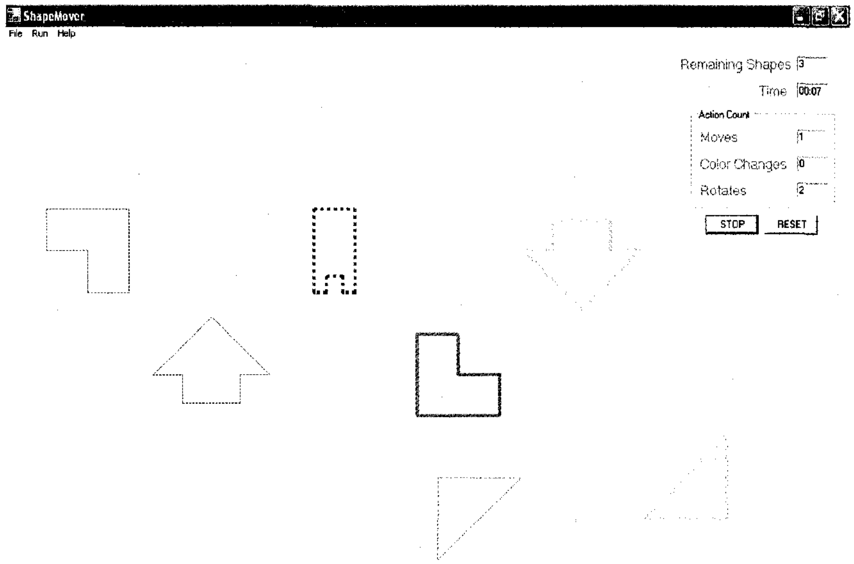
6) Tooth-Click Menu Interface Driver: To emulate the click capabilities of a two-button mouse, a pop-up menu driver was built. When the computer received the USB tooth-click message, a radial menu (shown in Fig. 2.2) was displayed at the cursor position, overlaid on any applications currently running. From the centre of this menu, the user flicked the cursor in one of four directions to activate either left click, right click, click and drag, or to close the menu with no click action. To produce a double click, the user instead produced a second tooth-click without moving the cursor out of the center of the radial menu. Clicks were generated at the cursor's position at the moment the menu was first activated.

B. Experiment Software

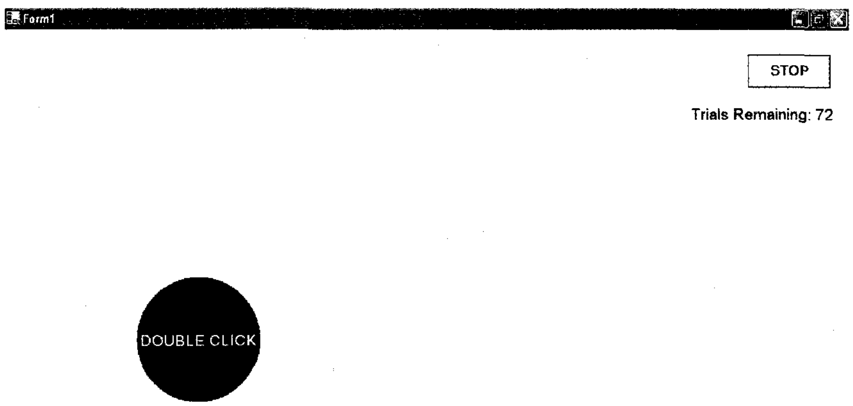
Two software programs were built and used for collecting mouse click data. Both programs provided prompts for different click types and recorded user performance when generating the mouse clicks.

1) Shape Moving Task: Four different shapes and their corresponding targets appeared on the screen, as shown in Fig. 2.3(a). The task required matching each shape's orientation, color, and position to its corresponding target. The user accomplished this task by producing different mouse clicks on the shapes. A right-click rotated the shape by 90 degrees (clockwise). A double-click cycled the shape's color (between three choices: magenta, blue, and green). Shapes were moved on the screen with click-and-drag mouse actions. Once the user correctly matched a shape to its target, the shape was locked in place and highlighted by a gold-colored border.

Trials began with a press of the "Start" button and ended when all four shapes had been locked at their proper targets. The program recorded the total time required to



a)



b)

Figure 2.3: Screen captures from the (a) Shape Moving Task, and (b) Reaction Task. The solid shapes in (a) were moved to their corresponding dashed-edged targets to complete the task. In the reaction task, the user performed different clicks on the buttons as they appeared on the screen.

complete the task and the number of clicks generated by the user. For the experiment's timed trials, all shape and target locations were predetermined, and the number of clicks required was held constant. Each trial required 19 clicks if completed with no mistakes. Clicks beyond the first 19 could therefore be counted as "mis-clicks" for the purpose of quantifying an accuracy score for each device.

Shapes were approximately 150x150 pixels in size and displayed on a 22" monitor, at 1680x1050 resolution.

2) Reaction Task: The reaction task program began with a single circular button displayed at the centre of the screen. The user performed a left click on this button to begin a trial. This centre button disappeared once it was clicked, and a second button appeared after a randomized one to three second delay in one of four positions located towards the perimeter of the screen (North, South, East, or West, see Fig. 2.3(b)). The user reacted to this second button by moving to and performing a specified click on the button. The time taken to generate the correct click, starting from the appearance of the second button, was recorded. The program then reverted to displaying the centre button, allowing the user to begin the next trial.

The buttons were 150 pixels in diameter and spaced at a 385-pixel radius from the screen's centre. Button sizes and locations were modeled after a centre-out task used in BCI research by Hochberg, Serruya et al. (Hochberg, Serruya et al. 2006).

C. Testing Protocol

The two experiment software programs were used to collect mouse click data using the three different button emulation devices. For the reaction task, 80 trials were recorded per device, and for the shape moving task, five trials were recorded per device. The time to complete the experiment ranged from 2.5 to 3.5 hours. In most cases, this was split into two sessions; one session devoted to each clicking task.

The tooth-click system was designed to provide computer mouse functionality for people with disabilities that would hinder their ability to use a standard mouse. The majority of people in the patient group did not have the hand function required to operate a standard mouse. Therefore, a baseline for comparison recorded with a standard mouse was deemed inappropriate.

For each task and device combination, adequate practice time was allowed. We found 10 trials of the reaction task and two trials of the shape moving task to be sufficient.

To account for learning effects, the order in which the devices were used was alternated from subject to subject. Devices were also alternated throughout the shape moving task. It was found that a large portion of the learning effect was eliminated during the allotted practice time.

Subjects were comfortably seated approximately one meter in front of the computer monitor. The experimental software was run on a 22-inch monitor running at 1680x1050 resolution. The equipment was portable, and since some people were seen outside of the laboratory setting, a 15.1-inch laptop running at 1280x800 resolution was also used.

D. Statistics

Data recorded during the two tasks did not follow a normal distribution. A logarithmic transform was attempted but the resulting transformed data set still failed normality testing ($p < 0.005$ using an Anderson-Darling test). Instead, data were compared using a one-way repeated measures ANOVA on ranks. Data sets contained an unequal number of records, so the Dunn's test was used for post-hoc comparisons.

E. Subject Population

The study was performed with the approval of The University of Alberta Human Research Ethics Board.

1) Control subjects: Ten able-bodied adults aged 20 to 38, five male and five female, acted as controls for the study. All were familiar with using computers, though none had prior experience with any of the assistive technologies used in the study.

2) Subjects with paralysis: The tooth-click mouse system was developed for people with paralysis or severe paresis of their upper extremities. A sample of 12 adults aged 20 to 50 with minimal hand function due to spinal cord injury (SCI) were used as the experimental population group. Subjects were recruited in Edmonton, Toronto, and Vancouver. Our ethical approval allowed measurements to be made in these cities at locations agreed upon with the subjects. All subjects were able to produce the stable head movements required to operate the head tracking system. Six people with Multiple Sclerosis (MS), Cerebral Palsy (CP), or Poliomyelitis also performed the experiments, but were analyzed separately as these conditions may introduce physical and cognitive disabilities beyond the impaired hand function, and would thus possibly lead to different results than found in the SCI group. A breakdown of the population tested in this study is shown in Table 2.1.

