Disability and Rehabilitation: Assistive Technology, January 2010; 5(1): 69–78

informa
healthcare

CASE STUDY

Evaluation of a non-invasive vocal cord vibration switch as an alternative access pathway for an individual with hypotonic cerebral palsy – a case study

JULIE CHAN, TIAGO H. FALK, GAIL TEACHMAN, JENNIFER MORIN-MCKEE & TOM CHAU

Bloorview Research Institute, Bloorview Kids Rehab, Toronto, Ontario, Canada

Accepted August 2009

Abstract

Purpose. A novel non-invasive vocal cord vibration switch for computer access was designed for an individual with hypotonic cerebral palsy. An evaluative case study was performed to compare the new device to an existing commercially available voice-activated switch in terms of sensitivity, specificity, speed, and user fatigue.

Method. The participant wrote pangram sentences with the two switches over 4 days with two sessions each day (morning and afternoon). The order of the switches was alternated and a new sentence was used each day. The user's perceived level of exertion was noted before and after each task and activation errors were logged for performance analysis. After using the device for 2 months, a qualitative survey was administered with the participant and his educational assistant.

Results. The vocal cord vibration switch outperformed the voice-activated switch in terms of sensitivity ($p < 10^{-4}$, *t*-test), speed ($p < 10^{-3}$), and user-perceived exertion ($p < 10^{-4}$). Qualitatively, both the participant and his educational assistant were more satisfied with the proposed switch relative to his existing solution.

Conclusions. The results of this study show that the vocal cord vibration switch provides a promising new alternative for individuals with severe and multiple disabilities who are able to hum or produce vocalizations.

Keywords: *Voice switch, vocalization response, augmentative and alternative communication (AAC), aided communication, computer access*

Introduction

Communication is one of the simplest forms of participation, but of 3.7% of Canadian children with a disability, 44.8% possess a disability related to speech, hence making communication a challenge [1]. The type and degree of speech disability vary between individuals and can range from difficulties with articulation of words to the inability to produce functional speech. Some of these difficulties may be a result of hearing loss, neurological disorders, brain injury, or physical impairment, and are often concomitant with other severe and multiple disabilities [2]. To help these individuals communicate, augmentative and alternative communication (AAC) interventions and access tools are often prescribed. Access tools, such as microswitches, are often used to access computers or other communication aids and have contributed to enhancing the overall achievement and quality of life of individuals with complex communication needs [3].

AAC systems include those that are unaided (e.g., gestures and signs) and aided, as well as both low tech (e.g., non-electronic communication boards) and high tech electronic solutions (e.g., speech generating devices). These systems allow individuals with complex communication needs to access their environment, interact with their communication partners, and experience increased opportunities for communication. Numerous studies have shown the effectiveness of AAC systems in positively impacting the communication skills of children

---

Correspondence: Dr. Tiago H. Falk, Bloorview Research Institute, Bloorview Kids Rehab, 150 Kilgour Road, Toronto, Ontario M4G 1R8, Canada.
Tel: +1 (416) 425-6220 ext. 3326. Fax: +1 (416) 425-1634. E-mail: tiago.falk@ieee.org

ISSN 1748-3107 print/ISSN 1748-3115 online © 2010 Informa UK Ltd.
DOI: 10.3109/17483100903278107

[4,5]; however, limited research exists to compare the effectiveness of these various types of AAC systems [6,7]. This leads to difficulties with effectively matching AAC systems with individuals, and tendencies in practice to use certain types of AAC systems with children despite limited evidence of their relative effectiveness [6]. As a result, it has been argued that the full potential of AAC systems has not been realized [8] and that the design of AAC technologies should be carefully examined. Ideally, the design of these technologies should promote the capabilities, preferences, and priorities of those who use them, and take into account their strengths and challenges [9]. However, the skills and communication needs of individuals using AAC systems vary, and the interventions that have been developed to meet these different needs have been met with varied levels of success [10]. It is important to discover why certain interventions succeed or fail with particular individuals, but efforts to determine this have been hindered by the current lack of detailed information about research participants and their communicative environments [11]. Therefore, in order to demonstrate the efficacy of AAC interventions, it is important to provide detailed participant descriptions.

Furthermore, it is not uncommon for AAC systems to possess less than ideal outcomes even though they may be the best option available for an individual. For example, individuals with extensive motor disabilities who are able to produce vocalizations, may use voice-activated switches, which have been found to be a reliable alternative [12,13]; however, the use of a voice-activated switch is often non-ideal. Either produced vocalizations are of levels insufficient for switch activation or users become very fatigued through continuous use of their voice throughout the day [14]. Research has shown that technical barriers, such as unreliable, slow and/or hard to use technology, often play a factor in negative AAC outcomes [15,16]. To address this issue, it has been recommended that an outcome-driven model be used in practice [17], and that AAC outcomes that consider the specific needs of users be adopted in the design of future AAC technologies [18].

In this article, we propose a new access technology for an individual with hypotonic cerebral palsy who currently uses a voice-activated switch. The new technology addresses issues presented by the voice-activated switch and is designed to improve upon its limitations. A detailed description of the participant and the proposed device is provided. An evaluative case study is described and performance comparisons are reported based on a writing task with an onscreen virtual keyboard performed with the proposed device and a commercial voice-activated switch.