Table 2.1: Breakdown of study participants.

	Male	Female	Total
SCI	8	4	12
Control	5	5	10
MS	3	0	3
CP	1	1	2
Post-Polio	1	0	1

2.3 Results

A. Tooth-Click Detection Algorithm

The detection algorithm evolved as the sensor was upgraded from a single-axis accelerometer to a tri-axial version. An example of the three channels of raw signal acquired from the accelerometer is shown in Fig. 2.4. Clicks are recognized by comparing the energy of peaks in the accelerometer signal to the energy of the surrounding signal. By defining certain criteria as detailed below, intentional tooth-clicks could be distinguished from noise. The criteria were established experimentally by analyzing hundreds of tooth-clicks and non-click artifacts recorded from nine able-bodied volunteers, and then modeling the energy distribution of these signals. A 1000 sample (nearly 100 ms) window centered on each click was identified for each axis. Fig. 2.5 (a) shows the central 200 samples (nearly 20 ms) of many clicks overlaid on one graph. It can be seen that the signal energy from most tooth-clicks decays to noise floor levels before and after the click peak, and this occurs within the 20 ms window. One click shows significant signal activity before the peak (two smaller peaks located 6 and 8 ms before the main peak). This could occur if the tooth-click was embedded in noise, such as during talking. It was decided that such clicks should be rejected by the detection algorithm, as the device should not trigger during speech. Fig. 2.5 (b), (c), and (d) show different representations of the tooth-click data that were used to conceptualize a model of tooth-click signal behavior.

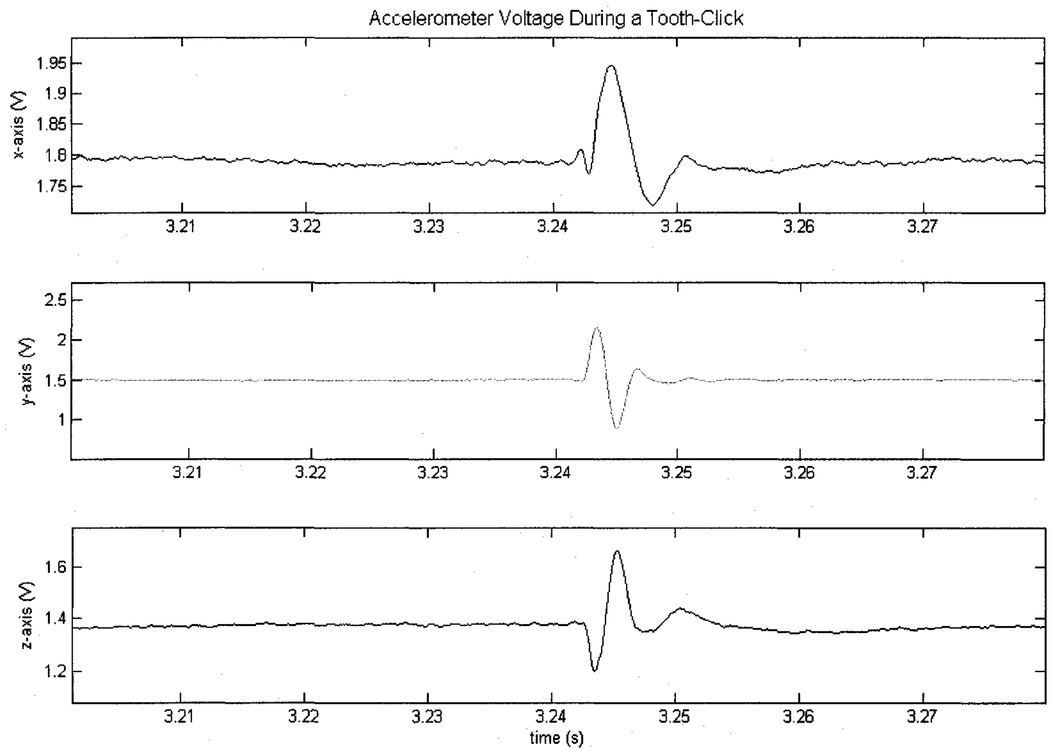


Figure 2.4: Raw tri-axial sensor data showing an intentional tooth-click. In this example, the perturbation is largest along the y-axis. All axes have been scaled independently here to highlight click features.

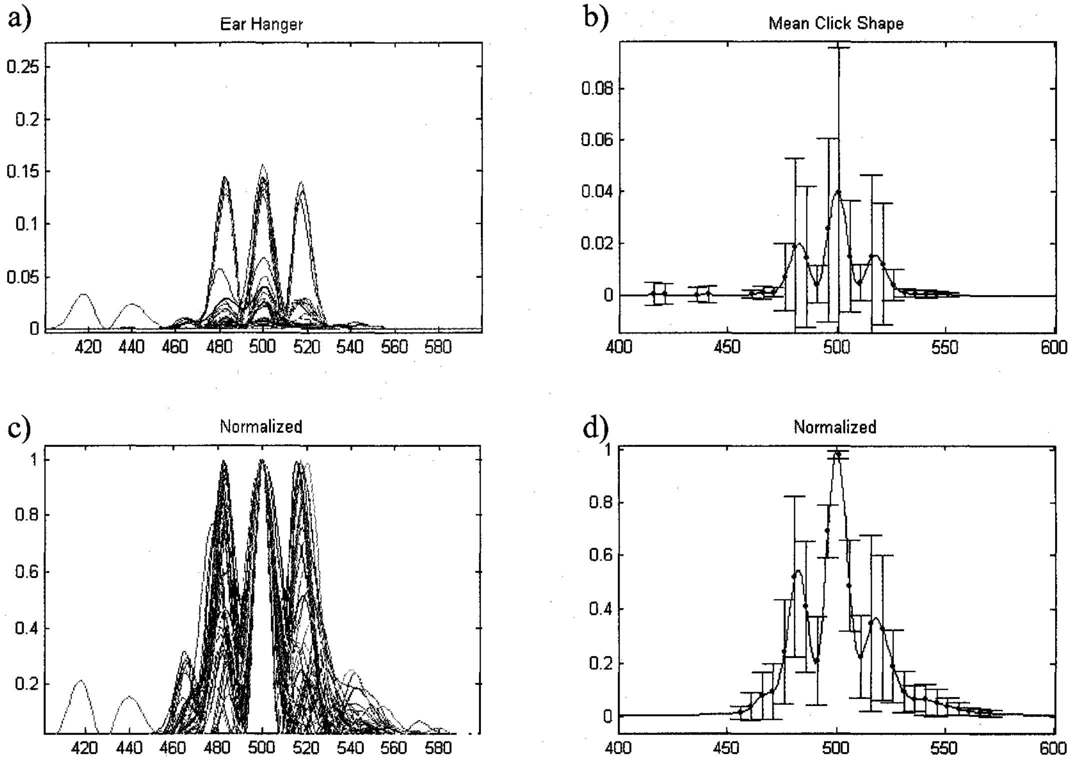


Figure 2.5: Tooth-click signals were aggregated to find trends usable by a detection algorithm. In a) several clicks (from all 3 axes) have been squared to obtain a representation of click energy on a single-axis basis. Each click's peak has been centered and the clicks overlapped. Shown are the central samples of a 1000 sample window. In b) the mean of these clicks, including error bars is shown. Figure c) shows the signals of a) normalized to each click's peak value. The mean and error bar representation of the normalized data is then shown in d). The three main peaks seen in d) are a typical feature of intentional tooth-clicks.

It was assumed that the tooth-clicks recorded from able-bodied subjects would be similar to tooth-clicks recorded from people with disabilities, and that a generalized detection algorithm for both population groups would suffice. This assumption was deemed valid after testing the device with people with disabilities.

The recognition algorithm identified candidate peaks which could have arisen from tooth-clicks and then classified those peaks as either tooth-clicks or non-clicks (noise). Before these higher level decision-making processes were possible, some signal conditioning was performed on the raw sensor data. Accelerometer data were first filtered using a combination of a derivative-boxcar filter and a windowed-sinc filter to both remove the DC offset and suppress high-frequency components above 650 Hz. The resulting signal was squared, and then separated into lobes by identifying consecutive local minima. The width of each lobe (in samples) and the sum of its sample values (i.e., a representation of signal energy) were stored in a lobe buffer. With an average lobe width of 15 samples, a 7.5:1 compression was achieved, and the data were in a convenient format for further processes in the detection algorithm. Other transforms, such as PCA, the fast Fourier transform (FFT), and wavelet analysis were considered for compression and analysis, but they were not used due to microprocessor bandwidth constraints, given that all signal processing must occur in real time. The signals of each axis were analyzed independently, as it was found that the loss of information incurred when combining the three axes negatively affected click detection reliability.

The identification of potential clicks was achieved by adaptive threshold detection. The algorithm was very similar to the one implemented by Colin Broughton in a previous version of the tooth-click detector device. In this version, the algorithm searched all three axes independently. Whenever a lobe entered the search buffer with an energy value that surpassed a threshold, the lobe was stored as the current largest lobe. Incoming lobes on that axis were then examined to see if their energy values were higher than this current largest lobe. If no new lobe surpassed the stored lobe within a span of 18 ms, it was marked for further processing by a classifier algorithm. If a new lobe did exceed the stored lobe's energy value, the lobe was stored as the new current largest lobe and the scan continued until 18 ms of lobe data passed with no new larger lobes found. The search window was set to 18 ms as this was just wide enough to ensure that all major lobes of a tooth-click were included in the search. In some cases, large tooth-clicks were followed by noise (possibly caused by additional contact between teeth as the jaw relaxed) that was above the threshold value for detection and located sufficiently far from the actual click that the algorithm falsely identified this noise as a potential click. The adaptive threshold portion of the search algorithm was implemented as a way of reducing such false-positive identification errors. The threshold value was constantly updated based on the lobe energy values of the previous two clicks detected. When applied to the test set of tooth-click data, noise following large clicks that was otherwise causing detection errors was safely ignored without affecting the detection of real clicks.

Each candidate click (from all three axes) was subject to additional processing in an attempt to classify the signal as either a tooth-click or non-click noise. Two classification tests were created to recognize clicks, based on the expected distribution of signal energy during and surrounding an intentional tooth-click. These tests occurred when a candidate lobe reached the centre of a 128 element lobe buffer, which represented approximately 200 ms of signal data. The first test attempted to establish three equal-width zones centered on the peak lobe, with 80% of the total energy from all three zones contained in the central zone. This was achieved by beginning with the peak lobe in the central zone and the two adjacent lobes in each of the other two zones. The energy distribution was evaluated, and if the central zone was found to contain 80% of the total energy or greater, the test ended. Otherwise, each zone was expanded by one or more lobes (attempting to keep zone widths as equal as possible) and the calculation repeated. If the 80% criterion was not met by the time the three zones had expanded to encompass the lobe buffer, the candidate click was rejected. Otherwise, the algorithm proceeded to enforce the second test, which examined the quiet zones surrounding a peak. This second test identified "quiet" zones encompassing at least 50 ms of lobes on either side of the three central zones identified in by first test. The lobes within these quiet zones were rank ordered according to their energy values. The top 10% of lobes were designated as the "impulse" set, while the remaining lobes were designated as the "ambient" set. The algorithm compared lobes in both sets to the candidate peak's energy value. The test required all lobes in the impulse set to be at least 6 dB under this value, and all lobes in the ambient set to be at least 12 dB under this value. Assuming that these comparisons were found to be true, the candidate signal was identified as a tooth-click. A positive detection on any single axis caused the transmission of a radio signal to the receiver. Clicks could be identified on more than one axis, though the radio transmission routine was limited to occur only once for a given tooth-click.

B. Reaction Time Task

Median reaction times of the control and SCI subject groups are shown in Fig 2.6(a). Table 2.2((a) and (b)) shows paired comparisons with post-hoc significance testing using Dunn's test (evaluated at $p<0.05$). Both subject groups had the fastest median reaction times using the sip-and-puff controller (Table 2.2(a)): tooth-click median reaction times were 18% to 24% longer than sip-and-puff times. Dwell selection was the slowest method in both subject groups with median reaction times around three times those of the other two devices. The between-group comparisons in Table 2.2b showed that the SCI group fared better than the controls using dwell selection, but there was no difference for the other two devices.

C. Shape Moving Task

Time to completion and the number of clicks required were recorded during the shape moving task. Median completion times are shown in Fig 2.6(b), with corresponding paired comparisons in Table 2.2((c) and (d)). Again, sip-and-puff control was the fastest, followed by tooth-click control, both of which were clearly superior to dwell selection (Table 2.2(c)). Sip-and-puff median completion times were 10% to 23% faster than tooth-click times, the differences reaching significance in the SCI group but not the control group. The SCI group had significantly different completion times than the control group when using dwell selection, but not when using sip-and-puff or tooth-click control.

The number of mis-clicks performed during a shape moving trial (Fig. 2.6(c) and Table 2.2((e) and (f)) was an indicator of device reliability. Mis-clicks were calculated as the difference between the total number of clicks performed and the minimum amount of clicks required to complete the task (which was set at 19 clicks required per trial). Users performed the fewest mis-clicks with dwell control, slightly more with tooth-click control, and by far the most with sip-and-puff control (Table 2.2(e)). No significant difference was found between tooth-click and dwell selection time scores for the control group, but the remaining between-device comparisons for both groups were statistically significant. Table 2.2(f) shows that the numbers of clicks required in the shape moving task were similar for the two subject groups, with no significant differences found in the between-group comparisons.