Methods

Participant description

Medical history and physical function. This study focused on a 19-year-old male, who we will refer to as John, with a well documented history of severe hypotonia. The exact cause of his hypotonia was unknown, but may have been related to a prenatal encephalopathy resulting in hypotonic cerebral palsy. From John's extensive medical rehabilitation history, it was evident that his development was profoundly impacted by significant motor limitations. At the age of four, he was unable to roll and required total support for sitting. He was later diagnosed with mitachondrial myopathy which was reported to have caused irreversible muscle deterioration. An assessment at age 10 found his motor abilities to be restricted to very minimal arm and hand control, little to no head movement, and some volitional motor control of his lower extremities (where control of his left side was greater than his right). Decreased endurance and fatigue were reported to be further physical limitations. Now, at age 19, John spends majority of his time seated in a tilt base wheelchair with a custom insert, tilted back at an angle between 20° and 45°. He is dependent on others for mobility and activities of daily living.

Cognitive function, language, and communication. In terms of his cognitive development, no records of any formal test results were available; however, in case notes written by his health care team, he was reported to be learning and adapting well within his environment. He demonstrated an age appropriate understanding of everyday conversations and new information. John presents with a motor speech disorder. As a result of his diagnosis of mitochondrial myopathy, his ability to speak is dependent on his overall muscle strength, which tends to fluctuate throughout the day. When not fatigued, John demonstrates the ability to produce 1–2 word phrases that are intelligible (i.e., 'yes', 'no', 'one', 'two', 'three', etc.). Usually, during the early part of the day when he is well rested, John communicates using short phrases and single words that are typically intelligible to familiar communication partners. As the day progresses, however, he becomes more fatigued and responds using tongue clicks (i.e., one tongue click for 'yes', two for 'no' and three for 'I do not know').

No records of formal hearing and vision test results were available but these are reported in the health record to be within normal limits. John has good ocular and facial muscle control, and as a result, he also relies on facial expressions and eye pointing to express himself. To participate in writing and computer activities, John uses a single-input switch to control an on-screen keyboard. During the period of this study, John participated actively in classroom activities and demonstrating a keen sense of humor. He was able to readily understand new instructions and adapted to changes introduced to his communication system.

History of switch use. In John's early years, it was decided that computer access would be important for his independence and development. Since then, he has accumulated almost 15 years of experience with assistive devices, including many trials of various access sites and switches for AAC devices. Potential switch access sites were identified based on movements he was able to easily and reliably repeat. Options that were experimented with and found to be unreliable or overly fatiguing included blink, chin, eyebrow, proximity, sip and puff, tongue, mechanical squeeze, and respiratory band switches.

Despite the many unsuccessful access options, a selected few were deemed promising. Prior to age 5, John was successful in using his right knee to access a single switch mounted on the bottom of his tray. This switch allowed him to use a Light Talker™ [5], an AAC device with speech and written output. However, necessary changes were made to his seating system and this access site was no longer suitable. The switch was then adapted by his father so that it could be accessed with his left foot through extension of his foot and leg; this was not ideal because his feet were not supported. Later, at age 6, he was prescribed a string switch that looped around his left ankle for computer access which allowed him to continue to use his left foot while also ensuring that his feet were supported. At age 9, a bite switch was tested but was not used because it caused fatigue and excessive drooling. At age 15, an investigation into John's switch access options found the foot switch, which he had used in the past, to be most successful (i.e., a mechanical button switch activated by leg extension); it required a lot of time for him to take his foot off the switch, but it was useful for activities such as book reading that did not require quick successive switch activations.

Further investigations into more optimal access solutions continued, and at age 18, a mechanomyographic (MMG) switch was developed as an alternative access switch used with his thumb. The MMG sensor functioned by measuring muscle vibrations that occurred during intentional muscle contractions, and was found to work best for John with activities that did not require timed responses. John used the MMG thumb switch to play simple single-switch online games. For activities that depended on timed responses, such as using a scanning array on the computer for written work, John was prescribed a voice-activated switch (Words + IST switch [19]). He used the vocalization 'ah' to activate the switch using a miniature close-talking microphone held near his mouth by a clip on his headband. He initially used tongue clicks with the voice-activated switch, but found the vocalizations to be easier to produce and more readily picked up by the switch.

At the time of writing, John's main modes of communication included both low tech and high tech AAC solutions. At school, he used a low-tech alphabet display, arranged according to frequency of use of letters, with partner-assisted scanning to express himself; this was reported to be highly effective but only when used with a skilled communication partner. For writing activities, he used the voice-activated switch with an on-screen virtual keyboard, WiViK® [20], with a 'Dvorak' keyboard layout and word prediction. His automatic scanning speed was 1.5 s. The voice-activated switch was the most reliable off-the-shelf high tech option for him, but it was reported to be less reliable than the low-tech alphabet display. The sensitivity of the voice-activated switch to John's vocalizations was poor and produced false activations when people were speaking in close proximity. It also failed to activate at times causing him to over-exert himself. The switch was not durable and required frequent maintenance, which could not be done on site and left John without computer access for extended periods of time. Because of the unreliability of his voice-activated switch, John most often communicated with partners via tongue clicks in response to yes/no questions. He found this to be exceptionally limiting and expressed interest in finding a more reliable switch option for independent computer access.

Occupations and preferences. John lived at home with his parents and siblings, and attended a high school with a special education program. Some of his pastimes included watching movies, playing video games, and browsing the internet, but he was dependent on others for assistance to engage in these occupations. John and his rehabilitation team discussed what he felt would be important toward increasing his independence. They created a list of the functions and features that he would like to control using assistive technology. In terms of functional activities, this list included personal and school writing, internet access and e-mail, computer games, video-games, environmental controls, and speech generation. John was interested in a system where writing and speech generating functions were integrated into one device. He wanted to have continued access to mouse-emulation, a virtual alphabet keyboard with word prediction and pre-programmed phrases to facilitate quick social 'chat'. With these features and a more reliable switch, he hoped to have more control over his daily activities and to experience more interaction with his environment.