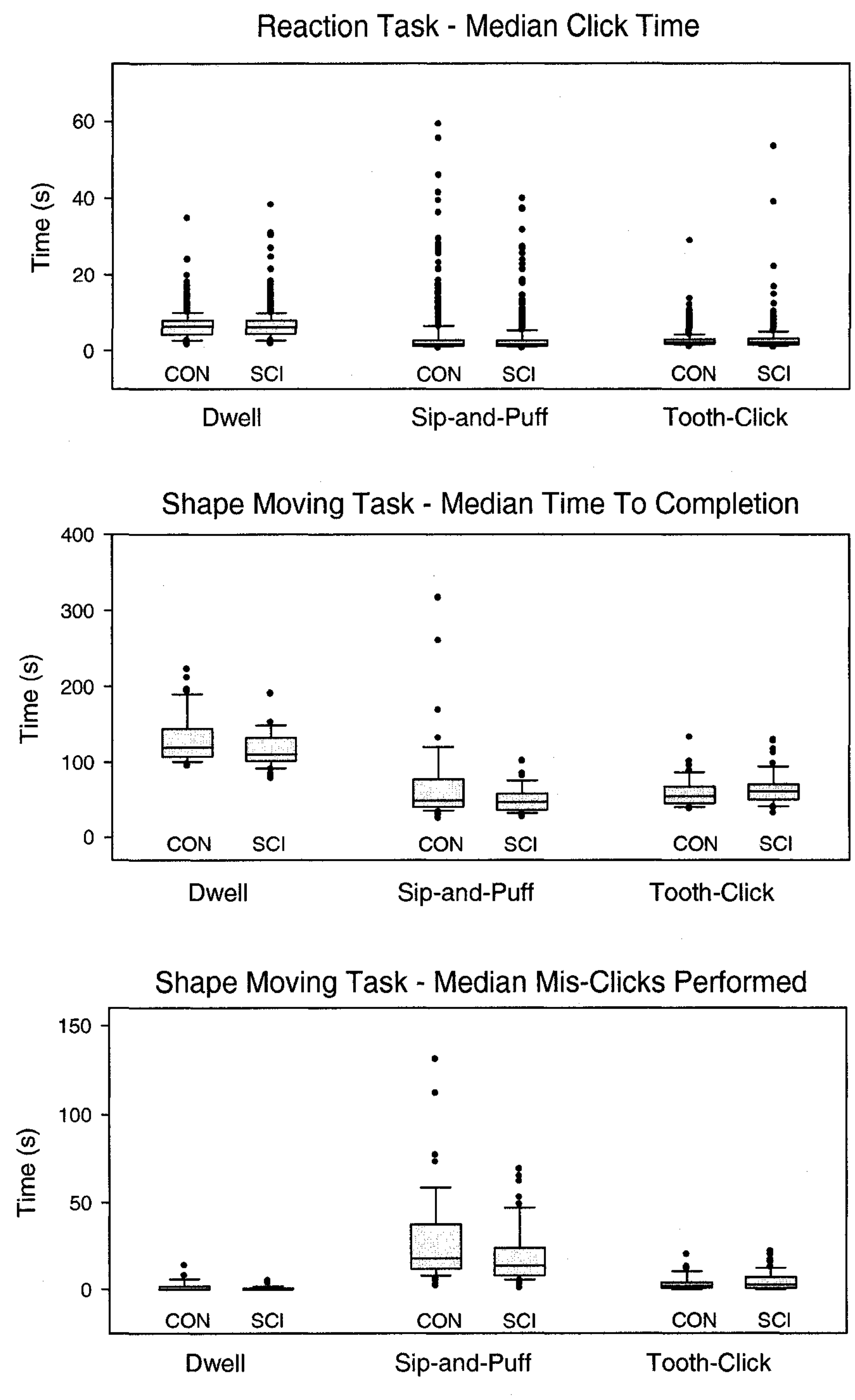


Figure 2.6: Summary of median performance scores, grouped by device. Plot (a) shows the median time taken to click in the reaction task, (b) shows the median time taken to complete the shape moving task, and (c) shows the amount of mis-clicks performed during the shape moving task. Each device grouping includes the control group (CON) and the SCI group (SCI). The box-and-whisker plots show median values (centre line), 25 and 75 percentiles (lower and upper edges of the box), and the 5 and 95 percentiles (whiskers). Dots indicate outliers beyond the 5 and 95 percentiles.

a) **Reaction Task - Time**

	TC vs SP	TC vs DW	SP vs DW
C	SP < TC (1.72, 2.09)	TC < DW (2.09, 6.41)	SP < DW (1.72, 6.41)
SCI	SP < TC (1.68, 2.20)	TC < DW (2.20, 5.91)	SP < DW (1.68, 5.91)

b)

	C vs SCI
TC	NSD (C=2.09, S=2.20)
SP	NSD (C=1.72, S=1.68)
DW	S < C (5.91, 6.41)

c) **Shape Moving Task - Time**

	TC vs SP	TC vs DW	SP vs DW
C	NSD (TC=54, SP=48.5)	TC < DW (54, 120.5)	TC < DW (48.5, 120.5)
SCI	SP < TC (47, 61)	TC < DW (61, 111)	SP < DW (47, 111)

d)

	C vs SCI
TC	NSD (C=54, S=61)
SP	NSD (C=48.5, S=47)
DW	S < C (111, 120.5)

e) **Shape Moving Task - Clicks**

	TC vs SP	TC vs DW	SP vs DW
C	TC < SP (2, 18)	NSD (TC=2, DW = 0.5)	DW < SP (0.5, 18)
SCI	TC < SP (3, 14)	DW < TC (0, 3)	DW < SP (0, 14)

f)

	C vs SCI
TC	NSD (C=2, S=3)
SP	NSD (C=18, S=14)
DW	NSD (C=0.5, S=0)

Table 2.2: Significant differences found from paired testing using Dunn's test. Charts summarize the relationships between devices and between subject populations for the reaction task median click times ((a) & (b)), the shape moving task time to completion ((c) & (d)), and the shape moving task total clicks required for completion ((e) & (f)). Median values are included in parentheses. Note: TC = tooth-click, SP = sip-and-puff, DW = dwell, C = control, S = SCI group, NSD = no significant difference.

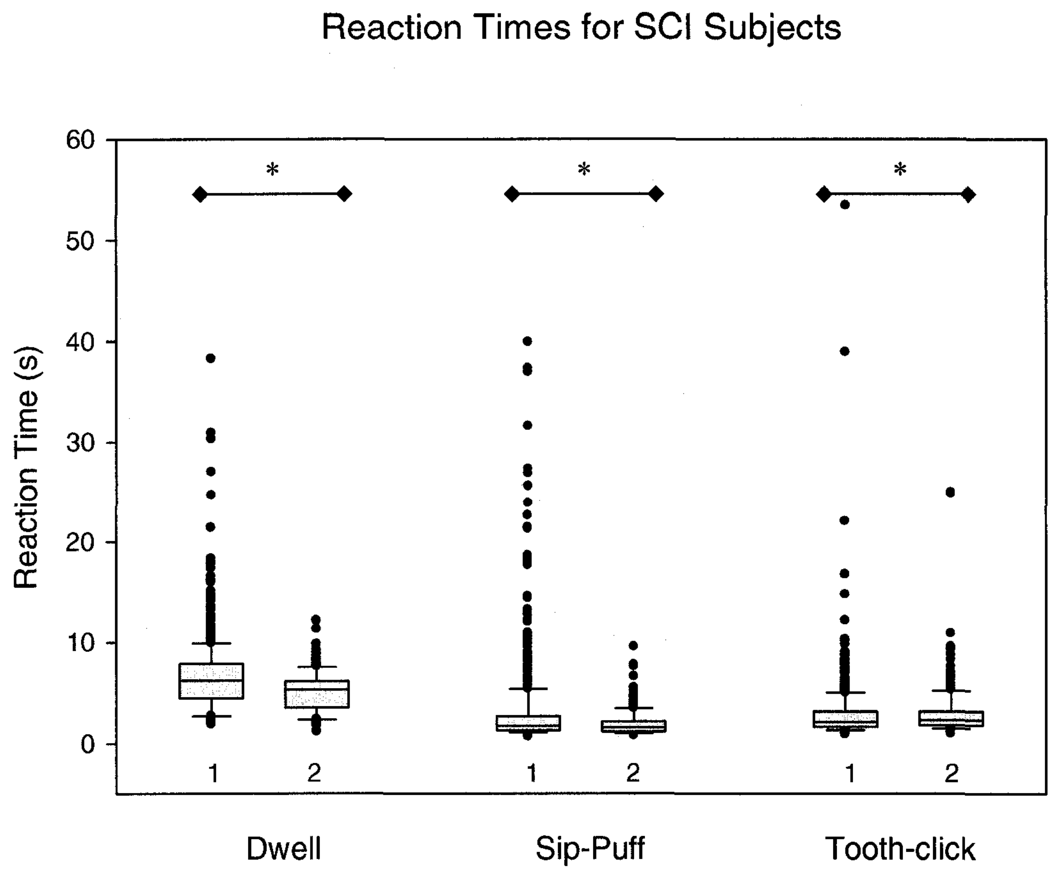


Figure 2.7: Median reaction time scores of SCI subjects using the three devices. Group 1 is naïve subjects while Group 2 is the subjects who had prior experience with sip-and-puff control. Experienced subjects showed faster reaction times with dwell and sip-and-puff control than naïve subjects, though the opposite relationship was found for the tooth-click device. All three between-group comparisons were statistically significant (P<0.05) using the Mann-Whitney rank sum test. Dots indicate outliers beyond the 5% and 95% intervals

Some SCI subjects had prior experience with a sip-and-puff controller. These people tended to be faster with the sip-and-puff controller than naïve subjects, but there was no difference between the two groups when using the tooth-click device. The comparison between reaction time scores of experienced and naïve subjects is shown in Fig 2.7. The advantage of prior experience influenced the between-device comparisons shown in Fig 2.6. The median reaction times for the naïve subjects were 6.23 s using dwell selection, 1.73 s using sip-and-puff, and 2.16 s using the tooth-click system. These results were still all significantly different according to the Mann-Whitney rank sum test ($p < 0.05$). The difference between sip-and-puff and tooth-click median reaction times is reduced by 17% for SCI subjects when experienced sip-and-puff users are excluded.