In our first meeting with John, through yes/no questions and tongue click responses, we learned about his love of horror, war, and action movies and video games. He requested that we incorporate an urban camouflage pattern into the appearance of his new device. In designing a new switch access solution for John, his family, teachers, and care worker stressed that fatigue was an important design consideration. His current method of using vocalizations to access a computer was the least fatiguing of the switch options that had been explored; therefore, the new device would be designed to respond to John's vocalizations and to improve upon current limitations of his voice-activated switch. Together, we reviewed information about the study and John formally consented to participate.

Device design

The developed device – henceforth termed 'throat vibration switch' – was designed to detect, in real-time, periodicities in vocal cord vibrations caused by vocalizations, a term used in this paper to include hums and voiced sounds. Traditionally, vocalizations are captured with a close-talking microphone and/or a throat microphone. Close-talking microphones, although more robust than airborne microphones, are still sensitive to environment noise and the speech output from the user's speech generating devices [21]. In order to reduce false activations, sound-based systems are commonly equipped with a "sensitivity" dial that when set to low, allows for increased robustness against environment noise. The major drawback is that loud vocalizations have to be produced for accurate switch activation, thus leading to premature fatigue [14]. To guard against environmental effects, throat microphones have been employed [13]. With throat microphones, however, false activations may occur because of user-generated artefacts such as coughs, throat clearings, heavy breathing, congested airways, or involuntary spastic head movements [22].

Direct benefits of harnessing vocal cord vibrations over airborne and/or throat microphones include (1) less effort required from the user to vocalize, as even silent hums can be used for switch activation, (2) measured vocal cord vibration signals are independent of environment noise, and (3) by detecting only periodic vocal cord vibrations, switch access becomes robust against user-generated artefacts such as coughs or congested airways. Figure 1 depicts a block diagram of the proposed system. Signals measured by an accelerometer held against the surface of the throat are input into the system, pre-processed and analyzed for periodicity. Switch activations are based on detecting periodic signal segments by means of thresholding and a normalized cross-correlation (NCC) function; more details are described later.

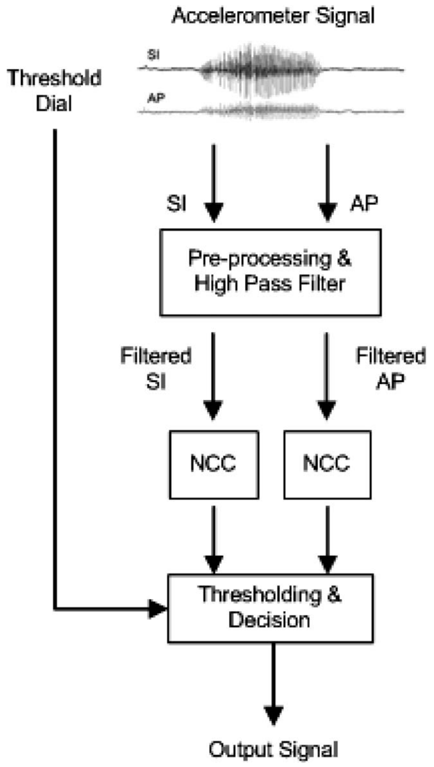

Figure 1. System block diagram of throat vibration switch.

Speech sounds are produced by forced air from the lungs as it passes between the vocal cords in the larynx at the base of the throat. Vibrations of the vocal cords create voiced sounds characterized by a high degree of periodicity also known as fundamental or pitch frequency. Voiced speech sounds include all vowel sounds and some consonants (e.g., r, d, and g) [23]. The typical fundamental frequency ranges for the human voice are 85–155 Hz for the adult male, 165–255 Hz for the adult female, and 208–410 Hz for an infant or child younger than 10-years of age [24]. Although hums and grunts are not categorized as voiced speech, they are considered as vocalizations here as they are created by periodic vibrations of the vocal cords. Figure 2(a) is an example of the high periodicity exhibited by a voiced speech segment. Other factors that may cause vibrations in the throat, such as movement of the body, laughing, coughing, and swallowing either occur outside the typical fundamental frequency ranges, exhibit low periodicity or are aperiodic. Given such properties, user-generated artefacts do not cause false switch activations, a common problem observed with conventional voice-activated switches based on