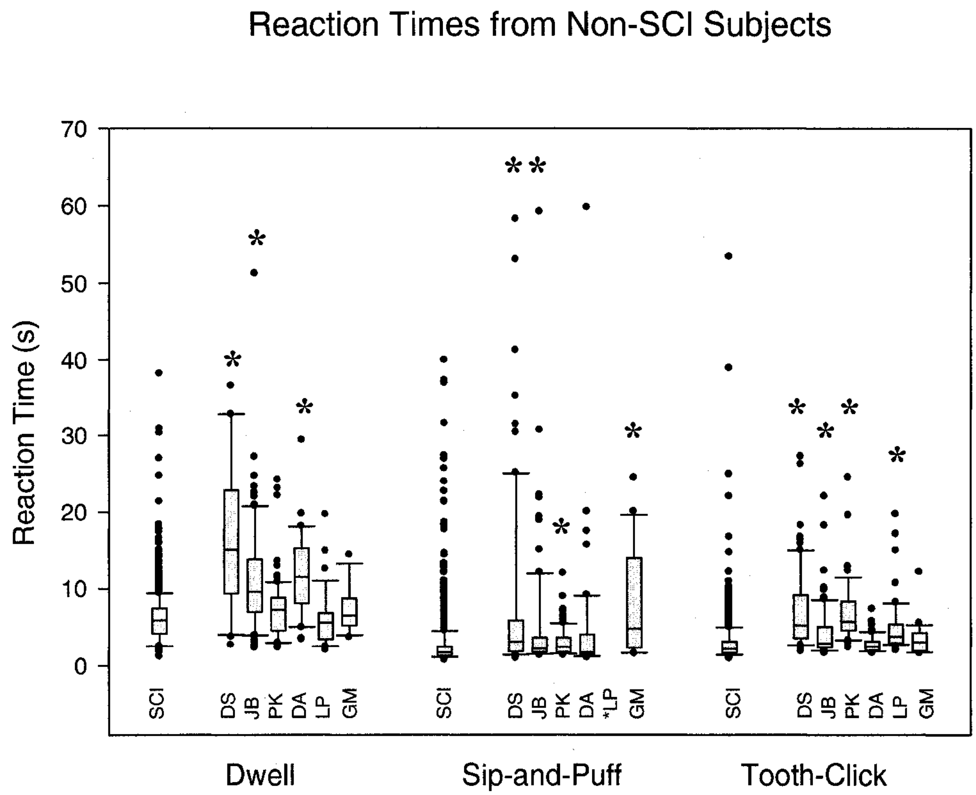


*Figure 2.8: Individual reaction task results for three devices from six subjects with disabilities affecting their hand function. Median values are shown, grouped according to the device used. For each grouping, the results from the SCI group are shown for comparison (labeled SCI). Subjects labeled DS, JB, and PK have multiple sclerosis, subjects DA and LP have cerebral palsy, and subject GM has post-polio. LP was unable to complete any trials using the sip-and-puff controller. Dots indicate outliers beyond the 5% and 95% intervals. Statistical differences between individuals and the SCI group are noted by *'s.*

Six people with limited hand function due to disabilities other than SCI also participated in the study. Of these people, one had post-polio syndrome, two had CP, and three had MS. These diseases and disorders can cause a broad spectrum of cognitive and physical disabilities, so it is difficult to make generalized inferences about this subject group. All subjects were all able to operate the head mouse, and performed the same tests as the other subjects from the control and patient groups, though sometimes performed fewer trials due to time constraints. Their individual results from the reaction task are shown in Fig 2.8. The performances of these six subjects were statistically worse than the SCI group (as determined by the Dunn's test at $p<0.05$) in most cases. This difference may be due to the physical and cognitive disabilities specific to the conditions seen in this group, which manifest differently than disabilities incurred from SCI. People with disabilities affecting their use of a head mouse device would likely benefit from evaluating a variety of devices to find the system that best meets their needs.

Subjects learnt how to use all three systems within five to ten minutes of practice. The data from the shape moving task showed no discernable learning trend after the allotted practice period. Regression lines were fitted to the individual plots of reaction time versus trial number. The mean r^2 value was 0.035 (standard deviation = 0.05), which was strong evidence that no learning effect was present. An example showing typical results of plotting reaction time data exponential regression lines is shown in Fig 2.9. The shape moving task was more cognitively demanding, and it was expected that users' performance scores would improve with practice. To reduce the learning effect, devices were used in an alternating manner throughout this task. The mean r^2 value for the shape moving task plots was 0.31 (standard deviation = 0.26), which showed that the learning effect was probably not entirely eliminated.

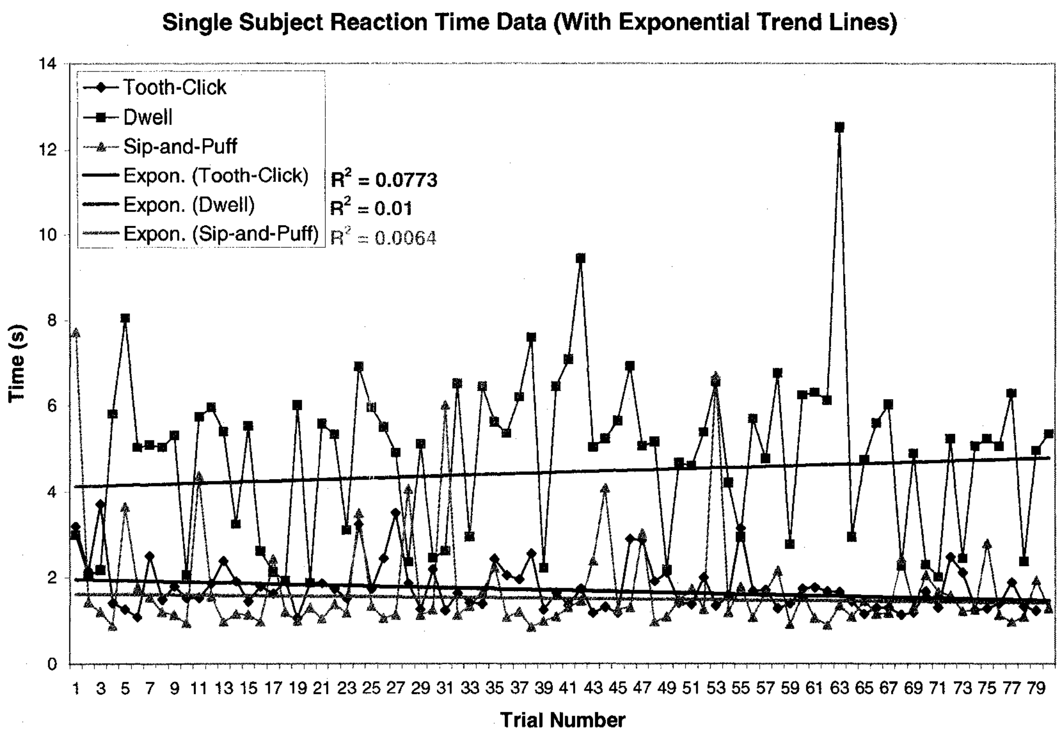


Figure 2.9: Plot of reaction time data vs. trial number for a single subject using the three devices to perform clicks. Best-fit exponential regression lines are shown, and the r^2 values indicate no learning effect for these data sets.