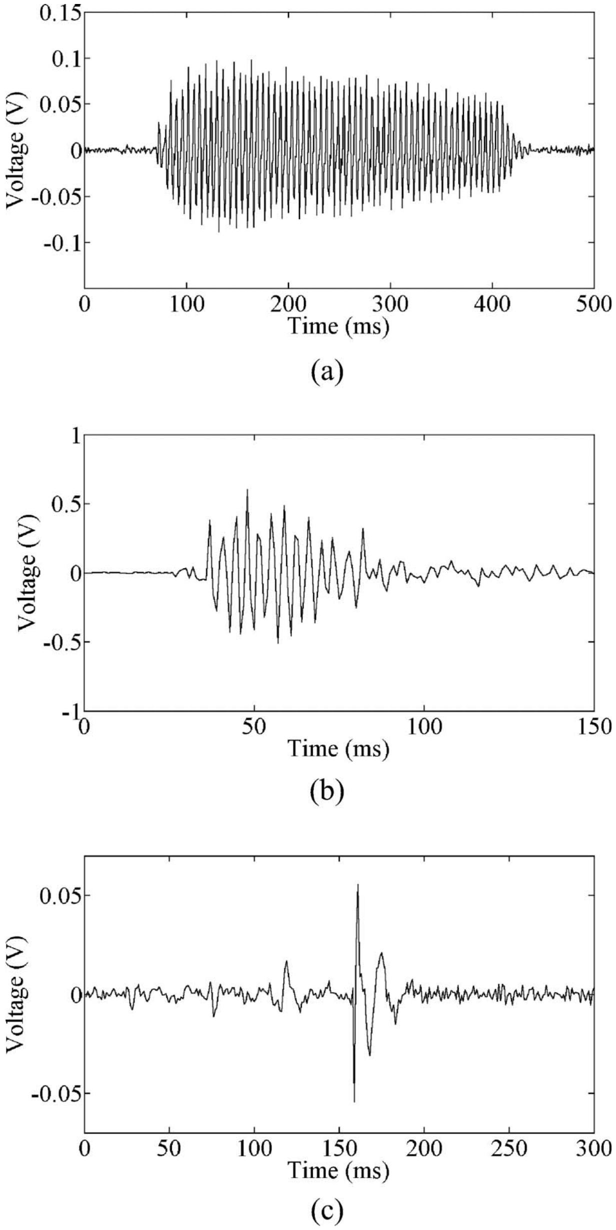

Figure 2. Representative accelerometry signal of (a) voiced speech, (b) cough, and (c) a swallow.

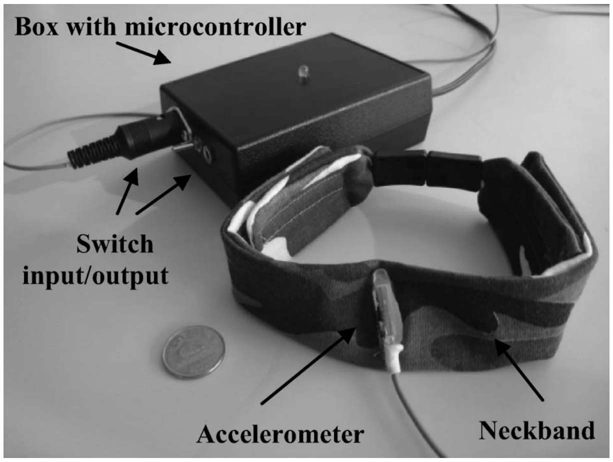

Figure 3. Throat vibration switch with accelerometer in silicone casing and cotton neckband.

throat microphones [22]. Figures 2 (b) and 2(c) illustrate examples of vibration signals captured by an accelerometer placed on the neck during a cough and a swallow, respectively. As observed, coughs exhibit low periodicity and swallows are aperidoic.

A small dual-axis accelerometer (ADXL322) encased in a molded silicone cover was used in our device to capture vocal cord vibrations. It was held in place to the anterior surface of the throat near the larynx by a neckband; Figure 3 depicts the device and the custom-made neckband. Vibrations were detected by the accelerometer in different places around the larynx region; hence, precise placement was not necessary. Flexibility of placement may be useful for individuals with scoliosis or other conditions that may affect posture. The accelerometer measured the vibrations of the throat along two axes: superior–inferior (SI) and anterior–posterior (AP). The vibration signals are output by the accelerometer as voltages, which were digitized and subsequently processed by the software algorithm described later.

The 'throat vibration switch' has three inputs: SI and AP accelerometer signals and a threshold dial; and two outputs: a standard switch and a USB keyboard. A different signal is sent depending on the selected output – a high voltage for the standard switch and an F11 keystroke for the keyboard. When connected to the computer via USB, the F11 keystroke signal may be used to trigger scanning and choice selection in WiViK®, which is the virtual keyboard that John is accustomed to using.

The device's vocalization detection algorithm was programmed onto a PIC24FJ64GA004 microcontroller. The algorithm calculated the NCC function of the SI and AP signal segments to detect periodicity in the signals; this function is commonly used in speech processing applications [25]. First, both signals were high pass filtered with a fifth-order Butterworth filter with a cut-off frequency of 50 Hz. The sampling rate of the device was set to 1 kHz, which effectively filtered out the higher frequency components of the signal and isolated the frequencies of interest (50–500 Hz). Then, the signals were processed in smaller segments or reading frames. The NCC function is defined as:

$$NCC(k) = \frac{1}{\sqrt{e_0 e_k}} \sum_{n=0}^{L_\omega - 1} s_\omega(n) s(n+k), \qquad k = 0, 1, \ldots, k_{\max}, \tag{1}$$

where $s(n)$ represents the zero-mean framed signal segment, $s_\omega(n) = s(n)\omega(n)$ is the windowed signal segment, $\omega(n)$ is the correlation window of size L_ω, L is the length of the reading frame, $k_{\max} < L - L_\omega$ is the maximum lag, and e_k is the energy of the windowed signal represented by:

$$e_k = \sum_{n=k}^{k+L_\omega} s_\omega^2(n). \tag{2}$$

The device used a reading frame length of 40 ms ($L = 40$) with a correlation window length of 20 ms ($L_\omega = 20$). These values were found to be optimal using sample vocalization signals from the research team and the participant. The NCC function results in values between -1 and 1, where values close to unity suggest strong periodicity.