D. Data Distribution

As mentioned in Methods, the data for the reaction time and the shape moving tasks were not normally distributed for any of the devices tested. Fig. 2.10 shows histograms of reaction time data from the SCI subjects when using each of the three

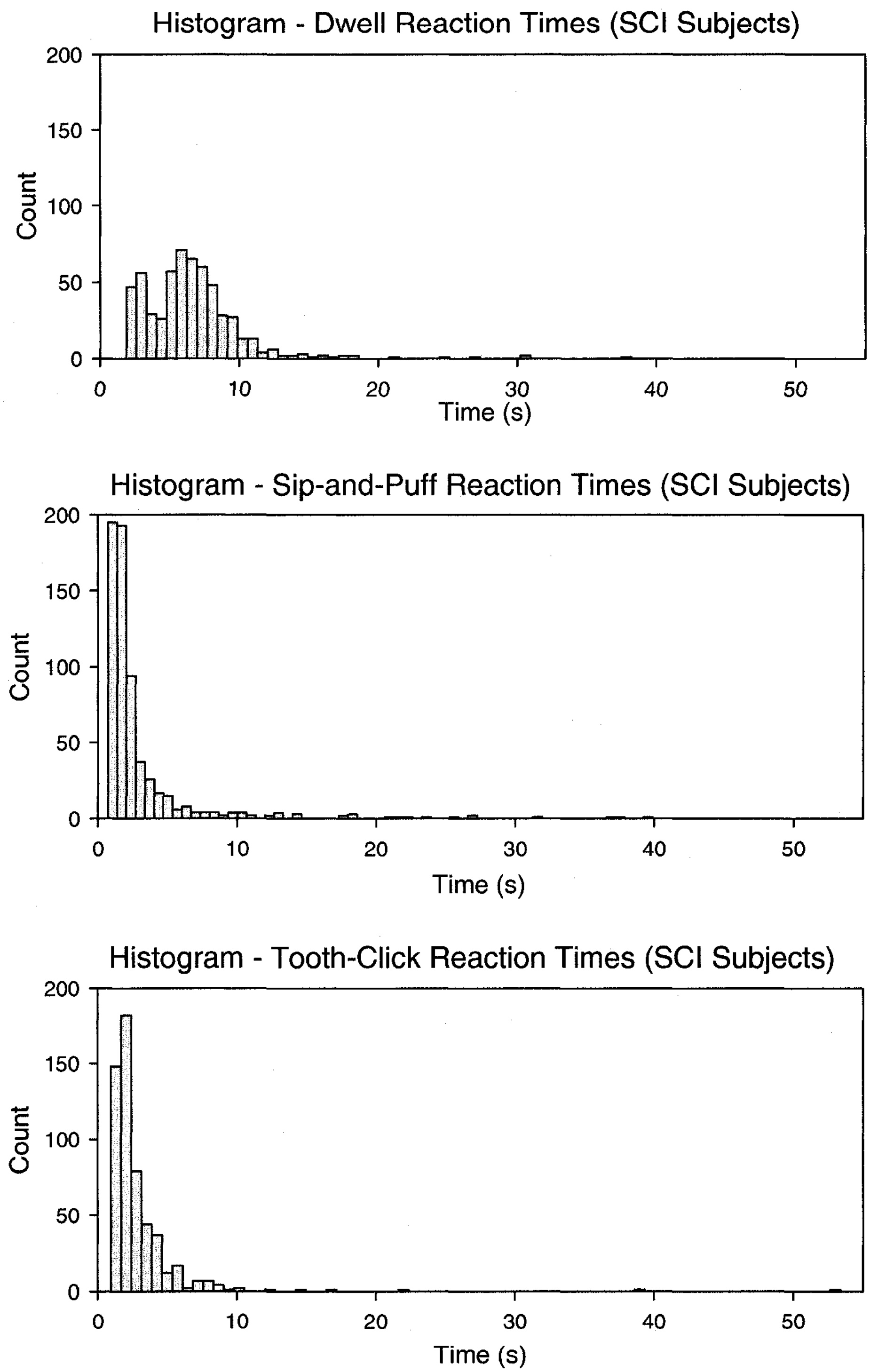


Figure 2.10: Histograms of reaction time data recorded from SCI subjects using dwell selection, sip-and-puff, and tooth-click control. The data were not normally distributed.

devices. The outliers beyond the 5 and 95 percentiles can be seen in Fig 2.6. The main cause of outliers when using the sip-and-puff device was the difficulty in producing double-clicks. This was a common problem with the sip-and-puff system. In contrast, the tooth-click outlier data points were generally due either to sub-optimal positioning of the sensor on the user's ear, or dropouts in the wireless link between the earpiece and the computer interface.

2.4 Discussion

From our study it was evident that the tooth-click system was usable by people with disabilities. It provided a viable alternative to sip-and-puff control and performed better than dwell selection. When judging the efficacy of a system, many variables must be taken into account, including those not measurable quantitatively. Other factors that might influence a person's selection of an assistive technology device include aesthetics, comfort, and the ability to use the device independently. The tooth-click detector was designed with these characteristics in mind – it was small and lightweight and fitted discreetly and comfortably behind the ear.

All equipment used in the study required occasional adjustments. Software adjustments were typically handled during the allocated practice trials. This included such adjustments as: modifying the cursor movement speed, adjusting threshold values of the head-mouse to minimize errors caused by reflections from some users' glasses, increasing or decreasing the dwell time required to generate clicks, and adjusting the sensitivity to jittery cursor movement when attempting to dwell at a target. Typical hardware adjustments included: initial positioning of the head tracking camera for each user, initial repositioning of the tooth-click detector's sensor arm if the jaw vibration signal was too weak, adjustments to the sip-and-puff mouth tube in cases where it was slipping out of the user's mouth, and repositioning of the tooth-click detector in cases where it was slipping out of place on the user's ear. For people with severe upper extremity paralysis, hardware adjustments were only possible with assistance. Software adjustments, however, were quite rare beyond the initial configuration. The lack of external hardware, including wearables, was one major benefit of the dwell system. In contrast, sip-and-puff users were tethered to their computers while wearing the sip-and-puff headset. This system was also the most invasive of the three, as it required a tube to be held in the user's mouth, and it required extra maintenance in cleaning and sterilizing mouth tubes after they had been used.

The majority of subjects, both in the control and SCI groups, had difficulty performing double clicks with the sip-and-puff system. From observation, it seemed the problem arose because users found it difficult to perform two puffs while maintaining a steady cursor position. To help subjects become comfortable with double clicking, some practice clicks were performed while the head tracking camera was disconnected. This allowed users to become familiar with the timing of the puff sequence, independently of the additional requirement of holding a steady head position. After a few successful trials, the head tracking camera was turned back on and the subjects were given time to practice the combined cursor control and clicking actions. Subjects seemed to find that this method of splitting the task into its components was helpful when learning to produce double clicks. Even after the extra practice, many of the mis-clicks recorded in the shape moving task continued to be the result of difficulty in performing double-clicks.

One subject was unable to use the tooth-click device because his teeth did not make contact cleanly enough to generate a jaw vibration signal that could be distinguished from background noise. Another subject was unable to use the sip-and-puff device because she could not produce enough airflow. All subjects were able to use the dwell method, with varying degrees of proficiency.

Wireless signal drop-out between the tooth click detector and the host computer occurred occasionally. This caused an increase in reaction times, but it was usually noticed during practice trials and remedied before test trials commenced. One remedy was to relocate the receiver. The other was to switch to an earlier prototype tooth-click detector with a stronger radio link. This was only necessary in the case of the five subjects studied in Vancouver, possibly because radio interference was greater in room used at this location. The few reaction times that were prolonged because of drop-outs resulted in outliers in the final data sets, but these had little influence on the median time scores.

The dwell method was the slowest but most reliable, whereas sip-and-puff control was the fastest and least reliable. We found that the tooth-click system provided a balance, approaching the speed of sip-and-puff control while maintaining reliability levels nearer to dwell control. Even though the median values indicated that the sip-and-puff controller was faster than the tooth-click system, the number of outliers in the sip-and-puff data made it unclear whether users would notice a speed difference between devices over the course of regular computer use. The accuracy data, however, showed that the tooth-click system was far more reliable than the sip-and-puff controller.

The four SCI subjects with prior experience of sip-and-puff control had amongst the best individual performance scores in the patient and SCI groups. It is reasonable to assume that experience with the tooth-click device would also result in improved performance. Short-term performance has a large influence over which AT products are prescribed (Anson, Glodek et al. 2003). After one session of use, five subjects from the patient group were asked which of the devices they preferred. The three who had not previously used sip-and-puff control said they preferred the tooth-click device, while the other two preferred the sip-and-puff device, with which they were familiar. A long-term study that systematically gathered user feedback on multiple aspects of the devices would be needed for a well-informed comparison. Such a study would be very useful for those interested in purchasing AT products.