Figure 4 shows a representative signal with a reading frame and correlation window indicated with a solid box and dashed box, respectively. Figures 5(a) and 5(b) illustrate representative NCC values calculated for a reading frame containing an aperiodic unvoiced speech segment and a periodic voiced speech segment, respectively. Because periodic signals have a periodic NCC function, as indicated by Figure 5(b), the proposed algorithm flagged a periodic vibration when two or more peak NCC values exceeded the threshold value. Once a vocalization is detected in either the SI or AP signal, an output signal is sent from the device and an LED indicator is turned on. The threshold value for our device was determined empirically to be 0.8. Nonetheless, to account for individual differences in vocal fold function, a threshold dial (potentiometer) was implemented in the final hardware solution to allow the user to adjust the threshold to values between 0.50 and 1.00. Lower threshold values allow whispered vocalizations, which exhibit lower periodicity [24], to also be detected.

During device development, a user-centred approach was applied to incorporate the user's preferences and needs into its function and form. Previous studies have shown that assistive technology outcomes rely heavily on user preferences as personal and psychosocial factors play an important role in its initial and continual adoption and use [26–28]. In terms of functionality, the device was designed to be more reliable, sensitive, faster, and less effortful to use. With the ability to detect softer vocalizations and hums, the device not only required less effort from John, but was also less disruptive in social situations. The form of the device considered factors such as user preferences, environments the device will be used in, size, durability, safety, and comfort. The neckband was made from a cotton blend fabric with an urban camouflage pattern, which was comfortable, light weight, and suited the user's preference. It was also fitted with adjustable straps and a quick-release clip for safety. The device was encased in a small, portable, durable plastic box.

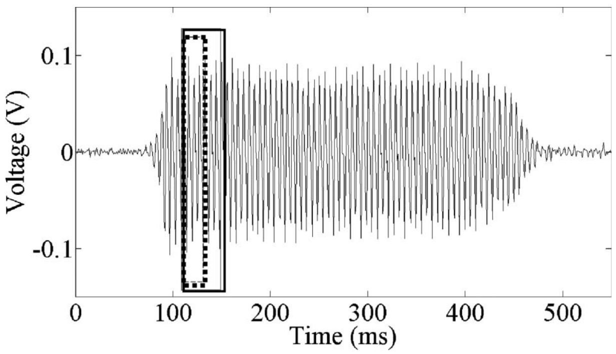

Figure 4. An example of a reading frame (solid box) and correlation window (dashed box) for an accelerometry signal during a voiced speech segment.

Experimental setting

The study was conducted at John's school in a quiet room to avoid issues with background noise causing excessive false activations with his current voice-activated solution. As a consequence, the effect of

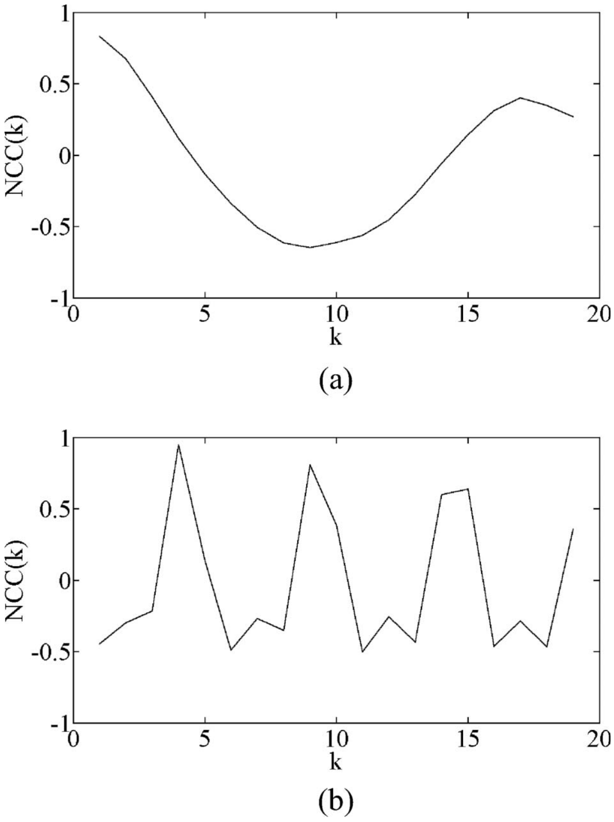

Figure 5. NCC function for a reading frame that (a) does not contain voiced speech and (b) contains a voiced speech segment.

the environment on switch performance was not examined in this study. The same quiet room was used for all sessions to keep the study environment as constant as possible. Sessions were conducted in the morning and the afternoon of the same day on four separate days to take into account the effect of the participant's level of fatigue on switch performance. Both switches were used during each session and the order of presentation of the switches was alternated between days. Pangram sentences were chosen for the participant to write with the switches using WiViK®. A pangram sentence task was chosen because each sentence would contain every letter of the alphabet at least once, and would therefore include most keys on the on-screen keyboard. Each sentence was divided into two portions, which was more manageable for the participant; each portion was written using a different switch.

Study materials

As described previously, the proposed 'throat vibration switch' was evaluated against a commercially available voice-activated switch: Words+ IST. This switch consisted of a miniature microphone linked to a battery powered unit and was connected to the computer via a mouse click emulator; sensitivity of the voice-activated switch was set to maximum to allow for softer vocalizations to be detected. Both switches were activated by vocalizations from the user which was the targeted response. Switch activations triggered scanning in WiViK®, with which the participant was already familiar. WiViK® settings on the laptop computer used in the study matched those on John's computer; he used a scan/repeat time of 1.50 s, delay factor of 2.0, speed factor of 2 and two scan cycles with the following automatic scanning features enabled: scanning sound, invisible cancel, and scan continuously. Word prediction was disabled for the study. In addition, a macro written in AutoHotkey, a keyboard macro program [29], was used to log the timing of switch activations during each session. This data were used to determine the time to complete each task. Other equipment used in the study included a laptop, video camera, and survey materials.

A scale of perceived exertion was adapted from the Borg scale to measure the participant's level of fatigue before and after each task. The Borg scale [30] is used worldwide by professionals in medicine, exercise physiology, psychology, cardiology, ergonomy, and sports. The scale was adapted from its 10 and 15 point formats to a 5 point scale for simplicity. As well, the descriptions for each level of the scale were changed to reflect the task. We asked the participant to rate how much effort was required and how tired he felt using the following 5-point scale: (1) Nothing at all, not tired; (2) A little, not tired; (3) Moderate, a little tired; (4) A lot, tired; and (5) Too much, very tired.

After the experimental sessions, John used the new switch for his everyday activities for 2 months. Following this trial, both John and his care worker were asked to rate their satisfaction with both switches using the nine device sub-scale items of the Quebec User Evaluation of Satisfaction with Assistive Technology (QUEST 2.0) questionnaire [31]. The QUEST 2.0 is an outcome measure with demonstrated reliability and construct validity [32] that uses a 5-point satisfaction rating scale where '1' indicates 'not satisfied at all' and '5' indicates 'very satisfied'. John and his care worker also responded to four open-ended qualitative questions regarding their experiences using the 'throat vibration switch' and comparing them to John's previous access solutions.

Data collection sessions

The data collection sessions for this study were spread out over 4 days with two sessions each day; one session in the morning (between 10 am and 11:30 am) and one in the afternoon (between 12 noon and 1:30 pm). In each session, the participant was presented with a pangram sentence of less than 40 characters divided into two parts or tasks. Both the 'throat vibration switch' and voice-activated switch were used in each session – one for each task. The order of use of the switches was alternated between days and remained the same for the morning and afternoon sessions of each day. The order of the tasks was switched between morning and afternoon sessions. For example, the Pangram sentence: 'the five boxing wizards jump quickly', can be divided into task A: 'the five boxing' and task B: 'wizards jump quickly'. With a switch order of 'throat vibration switch' followed by voice-activated switch, the morning data collection session would consist of task A written with the 'throat vibration switch' and task B written with the voice-activated switch, followed by an afternoon session of task B written with the 'throat vibration switch' then task A written with the voice-activated switch. A different pangram sentence was presented to the participant each day. The average duration of each task is reported in Table I.

The participant was asked to rate his level of exertion and perceived level of difficulty before and after each task. A rest period was given between the tasks so that the participant's perceived level of exertion would begin at the same level for each task in the session. Because the participant presented with

Table I. Performance metrics obtained with the proposed throat vibration switch and an existing voice-based solution (Words+).

	Throat vibration switch			Voice-activated switch		
Metrics	AM	PM	Overall	AM	PM	Overall
Sensitivity (%)	85.9	86.4	86.2	82.4	63.5	70.4
Specificity (%)	100	100	100	100	100	100
False negatives	18	18	36	27	96	123
Misses due to timing	5	14	19	3	7	10
Average time/key (s)	18.81 ± 2.45	22.20 ± 3.94	20.51 ± 1.70	24.28 ± 5.61	39.30 ± 2.52	31.79 ± 7.51
Average time/word (s)	108.24 ± 12.80	125.96 ± 33.68	117.10 ± 8.86	107.91 ± 18.05	222.19 ± 25.24	165.05 ± 57.14
Average time/task (s)	324.72 ± 38.41	379.64 ± 57.86	352.18 ± 27.46	371.63 ± 68.14	732.67 ± 70.83	552.15 ± 180.52
Average change in level of exertion/session	0.33	0.33	0.33	2.00	2.00	2.00
Single cycle breaks	1	2	3	2	5	7
Rest periods	0	0	0	1	8	9
Average time/rest period (s)	0	0	0	16.48 ± 0.00	18.99 ± 2.76	17.73 ± 1.25

a motor speech disorder, we used an adapted rating scale display and performed manual scanning for the participant by pointing to each rating level – the participant indicated his choice with a single tongue click for 'yes' when we pointed to the rating he wanted. We then confirmed the selection by asking if the level chosen was the participant's intended selection. Again, the participant would confirm with a single tongue click or correct the selection by indicating 'no' with two tongue clicks. The process would then be repeated until a confirmed rating choice was obtained. A video recording was made of each session to capture the activity of the on-screen keyboard, the LED indicator on the 'throat vibration switch' or the audible beeps of the voice-activated switch, and the participant's audible vocalizations. These recordings were used to log the number of errors that occurred during each session.

Results

Quantitative measures of sensitivity, specificity, types of errors, speed, and level of fatigue were used as performance metrics for each device. A summary of the throat vibration switch and voice-activated switch data are presented in Table I. 'Misses due to timing' occurred when John activated the switch either before or after the scan selection changed. The metric 'single cycle breaks' enumerates instances where John intentionally allowed the on-screen keyboard to scan past the desired character so as to give a brief rest period; whereas, 'rest periods' are instances where he indicated that he was going to take a break (by looking to the side) before continuing with the task.