Bibliography

Angelo, J., C. Deterding and J. Weisman (1991). "Comparing three head-pointing systems using a single subject design." Assist Technol **3**(2): 43-9.

Anson, D. K., M. Glodek, R. M. Peiffer, C. G. Rubino and P. T. Schwartz (2003). Long-term Speed and Accuracy of Morse code vs. Head-pointer Interface for Text Generation. RESNA 2004 Annual Conference. Orlando, FL.

Bradski, G. R. (1998). "Computer Vision Face Tracking for Use in a Perceptual User Interface,." Intel Technology Journal(Quarter 2).

Chen, Y. L. (2001). "Application of tilt sensors in human-computer mouse interface for people with disabilities." IEEE Trans Neural Syst Rehabil Eng **9**(3): 289-94.

Chen, Y. L., F. T. Tang, W. H. Chang, M. K. Wong, Y. Y. Shih and T. S. Kuo (1999). "The new design of an infrared-controlled human-computer interface for the disabled." IEEE Trans Rehabil Eng **7**(4): 474-81.

Drainoni, M. L., B. Houlihan, S. Williams, M. Vedrani, D. Esch, E. Lee-Hood and C. Weiner (2004). "Patterns of Internet use by persons with spinal cord injuries and relationship to health-related quality of life." Arch Phys Med Rehabil **85**(11): 1872-9.

Hitchcock, E. (2006). "Computer access for people after stroke." Top Stroke Rehabil **13**(3): 22-30.

Hochberg, L. R., M. D. Serruya, G. M. Friehs, J. A. Mukand, M. Saleh, A. H. Caplan, A. Branner, D. Chen, R. D. Penn and J. P. Donoghue (2006). "Neuronal ensemble control of prosthetic devices by a human with tetraplegia." Nature **442**(7099): 164-71.

Leuthardt, E. C., G. Schalk, J. R. Wolpaw, J. G. Ojemann and D. W. Moran (2004). "A brain-computer interface using electrocorticographic signals in humans." J Neural Eng **1**(2): 63-71.

Prochazka, A. (Nov. 1, 2005). Method and apparatus for controlling a device or process with vibrations generated by tooth clicks. US Patent 6 961 623.

Turpin, G., J. Armstrong, P. Frost, B. Fine, C. Ward and L. Pinnington (2005). "Evaluation of alternative computer input devices used by people with disabilities." J Med Eng Technol **29**(3): 119-29.

Wolpaw, J. R., D. J. McFarland, T. M. Vaughan and G. Schalk (2003). "The Wadsworth Center brain-computer interface (BCI) research and development program." IEEE Trans Neural Syst Rehabil Eng **11**(2): 204-7.

CHAPTER 3: GENERAL DISCUSSION AND CONCLUSIONS

This section serves as a discussion on additional relevant topics that were not fully developed in the previous chapter. First, the statistical interpretations of the data will be covered. This will be followed by discussion on the possibility of using the tooth-click technology in other applications. Finally, this section will conclude with some suggestions for future work that would help in moving from a proof-of-concept stage to a commercially viable product.

3.1 Interpretation of Data

As mentioned in Chapter 2, the data points collected during the reaction and shape moving tasks did not follow a normal distribution pattern. As such, median values were used to describe the results and to determine significant differences. The major implication of this was that the sip-and-puff control was found to be significantly faster than the tooth-click system. However, when examining mean values instead of median values, the reverse relationship was sometimes shown (though significance could not be found).

The reason for such trends in the data was that users had no trouble producing left-clicks and right-clicks when using the sip-and-puff device. Those click types simply required the user to move the cursor to position and produce a single sip or puff. Using the tooth-click system, the same clicks required the two-part selection process of clicking to produce a menu and moving the cursor to make a selection.

The advantage of the tooth-click system came when users attempted to produce click-and-drag or double-clicks. These required the same two-part selection process using tooth-click, meaning that they were no more difficult than producing single left or right clicks. However, these clicks were much more challenging to produce using the sip-and-puff system. Hence, for a large part of the experiment, users were producing mouse clicks slightly faster using the sip-and-puff device, but then stumbling when prompted to produce click-and-drag or double clicks. This led to a skewed distribution of time scores, which could not be normalized. The outliers had minimal influence on the median values that were reported, though they clearly did have an effect on the overall system performance. It thus became a matter of personal preference whether the fast but error-prone sip-and-puff system or the slightly slower but more consistent tooth-click system would be more effective for individual users.

3.2 Future Applications

This project evaluated the use of tooth-clicks in a computer access application, but it is not difficult to imagine other uses for the technology. Currently, the tooth-click detector is paired with a head-tracking camera for cursor control. A future prototype will pair the tooth-click detector with a gyro sensor for position tracking. Gyro-based head-mouse devices such as the system described by Kim & Cho (Kim and Cho 2002) already exist, so combining the two proven technologies should provide a convenient, all-in-one solution for cursor control and button clicking. If so desired, the configuration of the system could also be modified to be worn as a headband or set of glasses.

Looking beyond computer access, there are certainly other applications that may benefit from a hands-free wireless switch. Environmental control (for example, accessing lights or heating) is an obvious application that can help address independence concerns. A strong approach to developing more universal applications for the tooth-click interface would be to adopt the Bluetooth wireless protocol. This would increase compatibility between the tooth-click detector and other devices, and would allow users to interact with, for instance, a laptop or PDA and take advantage of existing solutions for accessibility, automation, and environmental control.

Yet another potential application is the use of the tooth-click detector's accelerometer as a microphone. With some relatively minor hardware changes, accelerometer recordings taken near the user's ear could be used as a source of voice input. One could envision this being used to transmit a stream of text input to a computer, or as a multi-modal switch that could recognize different vocalized commands. The scope of this technology is indeed large, and computer access is but one of many potential applications for a hands-free switch.

3.3 Suggestions for Future Work

The immediate goal of this research has been to see the tooth-click device used by people with disabilities in their homes with little or no assistance. To achieve this, a few technical aspects of the device should be improved. One ongoing development involves refining the casing of the tooth-click device to improve the fit for various ear sizes. During the study, it was sometimes necessary to reposition the tooth-click device on the subject's ear. This was usually only required when the user first put on the device, to ensure small tooth-clicks were sufficient to reliably activate the device. After this initial positioning, users were typically able to complete the clicking task without requiring any device repositioning. However, the trials in this study were often short (typically one to two minutes of continuous use before alternating to a different device during the shape moving task), so the amount of repositioning required over long periods of time could not be inferred from this study. For people with no hand function, repositioning the device was only possible with assistance. This is a drawback of any head-mounted peripheral device, and reducing the amount of repositioning required is an important goal for future device prototypes. Specifically, changing the sensor arm's curvature and materials used in its manufacturing may lead to a more snug fit. Alternatively, it may be worthwhile to adopt a customizable approach to the sensor arm and device geometry in attempt to provide a more personalized fit. Any major changes to the sensor geometry may require retuning of certain parameters in the algorithm. Currently, the device suffers from occasional radio dropout, which hopefully will be addressed by repositioning the antenna in the next prototype design. Maintaining a strong radio link and ensuring proper contact between the sensor and the ear are the two biggest factors that will improve the device's reliability.

Another concern for the implementation of the tooth-click device in people's homes is compatibility. The click menu is currently generated through a software driver that is called upon detecting a specific combination of USB character codes supplied by the receiver box. The driver would need to be examined for compatibility between different computer operating systems, and for use with different applications. The menu system currently does not properly produce clicks on context menus in programs such as Word or Excel, which are important software programs used in many workplaces. A different implementation of the code that produces the menu could fix this problem.