As can be seen in Table I, the throat vibration switch outperformed the voice-activated switch in terms of sensitivity ($p < 10^{-4}$, *t*-test), speed ($p < 10^{-3}$, *t*-test), and user-perceived level of fatigue ($p < 10^{-4}$, *t*-test). John indicated that the use of this switch was less tiring than the use of the voice-activated switch, which was reflected in the data. The slight decrease in speed and slight increase in number of breaks observed between morning and afternoon sessions was expected and attributable to John's level of fatigue, which was known to increase as the day progressed. There were more misses due to timing with the throat vibration switch than with the voice-activated switch; this may have been due to John's unfamiliarity with the response rate of the new switch. For example, selection errors or misses with the throat vibration switch occurred when John anticipated his scan selection and inadvertently activated the switch too early. A decrease in the number of misses is expected after extended use of the device as John will be able to adjust the current WiViK® scan rate (1.5 s) to best match his scanning proficiency.

The sensitivity of the voice-activated switch decreased significantly from morning to afternoon sessions, resulting in increased numbers of false negatives and rest periods, and decreased speed. A comparison between data for morning and afternoon sessions for the voice-activated switch demonstrated a marked decrease in performance, which showed the affect of fatigue on switch usage. John indicated that he felt more tired after completing tasks with the voice-activated switch, which was also reflected in his increased need for extended rest periods. The voice-activated switch had less misses because of timing than the throat vibration switch, misses only occurred when John activated the switch too late. This difference was attributed to his level of fatigue as the 1.5-s scan rate allowed him to rest between activations (positively impacting the results for this variable), but was not sufficient when he became increasingly fatigued. The specificities of both switches were identical (100%) as no false positives were observed.

With the QUEST 2.0 questionnaire, John's mean satisfaction score for the voice-activated switch was 2.25 (±0.71) and for the throat vibration switch was 4.62 (±0.52) suggesting increased satisfaction with the new switch. John's educational assistant reported mean satisfaction scores for the voice-activated switch of 2.87 (±0.64) and 4.87 (±0.35), for the throat vibration switch. One additional item (How satisfied are you with the look of your assistive device?) was added to the QUEST 2.0 items and was scored separately, as per the scoring protocol. Both John and his care worker rated this item at 3 for the voice-activated switch, noting it had too many pieces. Both rated this item at 4 for the throat vibration switch. John noted that he particularly liked the customized camouflaged fabric used to create the neck band.

In response to the four qualitative questions, both John and his care worker commented on the increased rate of text production that John experienced when using the throat vibration switch for word processing activities. Both commented that John was able to sustain use of the throat vibration switch for longer periods of time relative to the voice-activated switch, hence resulting in John being able to participate in a wider variety of activities including online social networking, games, creative writing, and surfing the web. John reported that he felt more independent using the throat vibration switch; his care worker felt that both switches required about the same amount of assistance but noted that she found the throat vibration switch to be more reliable. John noted that if he could change one thing about the throat vibration switch, he would like it to be wireless.

Discussion

The results presented in Table I indicate that the throat vibration switch was a notable enhancement over John's current voice-activated switch; it demonstrated increased sensitivity and speed, and decreased the level of fatigue experienced by the user. Moreover, the positive effect of introducing the throat vibration switch to the user was quite noticeable after our first data collection session as he continued to use it to communicate with us; he asked us about the kinds of movies we liked to watch and told us about his favourite music rock group (Slipknot). The enjoyment he experienced from having the ability to direct the conversation instead of just answering yes or no to our questions was as obvious as the grin on his face. His educational assistant commented that this was the first time she had ever seen him write such long messages with his computer. One of his messages was: 'can u make a WiViK page for y8.com the king of fighters i need to press two keys at once ol'. This new opportunity for communication can be very important in improving John's quality of life [33].

The throat vibration switch provides a promising new switch alternative for individuals with severe and multiple disabilities who are able to produce vocalizations. Although this article focused on one particular individual, the device lends itself to a larger user population as the ability to produce periodic vocal cord vibrations is not unique to individuals with hypotonic cerebral palsy [34]. Further research is needed to assess the throat vibration switch with other individuals with severe and/or multiple disabilities, to determine the generality of the findings, as well as their consistency over time, and to improve upon its current design. Some possible design improvements may include the adaptation of the switch to control a variety of other systems (e.g., devices for speech, mobility, and environmental control), the use of a wireless accelerometer, the detection of multiple pitch frequencies to allow for tertiary switch outputs, or the integration of an automatic adaptable threshold. The results obtained via the QUEST 2.0 questionnaire suggest that a higher level of satisfaction with the throat vibration switch is perceived relative to an existing commercial sound-based switch.

Conclusion

A new device called the 'throat vibration switch' was designed as an alternative access pathway for an individual with hypotonic cerebral palsy. The throat vibration switch outperformed a commercial voice-activated switch in terms of sensitivity, speed, and user-perceived level of exertion. Both the participant and his care worker were more satisfied with the throat vibration switch than with the voice-activated switch, noting that the former allowed the participant to work faster for longer periods of time on the computer and to participate in a wider variety of activities. Further research is needed to determine the generalizability of the findings to other user populations.

Acknowledgements

We thank Ka Lun Tam and Pierre Duez for their invaluable technical support. This research was funded by the Canada Research Chairs Program, the WB Foundation, and the Remad Foundation.

References

1. Statistics Canada – Social and Aboriginal Statistics Division. Participation and activity limitation survey 2006: Analytical report. Ottawa, ON: Ministry of Industry; Dec 2007. 89-628-XIE. 38. Available from: http://www.statcan.gc.ca/bsolc/olc-cel/olc-cel?catno=89-628-X&lang=eng
2. National Dissemination Center for Children with Disabilities. Internet. Electronic Citation. http://www.nichcy.org/Disabilities/Specific/Pages/SpeechLanguageImpairments.aspx. Last accessed April 2009. Washington, DC: NICHCY.
3. Lancioni GE, Singh NN, O'Reilly MF, Oliva D. Some recent research efforts on microswitches for persons with multiple disabilities. J Child Family Studies 2003;12:251–256.
4. DiCarlo CF, Banajee M. Using voice output devices to increase initiations of young children with disabilities. J Early Interv 2000;23:191–199.
5. Romski MA, Sevcik R, Adamson LB, Cheslock M. Toddlers, parent-implemented augmented language interventions, and communication development. Paper presented at the biennial conference of the International Society for Augmentative and Alternative Communication; Dusseldorf, Germany; 2006.
6. Light J, Drager K. AAC technologies for young children with complex communication needs: State of the science and future research directions. Augment Altern Commun 2007; 23:204–216.
7. Sevcik RA, Romski MA, Adamson LB. Measuring AAC interventions for individuals with severe developmental disabilities. Augment Altern Commun 1999;15:38–44.
8. Light J, Drager K. Improving the design of augmentative and alternative communication technologies for young children. Assist Technol 2002;14:17–32.
9. Blackstone S, Williams M, Wilkins D. Key principles underlying research and practice in AAC. Augment Altern Commun 2007;23:191–203.
10. Higginbotham JD, Shane H, Russell S, Caves K. Access to AAC: Present, past, and future. Augment Altern Commun 2007;23:243–257.
11. Pennington L, Marshall J, Goldbart J. Describing participants in AAC research and their communicative environments: Guidelines for research and practice. Disabil Rehabil 2007; 29:521–535.
12. Lancioni GE, Singh NN, O'Reilly MF, Sigafoos J, Green V, Chiapparino C, Stasolla F, Oliva D. A voice-detecting sensor and a scanning keyboard emulator to support word writing by two boys with extensive motor disabilities. Res Develop Disabil 2009;30:203–209.
13. Lancioni GE, Lems S. Using a microswitch for vocalization responses with persons with multiple disabilities. Rehabil Eng 2001;23:745–748.
14. Chang A, Karnell MP. Perceived phonatory effort and phonation threshold pressure across a prolonged voice loading task: A study of vocal fatigue. J Voice 2004;18:454–466.
15. Lund SK, Light J. Long-term outcomes for individuals who use augmentative and alternative communication: Part III – contributing factors. Augment Altern Commun 2007;23:323–325.
16. Smith MM, Connolly I. Roles of aided communication: Perspectives of adults who use AAC. Disabil Rehabil: Assist Technol 2008;3:260–273.
17. Long T, Huang L, Woodbridge M, Woolverton M, Minkel J. Integrating assistive technology into an outcome-driven model of service delivery. Infants Young Children 2003;16:272–283.
18. Lund SK, Light J. Long-term outcomes for individuals who use augmentative and alternative communication: Part I – what is a "good" outcome? Augment Altern Commun 2006; 22:284–299.
19. Words+. Internet. Electronic Citation. http://www.words-plus.com/website/products/input/istswtch.htm. Last accessed March 2009. Lancaster, CA: Simulations Plus.
20. WiViK. Internet. Electronic Citation. http://www.wivik.com/. Last accessed April 2009. Toronto, ON: Bloorview Kids Rehab.
21. Harada S, Wobbrock J, Landay J, Malkin J, Bilmes J. Longitudinal study of people learning to use continuous voice-based cursor control. In: Proceeding of the Conference in Human Factors in Computing Systems; 2009.
22. Lancioni G, Singh N, O'Reilly M, Oliva D, Groeneweg J. Enabling a girl with multiple disabilities to control her favourite stimuli through vocalization and a dual-microphone microswitch. J Vis Impair Blind 2005;99:133–140.
23. Wilson KG. The Columbia guide to standard American English. New York: Columbia University Press; 1993.
24. Baken RJ. Clinical measurement of speech and voice. London: Taylor and Francis Ltd; 1987.
25. Talkin D. A robust algorithm for pitch tracking (RAPT). In: Kleijn WB, Paliwal KK, editors. Speech coding and synthesis. Amsterdam: Elsevier; 1995. pp 495–518.
26. Scherer MJ. Outcomes of assistive technology use on quality of life. Disabil Rehabil 1996;18:439–448.
27. Scherer MJ, Sax C, Vanbiervliet A, Cushman LA, Scherer JV. Predictors of assistive technology use: The importance of personal and psychosocial factors. Disabil Rehabil 2005; 27:1321–1331.
28. Scherer MJ. The change in emphasis from people to person: Introduction to the special issue on assistive technology. Disabil Rehabil 2002;24:1–4.
29. AutoHotkey. Internet. 2009. Electronic Citation. http://www.autohotkey.com/. Last accessed April 2009.
30. Borg G. Borg's Perceived Exertion and Pain Scales. Stockholm: Human Kinetics; 1998.
31. Demers L, Weiss-Lambrou R, Ska B. Quebec user evaluation of satisfaction with assistive technology QUEST 2.0 – An outcome measure for assistive technology devices. Webster (NY): Institute for Matching Person and Technology, 2000.
32. Demers L, Weiss-Lambrou R, Ska B. The Quebec User satisfaction with assistive technology (QUEST 2.0): An overview and recent progress. Technol Disabil 2002;14:101–105.
33. Felce D, Perry J. Quality of life: Its definition and measurement. Res Develop Disabil 1995;16:51–74.
34. Yorkston KM, Beukelman DR, Strand EA, Bell KR. Laryngeal function. In: Yorkston KM, Beukelman DR, Strand EA, Bell KR. Management of motor speech disorders in children and adults. 2nd ed. Texas: Pro-ed; 1999. pp 327–358.