Finally, there are manufacturing concerns that must be addressed to ensure the device would be appropriate for home use. The device durability is currently under consideration. The next generation prototype is designed to fit in a plastic casing, though the sensor arm would be a potential weak point. The sensor arm is currently produced by casting the sensor and sensor leads inside a liquid plastic molding compound. This results in a semi-rigid arm that may not be durable enough to withstand repeated strain over long term use. More durable materials or a different manufacturing process should be evaluated when moving beyond the prototype stage.

3.4 Conclusion

The overall goal of this thesis has been to evaluate the effectiveness of detecting tooth-clicks for use as a control signal. The system built on existing work in the assistive technology field and addressed some of the complaints with current computer access products. The computer access model was used as it was an application that would greatly benefit from the hands-free nature of the tooth-click device.

The target population that would benefit from this project was people with upper extremity paralysis due to spinal cord injury, multiple sclerosis, cerebral palsy or other neuromuscular disorders. The only requirement was the ability to produce stable head and jaw movements. An experimental group of people with disabilities and a group of control subjects participated in the experiment to evaluate the technology. By directly comparing the tooth-click system with existing mouse alternatives, it was shown that people with disabilities were capable of controlling a computer by producing tooth-clicks as a means of generating mouse button clicks.

Users produced clicks 18-24% slower with the tooth-click device than when using a sip-and-puff controller, though the tooth-click system was less prone to mis-click errors. The tooth-click method was found to be 269-307% faster than dwell selection, which is currently a popular choice for hands-free mouse button control. There is ongoing work aimed at improving reliability of the tooth-click device, and repackaging the device to be as small and comfortable to wear as possible. Any

Bibliography

Kim, Y. W. and J. H. Cho (2002). A novel development of head-set type computer mouse using gyro sensors for the handicapped. Microtechnologies in Medicine & Biology 2nd Annual International IEEE-EMB Special Topic Conference on, Madison, WI, USA.

APPENDIX A: WORK DONE BY THE STUDENT

This appendix details the student's contributions to the project. Work performed will be listed chronologically with emphasis on the methodology employed.

First, a strategy for measuring the effectiveness of an alternative mouse system was developed. Existing studies evaluating pointing devices were reviewed to determine what characteristics were typically measured. The shape-moving task was invented as an interface for prompting the user for a specified number and variety of mouse clicks. The starting and goal conditions for each trial were pre-programmed to provide some variety between tasks while holding the number of clicks required constant. The software was developed in C# using Microsoft Visual Studio. Familiarity with C / C++ helped when learning the C# language, and plenty of online instructional resources online and help files were referenced.

Next, a temporal pattern recognition strategy was programmed into the USB receiver device. This version of the receiver interpreted incoming signals from the tooth-click detector, and based on the temporal spacing of the tooth-clicks, it output different mouse clicks to the computer. This was a relatively minor addition to a previous USB receiver program built by Michel Gauthier, which was capable of distinguishing between single and double clicks. The new code allowed for two different triple click patterns to be recognized, which enabled the generation of right mouse clicks and left-click-and-drags. Programming for this recognition program was done in assembly language using the Freescale CodeWarrior software. The operation code manual for the Texas Instruments MSP 430 F1611 processor was used for reference.

To provide more customizability, the temporal pattern recognition process was later moved from the receiver box to the computer in a software format. This new driver was built from scratch in C# and provided options to adjust the timing intervals for different temporal click patterns. Temporal patterns introduce lag as the program must buffer a specified time window following each tooth-click to determine whether that click was a single click or part of a multi-click sequence. The ability to adjust these time windows was useful to minimize lag for those users who were capable of producing tooth-clicks quickly, or alternatively allowing more time for slower clickers.

With a software driver in place, it was possible to experiment with menu interfaces for click generation. Reliability problems plagued the temporal pattern strategy so the focus was shifted to menu systems. Graphical menu and context menu interfaces were built in C#. The two were identical except for the manner in which the different mouse click choices were displayed. Both menus were activated by performing two tooth-clicks in quick succession and appeared directly below and to the right of the cursor position. Mouse clicks (right-click, double-click, and click-and-drag) were generated by performing a tooth-click on the appropriate menu item. Single left clicks were generated by performing a single tooth-click – this did not require any interaction with a menu. These menus were designed to be as familiar as possible and thus resembled menus seen in common software programs.

Later, a circular menu system was devised. The benefit of adopting a circular menu strategy was that it reduced the number of tooth-clicks required to generate any given mouse click. The menu is displayed upon generating a single tooth-click, and then menu items are selected by moving the cursor rather than requiring another tooth-click. Menu items were arranged to make the system as intuitive as possible. For instance, left or right mouse clicks are produced by moving the cursor to the left or right, respectively. Click-and-drag is produced by moving the cursor towards the bottom of the circular menu. A double click is produced by generating two tooth-clicks in succession (i.e., one tooth-click to generate the menu and another tooth-click without moving the cursor to close the menu and produce the double click). The suggestion and implementation of the circular menu system arose from the student's observations on how subjects were performing using the temporal click strategy and other menu systems.

The tooth-click detection algorithm (described in Appendix A) was developed with the assistance of Colin Broughton. Two different algorithms were designed in parallel, one built by Mr. Broughton and the other built by the student. The reason for splitting efforts was to benefit from different perspectives on the recognition problem and to compare the effectiveness of various strategies. It was found that there were enough features of distinct tooth-clicks that were noticeable to a human observer to differentiate them from noise. It was thus assumed that an intuitively designed algorithm would be appropriate, avoiding the need to resort to complex, brute force algorithms such as neural networks. Two people working independently on the problem gave a higher chance of identifying key signal characteristics useful for classifying clicks and non-clicks (e.g. peak amplitude, signal energy, peak-to-noise ratio, etc). The student built an algorithm (including digital filtering) from scratch using Matlab (aspects of which were later translated to C+). Several high-level decision modules were developed that tackled difficult problems such as discriminating between clicks and coughs, correctly identified double clicks, and eliminated false clicks during periods of noise.

To aid in developing the algorithms, the student collected a large database of tooth-click and non-tooth-click signals from many different people. This set of tooth-click samples was then split into two separate databases. One database was used in the development of the algorithms to provide adequate information about tooth-click properties. The second data set was left untouched until it was time to evaluate the algorithms. This separation addressed the problem of evaluating the algorithm with the same data set it was designed to solve.

From comparing the two algorithms, it was determined that a compromise between reliability and memory usage would be required. The stronger aspects of each algorithm were identified, and then Mr. Broughton condensed the resulting algorithm to an assembly language program that would fit in tooth-click device's memory.

The sensor placement was determined by building different sensor arm prototypes and taking recordings from volunteers at different locations near their ears. Various compounds were researched for the construction of a sensor arm, and a moldable liquid plastic was chosen to produce a semi-rigid arm that could bend and retain its shape. Sensor arm molds were designed using Rhino3D and built using the University's 3D Printer service. The resulting molds were cured with epoxy, sanded to smooth the surfaces, and waxed to allow easy recovery of cast parts. Sensor arms were built by positioning a sensor and sensor lead assembly (built by Mr. Gauthier) in the centre of the mold and casting the part with the liquid plastic compound.

The reaction task was inspired by previous literature describing pointing device evaluations. The reaction task software was built in C# and was capable of storing reaction time data for offline analysis.

Once the first device prototypes were ready (built by Mr. Al Dennington and Mr. Michel Gauthier), the comparative study as described in this report was designed and carried out by the student. Subjects were recruited by Ms. Su Ling Chong and The Neil Squire Centre (Vancouver). Experiment set up, supervision, and collection and analysis of the results was performed by the student. Statistical software packages Minitab, SigmaStat, and SigmaPlot were used for data analysis.

In the above description of work performed, there were several inventive steps taken by the student. The development of the circular menu system was a major contribution to the project. This method of selecting menu options is novel in the context of assistive technology. The shape-moving task provided a new method of measuring the speed and reliability of various input devices. The software used for this task was designed and coded entirely by the student. The addition of an adaptive threshold for tooth-click detection was an inventive step that reduced false-positive detection errors. Finally, the design of a sensor arm was an inventive step that also necessitated the development of a custom manufacturing process.